

1. HYDROGEOCHEMICAL CONCEPTUAL MODEL – GOATHILL NORTH ROCK PILE

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2. STATEMENT OF THE PROBLEM

What is the conceptual nature of the physical and chemical controls on the geochemical evolution of weathering in a mined rock pile similar to the Goathill North rock pile?

Objectives of the study include:

- Presenting a conceptual model of the hydrogeochemical conditions in a rock pile
- Outlining the major geochemical and hydrologic data relevant to the model
- Describing the consistency (or lack thereof) of the available data with the proposed model

3. PREVIOUS WORK

The Project's conceptual geologic model is described and evaluated in DRA -6. The general hydrologic conceptual model is presented in DRA-15. An approach to formulating a large-scale coupled conceptualization of flow and reactive geochemical transport is provided in DRA-38.

Site-wide chemistry of ground and surface water has recently been evaluated in great detail by the U.S. Geological Survey in a sequence of reports that are subsets of a project titled “Questa Baseline and Pre-Mining Ground-Water Investigation” (Nordstrom, 2007). Earlier conceptualizations of the system behavior are found in Robertson GeoConsultants (2000) and Lefebvre and Lamontagne (2002).

Other DRAs related to aspects of water chemistry and its potential impacts on mineral stabilities and clay-mineral formation include DRA-28A and DRA-29 through -34. The following DRA is based substantially on data and information presented in DRA-28a, “Water Chemistry – Goat Hill North Rock Pile”, to which the reader is referred.

4. TECHNICAL APPROACH

The approach used in this DRA is:

- Propose a conceptual hydrogeochemical model.
- Comment on specific features of the model that are important to the geochemical evolution of solids and waters in such a system.
- Evaluate the extent to which available data comports with the major features of the conceptual model.

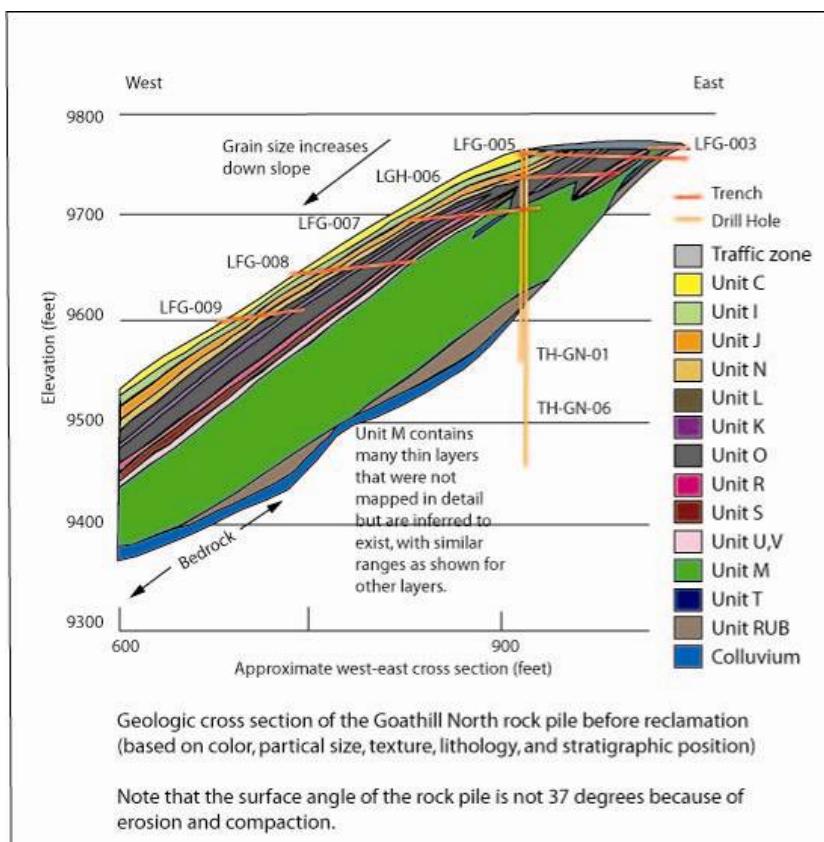
5. CONCEPTUAL MODEL

5.1 Geologic Framework and Context

The conceptual model of the Goathill system begins with the geologic framework of the rock pile (Figure 1, a schematic cross-section of the upper third of the stable portion of Goathill North rock pile [GHN], for which control is provided by trenches and vertical boreholes [DRA-6]). The rock pile is a generally stratified accumulation of aerially deposited, clastic sediments. As observed in GHN 25-40 years after initial deposition, the sediments are slightly consolidated and locally incipiently cemented with secondary gypsum and/or iron oxides/hydroxides (ferrihydrite to goethite) and hydroxysulfates (jarosite). The provenance of the rock fragments in the pile is known with substantial precision: they all were derived from hydrothermally-altered igneous rocks, predominantly andesites and rhyolites but also including some intermediate to alkaline intrusive rocks of essentially similar chemical composition, in the Questa molybdenum mine workings. Some of the rock in the rock pile probably had also been weathered in the natural supergene environment before open-pit mining began. There are two dominant hydrothermal-alteration assemblages seen in the rocks: propylitic and quartz-sericite-pyrite (or “phyllitic”). The nature of these alteration styles and their origin through hydrothermal metasomatic processes is discussed in DRA-6. A critical feature of the hydrothermally-altered rocks is that they typically contain pyrite, at concentrations from a fraction of 1% to local concentrations that may approach or even exceed 10%.

The mechanical derivation of the fragments of rock in the pile is atypical of natural sedimentary deposits, with the sediment derived by anthropogenic processes (blasting and scooping form rock faces, followed by rapid transport in haulage trucks, during which comminution of particles occurs) from. The rock, as mechanically eroded by the mine and placed in trucks, is poorly sorted, ranging in size from large boulders to clay-sized particles. Truck loads of mined rock were moved ca 10 road-km from the mine to a disposal area such as Goathill Gulch. High on the slope of the hillside, operators constructed a pad on which and from which mined rock could be discharged. In some cases, discharge was directly from the truck over the edge of the working pad; in other cases, rock was discharged to the pad and then pushed to the hillside by bulldozer. In both cases, the outcome was that the rock was transported subaerially, under gravity, down the existing slope. The natural slope was approximately 35° overall, but locally ranged over both steeper and shallower angles. The surface of the native ground was typically locally-derived colluvium and weathered bedrock (McLemore et al., 2006); the bedrock from which this was derived was generally similar in lithology and geologic history to the rock from which the rock-pile materials were developed, though lacking in molybdenum sufficiently elevated to justify mining. The colluvium typically includes a fine-grained soil matrix, the saturated hydraulic conductivity of which is orders of magnitude lower than the saturated hydraulic conductivity of the mined rock placed above it.

Figure 1 Geological conceptual model of the stable portion of GHN (from DRA-6). Rock material was generally placed at angle of repose (approximately 37°), but the dip of the individual layers was not consistent. The layers ranged in measured dip from 20° to 40°. Some variations are due to compaction of the rock-pile material since original placement, irregularities of the material that allowed for locally different depositional dips, and pinchouts in layers, but some of the range in dips also is due to recording apparent dips.



As the heterogeneous mined rock moved down the hillside, it formed sedimentary layers with a variety of geometries – lenses, stringers, aprons, wedges - along the slope, the details depending on the specifics of the load being placed, the specific manner and location of its placement, and the prior condition of the slope down which the rock was rolling. A general feature of all such depositional events is that there was a longitudinal coarsening of particles down because more massive rocks had greater momentum than did finer particles. It is apparent from watching similar truck-dump operations at other facilities today that there is some comminution of particles during the placement process also. Because the specific locations of dumping/pushing from the safety pad changed over the life of the operation, there was a tendency to form overlapping depositional units. The overall result is a stratified system, with spatially ranging extents of lateral continuity, ranging from perhaps a few tens of meters laterally (and generally widening downslope) to perhaps a hundred meters or more longitudinally down the principal axis of deposition. The overall angle of repose for the aerially-deposited sediments was approximately 36°, and this also is close to the average slope angle that is observed in macro-scale layers within the pile today. Please see DRAs-42, -43, -44, and -50 for

discussion of measured friction angle of GHN rock fragments and the pile's angle of repose.

After deposition (including during hiatuses in local deposition on portions of a pile as discharge areas moved), the unconsolidated surfaces of the pile were subject to erosion and mass wasting; gullying on final rock pile surfaces is well developed. Where such processes occurred during rock-pile construction, it would also have affected the details of subsequent sediment deposition. Based on theoretical considerations and studies at other mine sites, it is likely that subsequent to deposition there has been some consolidation of the rock piles at Questa. Quantitative studies elsewhere suggest that total consolidation in mined rock piles is on the order of 10% of the original depth and almost all of that occurs in the first 10 years after deposition (D. van Zyl, personal communication, 2007; W. Wilson, personal communication, 2007). The low strain and slow rate of this degree of compaction, as well as the absence of expelled water as would occur in compaction of marine sediments, leaves the depositional stratigraphy and structure largely intact.

5.2 Hydrogeologic Framework and Context

The conceptual model of water chemistry in Goathill North is that springs and seeps at the rock pile represent the accumulation of long-term seepage of infiltrating water that has accumulated in saturated (probably perched) zones above the base of the pile. The large-scale conceptualization of fluid flow in Goathill North is shown in Figure 2. The basis for this section is DRA-15, published and unpublished work by L.M. Cathles and colleagues (e.g., Cathles and Apps, 1975; Cathles, 1994), and the data and evaluations of DRA-28.

All water in the rock-pile system originated as infiltration of local meteoric water (Campbell and Hendrickx, 2006). The precipitation that feeds the system is very dilute, as is all natural precipitation (Berner and Berner, 1996). Water chemistry in the pile evolves due to air-water-rock chemical interactions in pore spaces along flow path. In Figure 1 rock clasts and minerals of ranging composition are shown schematically in colors. Pore space, shown in light blue is under negative pressure, but there can be film flow across solid surfaces and intra-rock pores (and some very small inter-rock pores) may be saturated or nearly so. A conceptualization of the physical system at small scale is shown in Figure 3. The major phase regions associated with this model are described further in Table 1, which also presents representative proportions of the total volume, based on controlled experimental results at bench scale (Cathles, personal communication, 2006). In typical rock dumps, gravitational self-compaction and migration of fines will decrease bulk porosity by about 10%, usually over a few years to perhaps a decade (L. M. Cathles, personal communication, 2006; D. van Zyl, personal communication, 2007). Note that in rock piles, or portions of rock piles, with high percentages of fines, V_f will increase and V_g decrease over time as the pile “wets up”, because the fines can retain higher moisture contents due to capillary forces than can coarse particles with large voids.

Figure 2 Conceptual Model of Fluid Flow, Goathill North Rockpile, with Goathill Spring. Net Precipitation = [Ppt-(Runoff +Evap)] = Infiltration. Counter-current flow of water downward (gravity) and air upward (buoyancy). Additional O₂ flux by diffusion across surface.

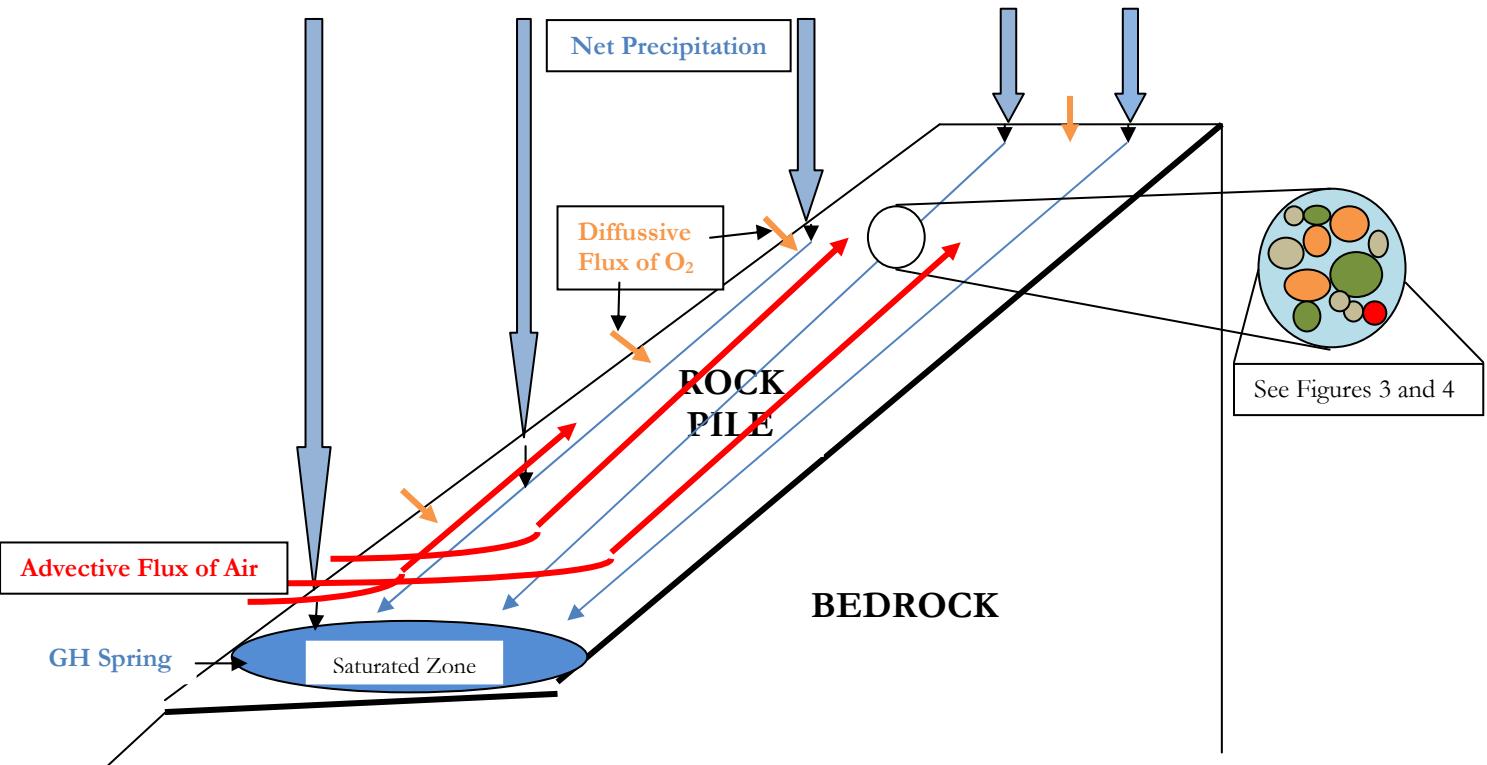
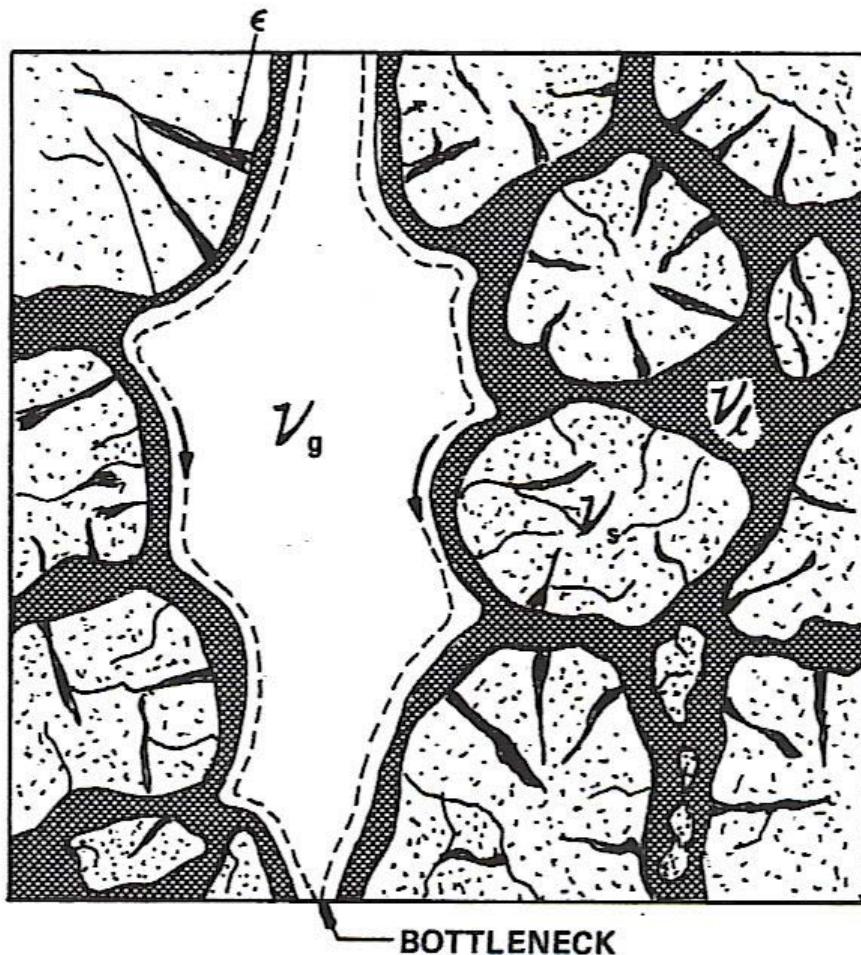


Table 1 Phase regions – Terminology [After unpublished report of work conducted in 1977, personal communication from L.M. Cathles, 2006]

Phase	Symbol (Fig. 2)	Dynamics	Test-Column (Volume Percent)
Solid rocks, including closed (but not open) pores within rock	V _s	Stagnant (dead space)	59%
Open porosity within rock	E	Stagnant (dead space)	2%
Water-filled void space between rocks	V _l	Mobile to aqueous solution	19%
Gas (air)-filled space between rocks	V _g	Mobile air flow or trapped air pockets	19%

Figure 3 Schematic static section through rock pile. Rock solid (V_s); Primary rock porosity (ϵ); Gas (air)-filled void (V_g); Water-filled void (V_l). [Figure based on unpublished report of work conducted in 1977, personal communication from L.M. Cathles, 2006]



As water is added to the rock pile (by percolation of infiltrating precipitation, and locally along the sole of the pile by flow of bedrock water in fractures that debouch into mined rock of the pile), the boundary-layer flow over rock particles increases, and at some point “bottlenecks” in inter-rock voids form as boundary layers overlap (bottom of Figure 3). At this stage, flooding of the bottlenecked pore occurs, with water filling the bottlenecked void and flowing then to the next most permeable zone above the bottleneck, again as film flow. The unsaturated pores below the bottleneck remain drained, and flow goes to fewer and fewer – but more and more permeable channels. Over time, fine layers (or matrix-supported layers that also include clasts) will become closer to saturation (negative pressures decrease), and the volumetric (and mass) flux of water downward under gravity through the fines will increase. Although probably never in a strictly true physical steady state, variations in flow associated with storm events and even seasonality typically dampens with depth (Freeze and Cherry, 1979), and deep percolation of water, averaged over areas of tens to hundreds of meters, steadies.

Clast-supported boulder layers, in contrast to matrix-supported, fine-grained layers which retain moisture, have inter-rock voids too large to allow significant saturation. These zones, which may be continuous over some tens to perhaps locally 100 meters along depositional strike of the sediments (see Section 5.1 above and DRA-6, are connected tortuously in the pile, and these coarse, clast-supported zones are the principal loci of convective air flow. The driving force for convective flow is buoyancy, derived either from heating (by the exothermic pyrite-oxidation process) or by the loss of O₂ from air as it reacts with sulfides in the rock pile. Flow of liquid water in the coarse layers is limited to film-flow across boulder surfaces. Although the rock pile is unsaturated, water percolates downward through the pile under gravity, primarily in fine-grained materials as discussed above, while air moves predominantly upward, and through the most permeable channels. The counter-current flow of water and air is shown schematically in Figure 3. The counter-current flow system develops because the construction of truck-dumped rock piles produces a bimodal distribution of permeabilities, with low permeabilities in the fine-grained matrix material and much higher, probably at least two orders of magnitude higher, permeabilities in the clast-supported coarse layers.

Figure 3 Schematic dynamic section through rock pile (From Cathles and Apps, 1975).
See also Figure 2.

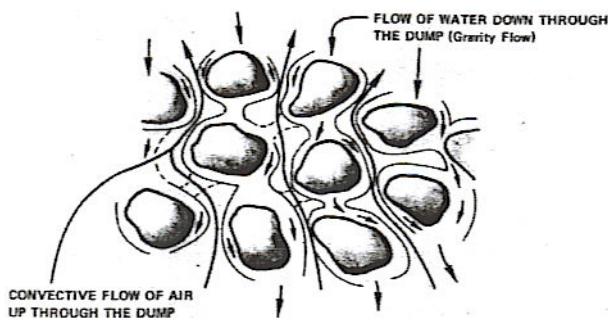


Fig. 1—Countercurrent interlocking flow of air and water through a leach dump. The flow of water is usually intermittent.

At depth within the pile, the unsaturated flow accumulates in a saturated zone that integrates the water chemistry as well as the physical flow. The accumulation of infiltration is concentrated at the interface of the rock pile with underlying, fine-grained and poorly transmissive colluvium, the permeability contrast allowing a perched zone of hydraulic saturation to form and persist (SRK, 2007).

5.3 Mineralogical Framework and Context

The particles in the rock pile are rocks or more rarely liberated single minerals derived by the mechanical breaking and subsequent transport of hydrothermally-altered igneous rocks (Section 5.1 above). The rock pile includes rocks whose protoliths were andesites,

rhyolites, and intermediate to silicic intrusive rocks. All the rocks in the pile contain some combination of a common set of minerals that comprises the vast majority of the total range of mineralogies seen throughout the rock pile: quart; plagioclase (typically near Ab90); K-feldspar, K-mica (muscovite/“sericite”, typically a 2M Illite by X-ray diffraction analysis); chlorite, epidote, calcite, kaolinite, gypsum, and pyrite. Fresh rock in the mine vicinity often contains fluorite, but fluorite is rarely observed in the current rock-pile materials. Iron oxides [often identifiable as goethite (FeOOH)] and a ferric hydroxysulfate [identifiable by X-ray as jarosite] are common in the matrix and as crusts on and partial replacements of pyrite. In addition to these minerals, a variety of other specific minerals have been identified in rock-pile samples (DRA-4).

Quartz and the two feldspars are primary igneous minerals, although in thin section the feldspars are almost always highly altered, usually especially so in the cores. Chlorite, epidote and calcite are typical of propylitically-altered rocks, which almost always contain pyrite also; the QSP-altered rocks have high concentrations of SiO_2 as quartz, abundant “sericite”, and highly elevated pyrite. Much of the rock has a porphyritic texture characterized by small quartz, plagioclase and K-feldspar phenocrysts in a very fine-grained to aphanitic, cloudy to brown groundmass, the mineralogic composition of which is very difficult to discern optically.

For the purposes of simple geochemical modeling (the scope of DRAs 28 – 33, which are supported by this report), we will consider a single rock composition as representative of rock fragments in the pile that can interact with air and water to (a) change water chemistry and (b) change mineralogy during weathering in the rock pile. The rock type we select is a hydrothermally-altered andesite, in which QSP alteration is superimposed on a pre-existing propylitic alteration. The model rock is based on a specific sample, GHN-JRM-0001 that has been analyzed petrographically by two independent systems (NMT and Mineral Services Canada). Attachment A presents a petrographic description of the smaple. Two representative thin sections of sample GHN-JRM-0001 are shown in Figure 5. [The detailed descriptions, labeled 2A and 2B below the photomicrographs are form MSC, 2008, the original petrographic report form which these are copied to this DRA.] Note that in saying this is a “representative” composition, we in no way imply that all rocks or rock fragments in Goathill North rock pile have exactly this composition. Rather, we use a single composition - one that includes the common rock-forming minerals of the andesite, rhyolite, and intermediate intrusive rocks, and trace minerals, especially sulfides and carbonates, that are widely distributed in all hydrothermally-altered samples – to have a specific composition to use in subsequent calculations that are intended to illustrate the trends expected in solids and aqueous solutions. This represents a “model” rock at a level of detail considered comparable to that available for other aspects of the system, including water chemistry, hydrogeologic flow mechanisms, and geotechnical properties of rock fragments.

In DRA-31, we attempt to calculate a forward-model (Alpers and Nordstrom, 1999) of the weathering of a representative GHN rock. The nature of the modeling task is to determine how close to the observed water chemistry and system mineralogy observed in the rock pile a simple geochemical can simulate results. To undertake such a model, we must start with a specific mineralogy, in terms of both mineral identification (and

composition) and proportions. Based on thin-section and microprobe studies, we consider gypsum, jarosite, and Fe-hydroxide (as Fe(OH)_3) to be secondary phases formed in the rock pile, so they are excluded from the nominal starting mineralogy. Kaolinite is known to be a hydrothermal mineral at Questa, and other Project studies [e.g., DRA-3; Graf et al., 2008] suggest that new kaolinite is not being formed, at least to date, in the rock pile. Therefore we treat kaolinite as a starting mineral. Additionally, although no fluorite was observed in the sample, its ubiquitous presence in the District as an auxiliary phase and the presence of elevated concentrations of dissolved fluoride in both GH Spring water and in ground and surface waters of the District lead us to include a small amount of fluorite in the model water. We exclude rutile from consideration because TiO_2 is probably essentially immobile in the low-temperature weathering system, and in any event it is not a mineral of interest for shear-strength considerations.

TABLE 2. Comparative mineralogy estimates, Sample GHN-JRM-0001 (Attachment A). Model mineral percentages are normalized to 100%. Blank: Not observed or not modeled. Models assume minor minerals at 1 wt %. MSC=Mineral Services Canada. UBC=University of British Columbia. NMIMT>New Mexico Institute of Mining and Technology. GCM- Geochimica. Note that Columns 1-3 are in Vol%; Column 4 in Wt%.

Mineral	MSC /Rietveld (UBC) – Vol%	NMIMT Quantitative Method – Vol%	GCM Model – Initial Rock – Vol%	GCM Model: Initial Rock – (Reacted Py + Jar+Goe+Gyp) Wt%
Quartz	41.5	38	41	40
K-spar	12.5	15	12	12
Plag	13.4	10	13	13
Chlorite	3.9	4	4	4
Illite	13.6	23	21	21
Biotite	4.8	0.01		
Epidote	Trace	0.1	1	1
Calcite	0.4	0.4	1	1
Kaolinite	1	1	1	1
Pyrite	3.8	3	5	3
Rutile	Trace	0.5		
Fluorite			1	1
Gypsum	1.6	0.8		1
Jarosite	1.5	2		2
Fe-Hydroxide	2	1		1

Figure 5a Photomicrograph, GHN-JRM-001 (MSC, 2008). Plane-Polarized Light.

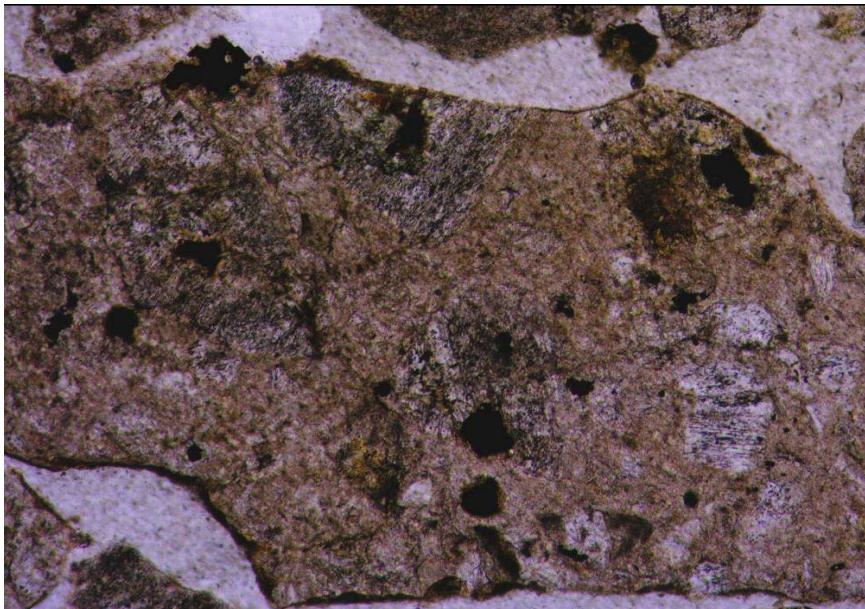


Fig. 2A: Photomicrograph of a porphyritic fragment in sample GHN-JRM-0001, showing the brownish groundmass and white to grey, altered plagioclase phenocrysts. Note the thin rim of Fe-oxides /hydroxides (dark brown) around the clast. Plane-Polarized Light, FOV = ~ 1 mm.

Figure 5b Photomicrograph, GHN-JRM-001 (MSC, 2008). Reflected Light.

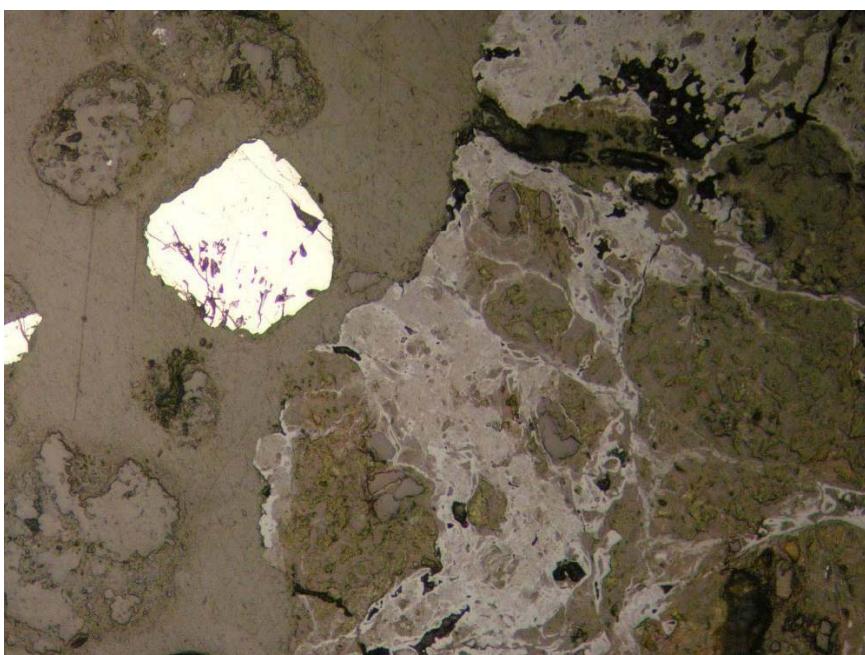


Fig. 2B: Close-up of sample GHN-JRM-0001, showing an unaltered pyrite grain next to a clast made up of cluster (possible former clasts) of illite-sericite in a matrix of Fe-oxides / hydroxides

around clasts. Note clean, but scalloped edges of pyrite; a reaction zone with accumulation of goethite or jarosite is not present on the pyrite itself. Reflected Light, FOV = ~ 1 mm.

5.4 Hydrogeochemical Framework and Context

Stable isotope geochemistry of pore water within the pile shows it to be of meteoric origin, modified by evaporation before or during the infiltration (DRA-12, Campbell and Hendrickx, 2006). Because meteoric water that initially infiltrates the rock pile is very dilute (e.g., Berner and Berner, 1996)¹, essentially all the solutes in water samples must derive from water-rock interactions along flow paths in the rock pile. Goathill North rock pile was constructed between 1969 and 1982, and pre-mining records do not show a pre-existing spring in this location; indeed, the potentiometric surface of bedrock is 475 feet (145 m) below the spring elevation (SRK, 2007). We conclude that the spring has developed over a period of 25 to 40 years due to infiltration of local precipitation through the rock pile and subsequent water-air-rock interactions within the rock pile.

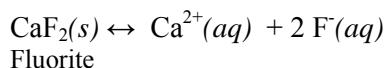
Typical water chemistry for Goathill Spring is shown in Table 3 (see DRA-28 for details).

Table 3 Typical Water Chemistry, Goathill Spring (2001-2007) [mg/L, except pH in su; Alkalinity in mg CaCO₃/L; T in °C; Q in L/s] – See DRA-28

pH	Total Alkalinity	TDS	Si	Ca	Mg	Na	K	T
2.78	< 5	20,000	50	370	740	9.4	2.1	10
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Cl	F	SO ₄	Al	Cu	Fe (total)	Mn	Q	DO
29	91	13,750	1400	10	690	430	0.63	7.5

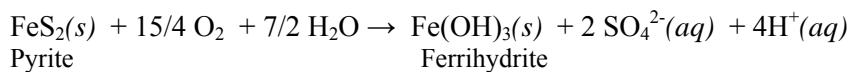
Given the observed mineralogy (e.g., Table 2), the water chemistry implies certain types of geochemical reactions are occurring in the rock-pile system:

- Simple dissolution, such as



- Redox reactions, such as

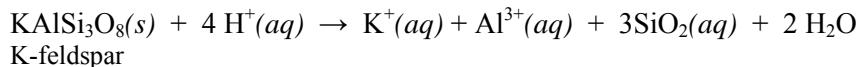
¹ Average annual precipitation at Santa Fe, NM (1975-1976) in mg/L except pH in su: Na: 0.06; K: 0.08; Mg: 0.15; Ca: 3.62; Cl: 0.33; SO₄: 2.95; pH 6.7 (Berner and Berner, 1996, Table 3.1, p. 73). Compare Table 3.



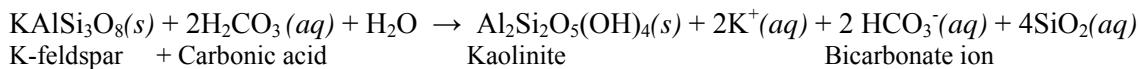
- Acid-Base Reactions, such as



And the special class of acid-base reaction, "hydrolysis" of silicates, such as



Note that the familiar form of the hydrolysis of K-feldspar producing kaolinite by incongruent dissolution is not consistent with the observed solution chemistry:



This reaction is common and well documented in near-surface weathering under circum-neutral pH, where the dominant weathering acid is carbonic, and bicarbonate is a stable product in solution. In the GH Spring water $\text{pH} < 3$, bicarbonate is not the stable form of dissolved CO_2 (note that dissolved carbonate alkalinity is non-detectable, see Table 3), and the major weathering agent is the strong acid, sulfuric. Note, too, that if kaolinite were a product of the hydrolysis reaction, the water would be low in dissolved Al (because it is tied up in the solid phase kaolinite), whereas in the GH Spring water, dissolved Al is very high, 1400 mg/L. Nordstrom (2007) shows that this is the case for many bedrock waters in the District, but for these waters, $\text{pH} > 5$ and bicarbonate would be a stable species. Additionally, as shown in Graf et al., 2008, stable-isotope analyses of clay minerals from local alteration scars and the GHN rock pile show no evidence of formation under low temperatures ($< 70\text{C}$), and detailed clay-mineralogy work and petrographic analysis has failed to identify any newly-formed clay minerals (DRA-3).

In addition to the elevated Al and silicon in solution (50 mg/L Si = 110 mg/L as SiO₂), the high Fe and sulfate in solution supports the pyrite oxidation process, and the elevated concentration of Mg, given the observed mineralogy, suggests that chlorite is dissolving. The low concentrations of Na and K suggest that feldspar hydrolysis is limited, probably by kinetic considerations (e.g., Brantley, 2005), although some K⁺ is being lost from solution as secondary jarosite. In addition to dissolution of fluorite, detailed microanalysis of Questa samples shows that the “sericite” contains significant substitution of F- for OH- in the hydroxyl position of the illite, and some of the observed 91 mg/L in GH Spring water may be from silicate dissolution also.

A critical observation that unites the aqueous chemistry, mineralogy, and hydrogeology of the rock pile is that it appears everywhere in the pile where observations have been made that iron is fully oxidized. As shown by field and modeling studies of rock piles (Cathles and Apps, 1975, Cathles, 1994, Ritchie, 2003), this requires that there be an advective flux of O₂ into the pile. If there is not, then at pyrite concentrations such as

those of the Questa piles, the interior of the system would rapidly (months) consume the available O₂, and the only access of O₂ to the system would be by diffusion across the dump surfaces. Although this doubtless occurs (the atmosphere is 21% O₂ by volume; see Figure 2), the mass flux of O₂ available via this route would lead to a system in which only the outer skin of the pile is oxidized, and the interior would remain anoxic. The ubiquitous presence of secondary ferric minerals such as jarosite as precipitates on clast surfaces and as incipient cements in matrix materials, requires that iron cycling be maintained by a sufficient fugacity of O₂ to convert ferrous to ferric iron rapidly. Although the ferrous-ferric conversion is catalyzed by microbiological components, the biota are obligate aerobes, and the ultimate oxidant must be O₂. As shown by Cathles and Apps (1975) and elaborated by the Australian researchers in the 1990s (Ritchie, 2003), the extensive and thorough oxidation of a rock pile requires that there be a substantial network of high-permeability features through which large fluxes of air can move. The O₂ in the air is not the principal direct oxidant of pyrite, but rather serves to replenish the ferric component of the aqueous iron system.

STATUS OF HYDROGEOCHEMICAL CONCEPTUAL MODEL

6.1 Sample Context and Consistency of the Data with the Conceptual Model

Hydrogeologic and geochemical data for GHN are addressed in detail in DRA-28a. That DRA specifically examines the consistency of field and laboratory data with the conceptual model presented here. The detailed geologic and hydrogeologic models are developed and defended in DRA-6 and DRA-15, respectively.

6.2 Assumptions

The major assumption of this analysis is only that the geologic observations and water analyses are sufficiently accurate and precise to be useful. The geologic observations are addressed in other DRAs, particularly DRA-1, -2, -3, -4, -5, and -6. The water chemistry has been developed under established quality-assurance and quality control programs at laboratories that have records of reliable analytical chemistry (DRA-28).

This DRA also assumes that the major principles of fluid flow described by Cathles and Apps (1975), Cathles (1994), and Ritchie (2003) are sound and can be applied to other waste rock dumps, such as those at Questa (DRA-15). Because those evaluations are physically based and because the rock piles of the porphyry molybdenum system at Questa is substantially related to the rock piles of the porphyry copper systems studied by Cathles and his colleagues, we think the underlying physics and chemistry that they describe is directly applicable to the formulation of a conceptual model of fluid flow and transport for the Questa rock piles.

6.3 Major Results Affecting Understanding of Mineral Stabilities in the Rock Pile

For the purposes of evaluating water-rock interaction, we take the narrow ranges of flow and water chemistry in Goathill Spring (DRA-28a) to represent “steady-state” flow conditions through Goathill North rock pile, using the specific solution chemistry for the sample of 14-Nov-01 and a mean and median flow rate of 0.6 L/s to represent the accumulated infiltration through the pile. In only 25 to 40 years, water-rock interaction, representing chemical weathering of sulfide-bearing, alumino-silicate rocks by well-oxygenated waters under unsaturated flow conditions, has generated a low-pH, high-acidity, high-TDS, high-sulfate water with abundant dissolved cations including Al, Fe, Mg, Mn, and Ca; in addition to dissolved SO₄, the waters are notably enriched in dissolved F, as one would expect for weathering of a Climax-type porphyry molybdenum system.

The thermodynamic consequences of this solution chemistry are explored in DRAs 30 and 31. Heuristic modeling of acid generation and neutralization is described in DRA 31. Additional heuristic modeling of the weathering of a model Questa rock, a pyrite-and calcite-bearing andesite that has strong quartz-sericite-pyrite (QSP) hydrothermal alteration superimposed on an earlier propylitic alteration is discussed in DRA – 31. That model is discussed in terms of observed mineralogical reactions in local natural analog sites and among samples evaluated on GHN and the local natural analogs. DRA-33 evaluates the GH Spring water chemistry via inverse mass-balance considerations, conditioned on the solubility controls described in this conceptual model and the thermodynamic results presented in DRAs-30 and 31. Finally, DRA-32 evaluates progressive evaporation of pore waters with compositions similar to GH Spring in light of observed mineralogy of surficial crusts that form at least seasonally on Questa rock piles.

6. RELIABILITY ANALYSIS

At this time, we consider that the balance of the geologic, hydrogeologic, and geochemical evidence supports the simple conceptual model summarized here in Figure 2. Geologic evidence for the nature and sedimentologic forms of the rock piles are highly reliable at the level of this model. All evidence, as well as theoretical calculations, show that the rock pile is unsaturated, except for local perched saturated zones near the base of the pile. The general mineralogy of the rocks observed in the rock pile and in local natural analogs are consistent with the observed water chemistry from Goathill Spring. Specific analysis of the reliability of the DRA analysis for Goathill Spring is provided in section 6 of DRA-28, which accompanies this document.

The major limitation of the analysis is the extent to which the general conceptualizations provided here can be applied to and documented in detail for a quantitative model of a rock pile equivalent to the old Goathill North pile. The limitations of existing data, in both spatial range (almost all available detail is derived from the upper one-third of the rock pile, and much of that comes from one detailed traverse (Trench 9, and detail in relating the geologic-hydrologic-mineralogic context limits the extent to which the existing conceptual models can be tested rigorously). This inherently limits the ability of the project to address rates of change of the mineralogy and the geotechnical

characteristics of the samples, which is a constraint on the predictive power of our understanding of the behavior of the rock pile during weathering.

There remain uncertainties associated with the conceptual model for fluid flow. The QRPWASP Team has consistently considered that water that initially infiltrates into the rock pile (past about 2 m depth) moves continuously through the rock in a manner that can be described by Richard's equations for fluid flow, although the rock pile is unsaturated and the coarse- and fine-zones of the rock pile have substantially different hydraulic properties. The available analysis (DRA-15) indicates that the upper 2 to 5 m of the rock pile are subject to substantial cycles of drying under the climatic conditions of the Questa site, leading to seasonal formation of evaporative salts on as much as 75% of the rock-pile surfaces (DRA-8). During wet periods, there is substantial, variable wetting of the rock pile down to depths of approximately 10 m. Below 10 m, the QRPWASP analysis infers from numerical modeling and limited field measurements that moisture contents do not vary substantially over periods on the order of a year. There is compelling evidence from field observations and the large-scale behavior of the rock pile that, in three dimensions, there is tortuous connectivity of both the fine (water transmitting) and coarse (air transmitting layers, so that the system behaves continuously with respect to fluid flow at the scale of the entire rock pile.

That is not to say that the system behaves as, or has been modeled as, a single equivalent porous medium. There is substantial evidence, from the Questa rock piles (Sections 4.2, 4.4, 4.6.2, and 5.2; also DRA-29) and other rock piles (e.g., Smith and Beckie, 2003; Ritchie, 2003), that there are zones of preferential flow, both upward of air and downward of water. At the scale of whole rock piles, essentially all applied models use the Richard's equation approach, not only because it produces plausible results, but also because it is the only approach to modeling for which practicable programs of data collection are possible.

The best connection between field observations and modeling as to the physics of flow in GHN is the observation of the establishment of a steady flow regime at GH Spring in something less than 40 years (the rock pile age is 25 to 40 years), along with the recently computed particle-tracking model that shows transit times from recharge to discharge in the modeled rock pile ranging from a few to a few tens of years when tested against the best estimate range of Questa modeling boundary conditions and hydraulic properties (SVS, 2008).

However, not all project data are consistent with this approach. The most significant anomaly known now is that water collected from GH Spring and other seeps near the toe of the rock pile do not show a stable-isotope signature indicating substantial evaporation from local meteoric water, although their solution chemistry implies significant exposure to rock-pile materials. Hydrogeologic modeling and water-balance considerations require that up to 60% of ambient precipitation does not infiltrate into the pile. There is little evidence of overland flow or other runoff beyond small-scale gullying, and the QRPWASP model assumes that the overwhelming majority of the water that does not flow into and through the rock pile has been evaporated. Additionally, small samples of

pore water collected in the upper third of the rock pile have stable-isotope signatures for hydrogen and oxygen that indicate evaporation, although not to levels of 60% (DRA-12).

If the spring flow at GH Spring represents a well-integrated sample of steady-state flow through the rock pile, the lack of an evaporated isotope signature is hard to reconcile with a continuum flow model for deep infiltration through the rock pile. The stable-isotope signature can be explained if waters rapidly infiltrate along preferential pathways in the shallow system, bypassing the portion of the flow domain sampled in the shallow isotope studies, then coalesce to form the saturated flow that discharge at the GH Spring.

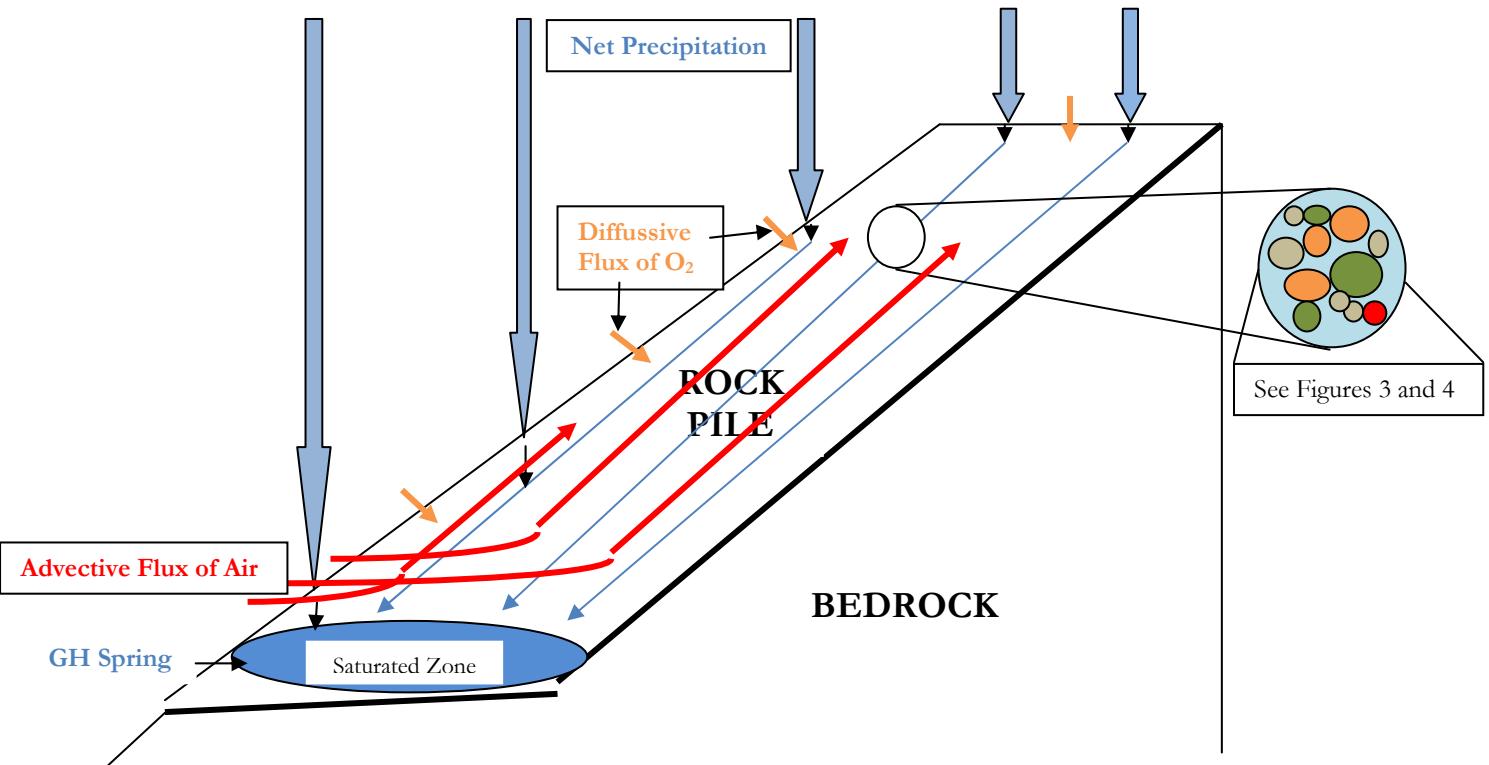
Although this is a physically plausible recharge scenario, it has not been demonstrated or observed at GHN and so remains speculative. While other information and inference (DRA-28 and -29; SRK, 2007) supports the interpretation of GH Spring as consistent with a dual-porosity modeled continuum flow system, the isotopic anomaly needs resolution before the flow modeling and geochemistry of GHN can be fully coordinated.

Notwithstanding these limitations, we consider that the weight of evidence assembled by the entire QRPWASP supports the conceptual model of the hydrogeochemical behavior of a rock pile set out here to be reliable as an description of how such a system behaves in terms of general physics of fluid flow and the direction and nature of chemical changes of both solids and liquids.

7. CURRENT CONCLUSION

For the purposes of evaluating water-rock interaction in a rock pile at Questa, we consider that the evidence is strong to support the following conceptual model summarized at large scale as Figure 2, and repeated here:

Conceptual Model of Fluid Flow, Goathill North Rockpile, with Goathill Spring. Net Precipitation = [Ppt-(Runoff +Evap)] = Infiltration. Counter-current flow of water downward (gravity) and air upward (buoyancy). Additional O₂ flux by diffusion across surface.



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ATTACHMENT A: PETROGRAPHIC DESCRIPTION – GHN-JRM-0001

Sample GHN-JRM-0001 [Protolithology: Andesite. QSP alteration superimposed on Propylitic]

Hand sample description:

The sample consists of small subangular light grey mineral and rock fragments, less than 5mm in length. Fragments stained by orange-red Fe-oxides /hydroxides are rare. The sample is not magnetic and does not react with cold dilute HCl. A variably strong yellow stain is produced in 10-15% of the clasts, typically occurring as groundmass around phenocrysts and produced by the reaction of sodium cobaltinitrite and K-feldspar. Very small grains of likely pyrite are disseminated throughout clasts (~5%).

Thin section description:

In this pervasively altered sample, fragments locally preserve a porphyritic texture characterized by small quartz, plagioclase and K-feldspar phenocrysts in a very fine-grained to aphanitic, cloudy to brown groundmass that typically could not be reliably identified optically. Very fine-grained to microcrystalline quartz, anhedral K-feldspar and plagioclase laths were however recognized forming the groundmass of some clasts.

Clusters of epidote ± chlorite occur within plagioclase phenocrysts, suggesting propylitic alteration of primary plagioclase to albite. Aggregates of chlorite ± rutile ± shreedy biotite also occur in porphyritic clasts, suggesting replacement of earlier mafic phases. Feldspars are also commonly altered by illite-sericite leading in the most altered clasts to a granular mixture of quartz ± illite-sericite ± pyrite, sporadically associated with possible kaolinite.

Pyrite is variably replaced by masses of Fe-oxides / hydroxides that also coat few clasts or form the interstitial groundmass of clastic fragments, locally associated with micro- to cryptocrystalline jarosite.

Possible gypsum was observed in clasts with epidote ± chlorite.

TABLE 1. Comparative mineralogy estimates, Sample GHN-JRM-0001 (Attachment A). Model mineral percentages are normalized to 100%. Blank: Not observed or not modeled. Models assume minor minerals at 1 wt %. MSC=Mineral Services Canada. UBC=University of British Columbia. NMIMT=New Mexico Institute of Mining and Technology. GCM- Geochimica. Note that Columns 1-3 are in Vol%; Column 4 in Wt%.

Mineral	MSC /Rietveld (UBC) – Vol%	NMIMT Quantitative Method – Vol%	GCM Model – Initial Rock – Vol%	GCM Model: Initial Rock – (Reacted Py + Jar+Goe+Gyp) Wt%
Quartz	41.5	38	41	40
K-spar	12.5	15	12	12
Plag	13.4	10	13	13
Chlorite	3.9	4	4	4
Illite	13.6	23	21	21
Biotite	4.8	0.01		
Epidote	Trace	0.1	1	1
Calcite	0.4	0.4	1	1
Kaolinite	1	1	1	1
Pyrite	3.8	3	5	3
Rutile	Trace	0.5		
Fluorite			1	1
Gypsum	1.6	0.8		1
Jarosite	1.5	2		2
Fe-Hydroxide	2	1		1