AQUIFER VULNERABILITY MAPPING IN KARSTIC TERRAIN ANTAMINA MINE, PERU

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Abstract

Antamina is a large open-pit copper and zinc mine located within the Central Andes of Northern Peru at an altitude of 4300 masl. The facilities are situated within the headwaters of several watersheds, within the Amazon basin. Nearby villages rely heavily on springs and streams for drinking and irrigation water. The principle source of baseflow during the dry season is from Cretaceous karstic limestone aquifers.

Antamina will produce nearly 1.4 billion tonnes of waste rock over its mine life. Finding suitable sites for storing large volumes of waste rock is often a challenging task – especially in karstic, alpine terrain. Detailed hydrogeological investigations are essential for delineating the karstic hydrogeologic watersheds associated with the proposed waste facilities, which are often very different than topographic (hydrologic) watersheds. Contamination vulnerability mapping at Antamina consisted of geological and karst mapping, geophysical surveys, geochemical testing, dye-tracer studies, drilling and aquifer testing. Detailed mapping followed by dye-tracer studies proved to be the most cost-effective methods for characterizing the karst aquifer systems. The results were used to optimize waste rock management at the site to minimize potential impacts on groundwater resources.

Introduction

The Antamina copper-zinc mine is located approximately 270 km due north of Lima within the Central Andes of Northern Peru, at an altitude of 4300 masl. The mine is situated on the eastern side of the Cordillera Blanca within the upper catchment of the Marañon River - a tributary of the Amazon River (see Figure 1). The Andean belt is a complex orogenic system containing several cordilleras, plateaus, basins and valleys. Approximately 10% percent of the surface area of the Peruvian Andes is covered by karstic limestones of Cretaceous age. These uplifted carbonate terrains are host to many polymetallic ore deposits occurring as porphyry, skarn, and replacement-type deposits. The waste facilities associated with these mines are often located within the same karstic terrains, potentially putting local (and possibly regional) karstic aquifers at risk of contamination. Local communities rely heavily on seeps, springs and rivers associated with these karstic aquifers for drinking water and irrigation water. Protecting the water resources in the areas of waste facilities has become one of the main priorities and challenges of the environmental department at Antamina.

Figure 1. Location Map

The contamination vulnerability of these aquifers needs to be assessed well in advance of mine development. The degree of risk with respect to development of mine waste facilities depends on the permeability and depth of the surface soils, the frequency of karst openings, the surface roughness, and the density and depth of penetration of the karst features. Less important is the distance from the proposed waste facility to the sensitive receptors (e.g. springs) since the high ground water velocities in karst reduces the potential for contaminant attenuation.

The main objectives of the studies undertaken at Antamina were to develop conceptual hydrogeological models for the proposed waste rock disposal areas in the Vallecito and Tucush Valleys, characterize the current ground water and seep/spring quality, and develop sound water quality monitoring programs related to waste disposal area development. This information was then used to modify the final configuration of the dumps to minimize potential impacts on water resources.

Study Approach

Defining the recharge and discharge areas related to the proposed waste storage facilities was key to recommending acceptable waste areas, disposal procedures and water quality monitoring locations.

Most of the water transport in karst is through highly localized and hydraulically-integrated conduits in the bedrock. Although drilling and monitoring well installation programs are the most commonly used investigation approach for characterizing hydrogeologic regimes and conducting ground water monitoring, the possibility of intersecting the main flow conduits within the karst system with drill holes is often very low. Seldom are ground water monitoring wells successful as a stand-alone system for monitoring ground water quality of waste facilities developed in karstic terrains.

Often the most cost-effective and reliable source of ground water quality information within karstic terrain are springs which have hydraulic connection to the facility being assessed. In many cases, karst springs provide a composite sample of the water moving through the karst aquifer. Dye tracing approaches are more conducive to mapping the ground water flows and determining which springs and monitoring wells have hydraulic connection with the waste facilities.

A heavy focus was therefore placed on field mapping of karstic features (recharge areas) and springs/streams (discharge areas) followed by dye-tracing studies. Field mapping methods included geologic mapping (stratigraphic and structural), air photo and satellite image interpretation, fracture trace analysis, geochemical characterization, soil types and thickness mapping, karst surface mapping and spring mapping.

Information derived from the field mapping was used to develop conceptual hydrogeological models for the waste sites and surrounding areas which included the following elements:

1. Recharge and discharge areas within the valleys with proposed waste rock disposal facilities;
2. Aquifer extent (hydrogeologic watersheds);
3. Lithologic units and faults which may act as flow boundaries or pathways;
4. Karst features that may act as flow paths; and
5. The potential for inter-basin hydraulic connection.

Mining and Mine Waste at Antamina

Antamina is a structurally-controlled polymetallic skarn orebody formed from successive intrusive phases of quartz-monzonite porphyry into Cretaceous aged limestones. Extensive hydrothermal alteration produced copper orebodies at the limestone contact, with zinc, lead and bismuth occurring in any rock type but typically at the green garnet contacts with limestone, marble and hornfels. Molybdenum is present in the intrusive core and silver is found in any of the skarn lithologies.

A total of 26.4 million Tonnes (Mt) of ore was processed in 2003, at average grades of 1.19% copper and 1.86% zinc, with 112.3 Mt of material being moved. Therefore, approximately 85 Mt of waste rock were produced in one year alone. Over the course of the mine life, an estimated 1.37 billion tonnes of waste rock is expected to be produced. Three main waste dump areas have been designated around the open pit mine. The East Dump, presently the only active dump, will be receiving up to 690 Mt of ‘random’ waste (i.e. both reactive and non-reactive waste). The Tucush dump, presently being developed, will receive about 590 Mt of non-reactive waste. The balance (about 90 Mt) will go to a smaller dump within the Vallecito Valley (see Figure 2). In addition, about 170 Mt of low grade ore will be temporarily stockpiled within the Antamina valley for future processing at the end of the mine life.

The Tucush, Vallecito and Antamina Valleys are partially underlain by karstic limestone of the Jumasha Formation (see Figure 2). The final areas of the Tucush and Vallecito dumps were originally designed to be 270 ha and 50 ha, respectively. The height of the dumps above the valley floors were expected to be approximately 200 m for Vallecito and 300 m for Tucush.

Physical Setting

Climate

The area has a typical Andean climate with two distinct seasons. The winter season, from April to October, is dry and cold. Most of the rainfall occurs during the warmer summer season, lasting from November through March. Elevation plays an important role in the climate and precipitation depths, producing several distinct microclimates within close proximity to the mine. Annual precipitation values for the mine and surrounding area range from about 1200 to 1500 mm.

Topography and Drainage

The topography in the area is characterized by steep, sharp limestone ridges and peaks, with peak altitudes ranging from 4,700 to 4,900 masl. The dominant ridge and valley trend is northwest (e.g. Vallecito and Tucush Valleys), reflecting the regional structural and tectonic fabric, with shorter structurally controlled northeast trending valleys such as the Antamina, Callapo, and Ayash Valleys.

The Tucush Valley is a 4.5 km long V-shaped valley located approximately 500 m northeast of the mine (see Figure 2). The valley has a depth of 400 to 600 m below the enclosing ridges. The catchment area of the valley is approximately 800 ha, however, only the southwest portion of the valley (covering 440 ha) contributes to surface water flow. The remaining 360 ha, situated on the northeast side of the valley, is underlain by karstic limestone, which diverts percolated water from the Tucush watershed laterally to the Ayash watershed. Waste rock disposal within the valley began in mid 2004.

The Vallecito Valley is a 1.3 km long U-shaped glacial valley located approximately 2 km southwest of the mine. Vallecito is a hanging valley - the product of different rates of glacial erosion between the main valley (Antamina) and the Vallecito Valley. The surface water catchment area of Vallecito (as defined by topography) is approximately 150 ha; however, only 66 ha (44 % of the watershed) is estimated to contribute to surface water flow due to low runoff coefficients within the karstic terrain. Surface water drainage is directed mainly to the Antamina Valley. The east wall of the Vallecito Valley showing the rough karstic surface is shown in Photo 1.

Surficial Geology

The non-karstic valley slopes are largely covered by low-permeability clayey residual soils formed from decomposition of the limestone and/or clayey colluvial soils formed from hillside erosion. The bases of the valleys are also lined with low-permeability glaciolacustrine, glacial till and residual clay soils with thickness up to 30 m. Although most of the proposed waste dumps were underlain by low-permeability soils, minimizing vertical percolation to the underlying limestone aquifers, approximately 16 % of the originally proposed Vallecito dump (43 ha) was underlain largely by bare karstic limestone. Approximately 22% of the original Tucush dump design (11 ha) was underlain by karstic limestone.

Bedrock Geology

The Cretaceous sedimentary sequence within the Antamina area is comprised of two main units:

1) A lower sequence made up primarily of clastic sediments (sandstones, quartzites, shales and minor carbonates). The lower clastic formations, including the Chimu, Santa, Carhuaz, and Farrat, together constitute the Goyllarisquizga Group. Karst is moderately developed within the Santa Formation.
2) An upper sequence consisting of a mainly calcareous facies (limestones, marls, sandstones and calcareous shales). Formations which comprise this facies include the Pariahuanca, Pariatambo, Jumasha and Celendin Formations.

All bedding is inclined at an average dip of about 70^{o}. Karst is more developed in the Middle Member of the Jumasha Formation compared to other members of the Jumasha or other limestone formations in the area. The Middle Member of the Jumasha is the most representative of the formation consisting of a medium- to thickly-bedded sequence of light grey limestones (weathered surface). The thickness of the Middle Member ranges from about 800 to 1000 m within the Antamina area.

Figure 2. Site Map

Figure 3. Geologic Section between Vallecito Valley and Tucush Valley

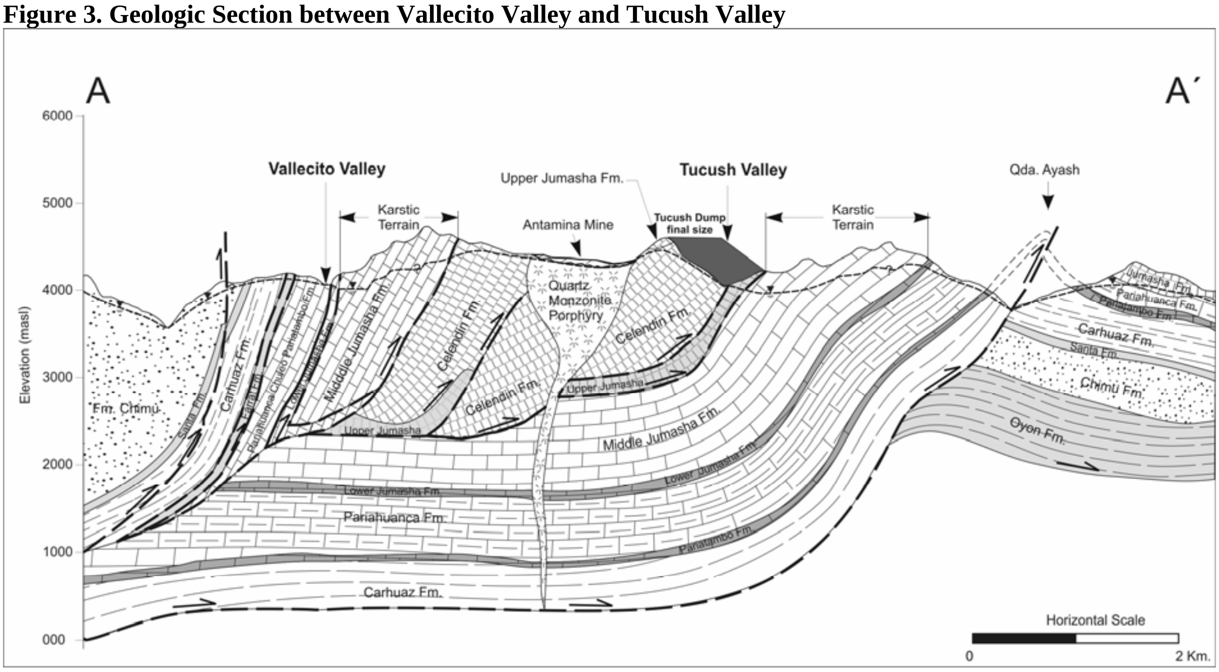


Photo 1. East Side of Vallecito Valley showing Karstic Jumasha Formation

The formations between the Jumasha and the Santa (Pariahuanca-Chulec-Pariatambo, Farrat and Carhuaz) appear to be a barriers to lateral movement of water from the Jumasha Formation. Similarly, the Upper Jumasha and Celendín Formation are expected to be hydraulic barriers. An interpreted geologic section between the Vallecito and Ayash Valleys is shown in Figure 3.

The Celendin Formation forms the west wall and the floor of the Tucush Valley and the east contact with the Jumasha Formation west of the open pit. The Celendin formation is a clayey unit consisting mainly of nodular grey marls and marly limestones interbedded with well-stratified calcareous mudstones and siltstones and thinly-bedded limestones. The formation is much less resistant than the adjacent Jumasha Formation and forms rounded hills covered with residual soils. The thickness of the formation ranges from approximately 200 to 500 m in the area.

Karst Features

The word "karst" refers to a type of terrain formed on carbonate rock where ground water has solutionally enlarged openings to form a subsurface drainage system. Karst features in the Vallecito and Tucush Valleys include small-scale surficial dissolution features (karren), and larger scale features such as dolines (sinkholes), karst shafts and swallow holes.

The upper reaches of the ridges have limited soil cover and a high density of karstic features. Runoff is expected to be low on the karst ridges and percolation high. The uppermost layer of the karstic limestone, which is extremely well-drained due to a high density of interconnected open fissures, is termed "epikarst". The epikarst layer within karstic terrains is normally between 3 to 10 m thick but it may be considerably deeper in alpine terrains such as that found at Antamina. This layer is dry for most of the year, but participates significantly in the subsurface transport of stormwater immediately following a precipitation event. The epikarst layer is largely responsible for the rapid "flashy" spring flows during and after high rainfalls at Antamina.

Sinkholes were identified through air photo interpretation and later mapped in detail in the field. The surface diameter of the sinkholes range from 5 to 25 m and are commonly filled with clayey soils. Deep dissolution features surround the perimeter of the sinkholes, and drain the stormwater overflow from the sinkhole after significant rain events.

Over 50 significant karstic shafts were identified within the Jumasha Formation on the east side of the Vallecito Valley and within the Jumasha which continues south of the Antamina Valley. Similar numbers of karst shafts were found within the Middle Member of the Jumasha Formation in the Tucush Valley. The shaft openings range in diameter from 0.5 – 5 m with depths ranging of 5 m to over 100 m. The shafts commonly occur at the intersection of bedding plane faults and major fractures or minor faults striking roughly perpendicular to the bedding. The deeper shafts are believed to be well connected to the water table and responsible for "funnelling" water from the epikarst layer to spring discharge areas.

Conduit and cave development appear be more concentrated within the following settings:

1. Along bedding planes of dissolution-prone units (particularly cleaner limestones of the Middle Jumasha Formation);
2. Zones of fracture concentration;

3. Bedding plane faults and cross-cutting faults;
4. Syncline and anticline axes;
5. Contacts between non-carbonate and carbonate bedrock units; and
6. Ground-water discharge points (major river valleys such as Rio Mosna).

Leachate Production from Waste Rock Areas

Potential environmental issues from developing mine waste facilities in any type of terrain include: 1) mobilization of heavy metals due to acid generation from possible sulphides; and 2) increased nitrate, hardness, and sulphate concentrations in the ground water. The amount of percolation into the waste rock pile is dependent on precipitation and evaporation rates, the slope of the waste rock pile surface and grain size, which largely determines the hydraulic conductivity of the material.

The grain size distributions of ore and waste rock at Antamina are highly variable, depending mainly on rock type. The non-reactive rock, consisting mainly of limestone, marble and hornfels, is typically coarse and blocky and highly permeable, while the reactive rock, consisting mainly of intrusive and skarns, is highly friable, resulting in a fine-grained mass and lower permeabilities.

Based on the current concepts for waste rock disposal, the rock currently destined to the Tucush Valley is coarse, blocky limestone with low sulphur content. Infiltration into this type of waste rock is expected to be high – possibly as much as 70% of the annual precipitation depths, or approximately 1050 mm/year. Based on this assumption, leachate generation from the Tucush dump is expected to be in the order of 90 L/sec (annual average). Seepage rates in to the foundations are expected to be in the order of 22 – 35 L/sec; however, seepage losses can be significantly reduced by keeping the waste rock off the karst and by using underdrains at the base of the valley.

Environmental Issues Related to Mine Waste Disposal Areas in Karstic Terrain

Ground water flow in karst aquifers is typically more rapid than in fractured rock or granular aquifers. Velocities of hundreds of meters per day are common in karstic aquifers with well developed conduit systems. Fractured rock or granular aquifers commonly fall within the centimeters to meters per day velocity range. Seepage from mine waste facilities can therefore travel great distances within short periods of time. The rapid travel times and conduit flow reduce the potential for reduction of contaminant concentrations through filtration, adsorption or other processes. Due to the complexity of karstic aquifers, once seepage from waste facilities migrates to a karstic system it is extremely difficult (and commonly impossible) to recover by means of pump-back systems. The end result is a reduction in water quality at the spring discharge areas.

The main hydrogeological issue related to the Antamina waste disposal areas is off-site migration of seepage via karstic limestone which underlies the Antamina stockpiles and forms the east walls of both the Vallecito and Tucush Valleys. Ground water from both karstic limestone ridges discharges at crosscutting valleys. Determining which of these valleys were hydraulically connected to the waste facilities was critical for the dump design and ground water monitoring programs. Preliminary studies indicated that drainage from the existing ore stockpile in the Antamina Valley, and the proposed waste dumps in Vallecito and Tucush, could discharge into any one of the adjacent valleys (Itasca, 2004).

The potential for more regional ground water movement was also identified. The Rio Mosna/Puchca (located approximately 14 km to the northwest) has a very large surface water catchment area and a much lower drainage level compared to smaller valleys local to the mine. At an elevation of 2700 masl, the Rio Puchca has a regional hydraulic influence on the aquifers in the area. Detailed hydrogeologic mapping and tracer studies were carried out to asses whether or not the Rio Puchca/Mosna could have a hydraulic influence on the aquifers at the Antamina mine.

Dye-Tracer Tests

Five separate tracer tests were conducted to identify discharge zones related to the karstic aquifers underlying the proposed waste dumps: 3 within the Tucush-Ayash Valley area and 2 within the Vallecito-Antamina Valley area. Deep karst shafts, identified by mapping, were typically chosen as the introduction points for the tracer dye since these were considered to have the best potential for passing rapidly through the unsaturated layer to the water table. Two additional dye introduction points were used: an 8-inch diameter pumping well which intersected a highly transmissive fracture zone at the toe of the proposed Tucush dump, and a swallow hole within the Ayash Valley, located about 2 km southeast of the proposed dump in Tucush. The dye introduction points are shown on Figure 2. Three separate dyes were used in the studies:

1. Fluorescein (also commonly called uranine) is Acid Yellow 73, Color Index Number 45350;
2. Eosine (sometimes spelled eosin) is Acid Red 87, Color Index Number 45380; and
3. Rhodamine WT is Acid Red 388; it has no assigned Color Index Number.

Tracer monitoring was performed using activated charcoal samplers. These samplers adsorb and retain the tracer dyes used in the investigation, and thus serve as continuous samplers. The charcoal samplers were collected at weekly to monthly intervals, depending on the remoteness of the sampling stations. This qualitative approach to dye-tracing gives a yes or no answer as to whether or not the dye travels to a certain location. However, as a general rule, Aley (2002) has found that activated charcoal samplers left in place with moving water will typically yield dye concentrations under laboratory analysis about 400 times greater than the mean dye concentrations present in the water. Sampling with activated carbon samplers can be done rather inexpensively and is best suited for remote, rugged locations where equipment cannot be easily moved. Analysis of the carbon samplers was performed by Ozark Underground Laboratories in Protem, Mo., USA.

Trace in Karst Shaft – East Side of Vallecito Valley

Four kg of Fluorescein dye mixture containing 75% dye and 25% deluent was mixed with 40 L of water and introduced into a ~100m deep karst shaft located on the east wall of the Vallecito Valley, approximately 400 m north of the Antamina Valley (see Figure 2). Normally a large volume of water is added to flush the dye through the unsaturated zone to the water table, however, this was done due to the remoteness of the shaft. In cases like this, rainfall events are needed to flush the dye from the walls and base of the shaft to the water table.

Fluorescein was detected within the first month after dye introduction in the stream at Qda. Callapo (a NE-SW crosscutting valley situated 4 km north of the introduction site). The charcoal sampler had a cumulative concentration of 250 ppb. This was surprising since the presumed flow direction in the limestone aquifer at Vallecito prior to the tracer test was in the opposite direction toward the Antamina Valley – only 400m away from the karst shaft (see Figure 2). Most of the fluorescein dye was flushed through within the first week, however, residual dye was still observed 10 weeks after the dye was introduced. No fluorescein was detected in the Antamina Valley, indicating a north flow direction in the karst from the Vallecito Valley.

On this basis, it was considered likely that if waste rock was placed over the Jumasha Formation within the Vallecito Valley, there would be uncontrolled migration of contaminants to the Callapo Valley.

Trace in Karst Shafts – Upper Chipta Valley (south of the Antamina Valley)

Four kilograms of liquid Rhodamine WT tracer dye mixture containing 20% dye and 80% deluent was introduced into two sub-vertical karst shafts situated approximately 1 km south of the Antamina Valley (see Figure 2). The purpose of this tracer test was to determine the potential for ground water movement from the Antamina Valley stockpiles south toward the Juproc Valley. The shafts were 50 m apart along the same bedding plane and open to approximately 10 m. It remains unknown if these shafts extend deeper or if they terminate within the epikarst layer. Due to access difficulties, only 40 litres of water were introduced to flush the tracer dye deeper into the ground water system. The tracer test was monitored using activated charcoal samplers.

Within the first month, Rhodamine WT was detected in the Chipta spring (situated approximately 500 m southwest of the introduction points) at a cumulative concentration of 3090 ppb. Rhodamine dye was not detected in the Antamina Valley (upstream of Chipta Valley confluence) or within the Juproc Valley (i.e. the valley to the south which crosscuts the karstic limestone).

The spring at Chipta is at a higher elevation than the Antamina Valley, suggesting higher hydraulic heads in the limestone to the south compared to the heads within the Antamina Valley. Based on this, and the water levels obtained from piezometers, a ground water flow component south of the Antamina Valley into the Jumasha limestone aquifer appeared unlikely.

Trace in Karst Shaft – East Side of Tucush Valley

Approximately 1.4 kg of Fluorescein dye was introduced into a large sub-vertical karst shaft on the east side of the Tucush Valley and flushed with ~34,000 liters of water (see Photo 2). The Fluorescein was detected at one bedrock monitoring well located at the base of the Tucush Valley and within the Ayash stream. The location of the karst shaft introduction and detection points are shown in Figure 2. The fact that the dye travelled to the base of the Tucush Valley supports the idea of structural controls (e.g. either low or high permeability faults) directing the flow laterally from the karst aquifer.

The tracer test showed that ground water flow from the proposed waste dump was southeast toward the Ayash Valley rather than west toward the Callapo Valley (or further yet toward Rio Puchca/Mosna).

Photo 2. Introduction of Fluorescein to Karst Shaft in Tucush Valley

Conceptual Hydrogeologic Model of Karst Aquifers

Karst Recharge

The mine is located between two steeply dipping, northwest trending limestone ridges which act as both geographic and hydrologic boundaries around the mine. Over the last several million years, dissolution along fractures and bedding planes changed the carbonate aquifers from diffuse-flow systems (with water moving as laminar flow through narrow fractures) to conduit-flow aquifers with water moving primarily as turbulent flow through well-developed conduit systems. Conduit development within the Jumasha Formation is expected to be deeper than 100 m, based on depth soundings of karst shafts.

The epikarst layer at Antamina appears to range in thickness from 2m to >10m (depending on the solubility and fracture density of the limestone). The epikarst layer allows rapid infiltration and short-term storage of large quantities of recharge. Below the epikarst layer, solutional features are less frequent and water movement is confined to highly localized features such as karst shafts. Some of the infiltrated water is directed along the base of the epikarst to topographically controlled discharge zones; however, most of the infiltrated water is "funnelled" downward through these highly localized karstic pipes and shafts to the water table. Conduit, and potentially cave, development is expected at the water table where much of the ground water movement in the karst takes place.

The orientation of conduits in the vadose zone appear to be controlled by the dip of the strata (which varies between 60 to 80 degrees), and by sub-vertical fractures and faults oriented roughly perpendicular to the bedding. The predominant direction of percolated water into the vadose zone should generally be downwards along these structures.

Ground Water Movement in Karstic Aquifers

Ground water movement in the karst phreatic zone in the Jumasha Formation is expected to be principally parallel to the formation strike. The Jumasha is expected to behave like a hydraulic sink with ground water movement toward the karst from djacent, lower permeability sedimentary formations (see Figure 3). Anisotropy in karstic aquifer is created due to: 1) bedding plane fractures, 2) bedding plane faults (creating additional fracturing and clayey gauge), 3) the Vallecito and Tucush regional faults, and 4) adjacent sedimentary rocks which create low permeability hydraulic boundaries.

The water table surface is likely to be highly variable due to extreme variations in hydraulic conductivity normally found throughout karstic limestone aquifers, and hydraulic compartmentalization caused by faulting. The hydraulic conductivity of an unfractured (massive) limestone could be less than 10^{-9} m/sec and a fractured limestone as high as 10^{-2} m/sec. Turbulent flow occurs in karstic limestone when permeabilities exceed 10^{-2} m/sec - typically when fractures become wider than a few millimetres. Ground water moves from these zones of less fractured and massive limestone to the main conduits. Hydraulic mounding is expected between the karst shafts and other major conduits connecting the surface to the water table.

Ground water movement parallel to the strike of the formations can be interrupted due to localized crosscutting transversal faults within the Callapo, Yanacancha, Callapo and Ayash Valleys (see Figure 4C). Fault displacement, resulting in fault gauge, brecciation and fracturing likely creates hydraulic compartmentalization and redirection of the water within the aquifer to ground water discharge areas. The tracer test within the east wall of the Tucush Valley supports the idea that water can be directed along these crosscutting structures (perpendicular to the strike and main flow direction of the limestone). Similarly, the transverse fault in the Callapo Valley appears to be restricting ground water movement past the Callapo Valley within the karstic limestone. These concepts are represented in the hydrogeologic sections shown in Figure 4.

Karst Discharge

The karstic Jumasha aquifer discharges at topographic lows (valleys) which crosscut the Jumasha Formation. There are four local valleys which crosscut the two karstic aquifers which underlie the proposed waste dumps. They are:

Ayash Valley – located approximately 2 km southeast of the proposed Tucush waste dump at an elevation of approximately 3800 m. This is the main discharge zone for the Tucush Valley. Karst aquifer discharge is primarily to the base of the alluvial aquifer beneath the Ayash River. There is also one spring called "Ishpac" which discharges approximately 10 m above the base of the valley floor (see Photo 3). This spring flows almost continuous year round with average flow rates between 10 to 20 L/sec. Higher flow rates have been observed shortly after heavy rainfall events. The tracer studies showed that this spring, which is important for the community of Ayash, was *not* hydraulically connected with the karst shaft near the proposed Tucush dump.

Antamina Valley – located at an elevation of approximately 4000 m (immediately south of the Vallecito Valley) and approximately 80 m below the floor of the Vallecito Valley. Some ground water flow from the epikarst flows to the Antamina Valley from the north and south sides of the valley. Very little spring discharge occurs within this valley suggesting that it is not a significant discharge area from the phreatic zone of the karst aquifer. Tracer testing in the karst shaft at Vallecito also supports this interpretation.

Callapo Valley - located approximately 4 km northwest of the Vallecito Valley. The west contact of the Jumasha Formation intersects the base of the valley at an elevation of approximately 3950 m. The karst shaft tracer test within the east wall of the Vallecito Valley showed hydraulic connection between the Vallecito Valley and Callapo. The Callapo stream is fed by springs which discharge to the alluvial aquifer. Baseflows of the Callapo stream increase by an estimated 100 L/sec crossing the karstic limestone. Higher spring discharges likely occur during rainfall events and peak wet season periods.

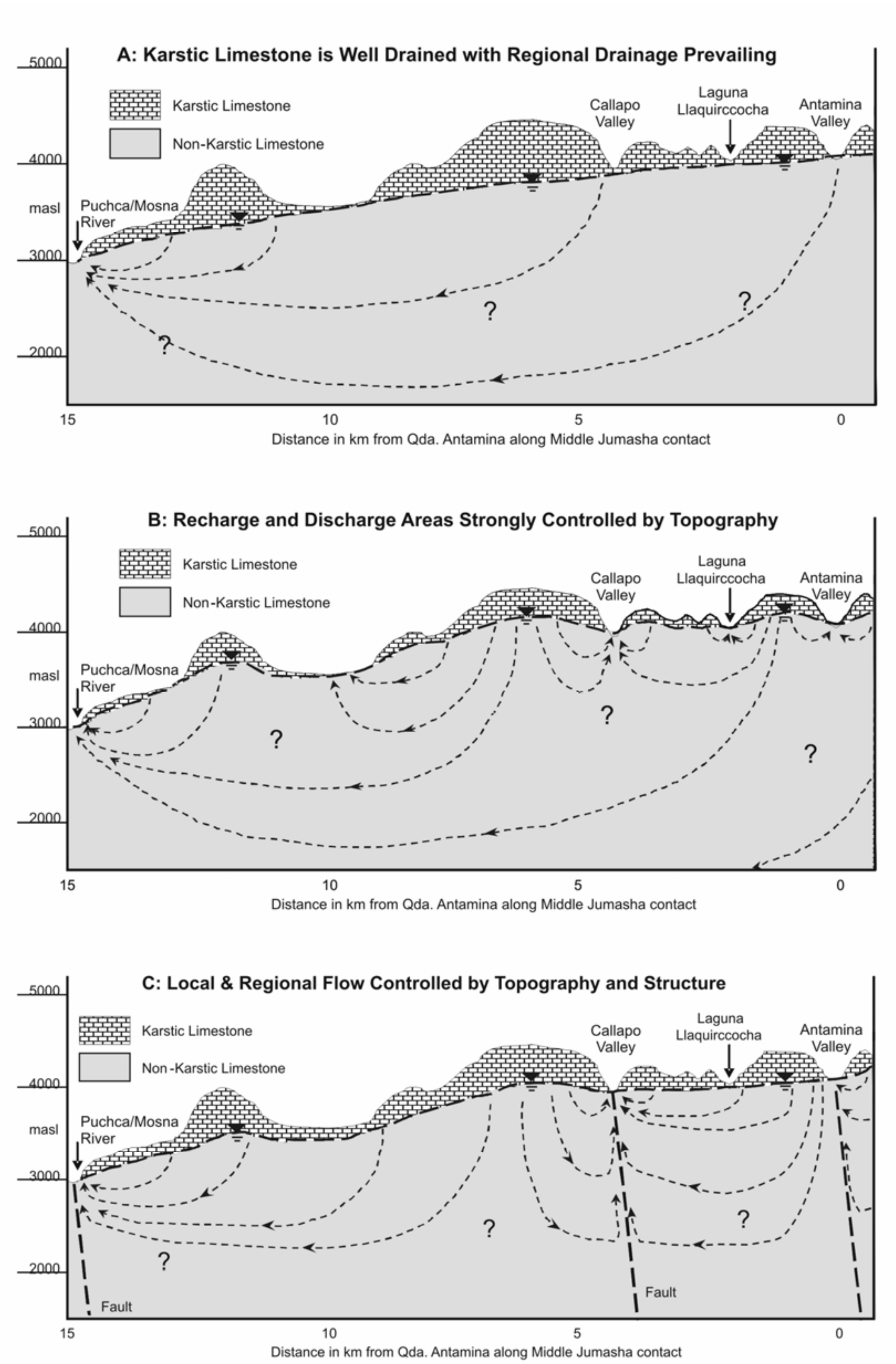
Photo 3: Ishpac Spring in Ayash Valley

Juproc Valley - located approximately 3 km south of the Antamina Valley. The west contact of the Jumasha Formation intersects the base of the valley at an elevation of approximately 4025 m. This valley is fed by karstic springs at several locations, however, there is little evidence to suggest hydraulic connection with any of the proposed or existing waste facilities.

Regional Ground Water Flow

Three possible concepts of regional drainage within the karstic Jumasha aquifer between the Antamina Valley and the Puchca/Mosna River is shown in Figure 4. The section has been drawn along the contact between the Lower and Middle Members of the Jumasha Formation paralleling the main thrust fault which runs through the Vallecito Valley. If karst development extended as deep as 500 m, there would be some potential for regional ground water movement from Vallecito to Rio Puchca (refer to scenario A in Figure 4). However, extreme karst development such as this is

Figure 4. Regional Ground Water Flow Concepts



uncommon and there is no evidence in the area to support it. The karst layer probably conforms to the local topography with karst development extending as deep as 200-300 m (refer to flow scenario B in Figure 4). Faulting within the valleys further reduces the potential for regional flow to occur along the Jumasha aquifer. Therefore, the current concept for flow along the Jumasha Formation between the Antamina Valley and the Puchca/Mosna River is shown in flow schematic C in Figure 4.

Hydrogeologic Investigation of the Antamina Valley Ore Stockpiles

The limestone walls of the Antamina Valley do not have caves or defined springs implying that the valley is not a regional discharge zone and that there is a low potential for lateral seepage from the existing ore stockpile. However, several distinct northeast-trending bedding plane faults exist within both karstic limestone ridges which border the valley. Deep erosional features have formed along the trace of these faults within the Antamina Valley (see Photo 4). Although karst development is not apparent within the walls of the Antamina Valley, several deep karstic shafts can be found associated with these faults along the limestone ridges at higher elevations.

Seepage losses from the low-grade ore stockpiles through these bedding plane faults into underlying and adjacent karstic limestone was identified as a possible contaminant loss mechanism. A drilling program was designed to assess the permeability of these bedding plane faults, the piezometric levels in the limestone relative to the ore stockpiles, and the potential for karst development within the faults adjacent to the stockpiles. Four test holes were drilled into the north and south walls of the Antamina Valley targeting the most prominent bedding plane faults identified through mapping (see Figure 5). The core samples showed brecciation within all of the faults, however, in all cases, the breccias were "healed" with calcite infilling. Packer-based permeability testing showed low hydraulic conductivity values for the fault zone (in the range of 10^{-9} to 10^{-7} m/sec). Although open fractures related to these faults were not present, the calcite-filled breccia appears to be more prone to dissolution compared to the surrounding limestone (based on the propensity for karst development along these faults).

The piezometric levels measured on the south side of the Antamina Valley suggested conditions were favourable for hydraulic containment in this area. Multi-level piezometers installed on south of the ore stockpiles showed artesian conditions, indicating high phreatic levels in the karstic Jumasha. This suggests that the Antamina Valley is a discharge zone for ground water originating south of the Antamina Valley. The tracer test in the karst shaft with detection in the Chipta Spring supported the concept that the south side of the Antamina Valley is a ground water discharge zone rather than a recharge zone to the karstic aquifer.

The piezometric levels measured in the north wall of the Antamina Valley suggest this area is not as favourable for hydraulic containment. The multi-level piezometer indicates a strong downward hydraulic gradient between the shallow/upper fractured bedrock zone of the north valley wall and the deeper bedrock (refer to Figures 6 and 7). No karstic features were intersected by the drill hole and the fractures encountered had low permeability. In most cases, a low permeability rock should produce poorly drained conditions with elevated hydraulic heads, however, this does not appear to be the case. The low piezometric levels suggest that karstic conduits may be draining the surrounding fractured limestone, resulting in low hydraulic heads.

Although the piezometric information supports the concept that the Jumasha Formation is acting as a drain with a northward component of flow, low-permeability valley floor cover and a low density of karstic features underlying and adjacent to the stockpile appear to be restricting flow.

Figure 5. Drilling Investigation – Antamina Valley

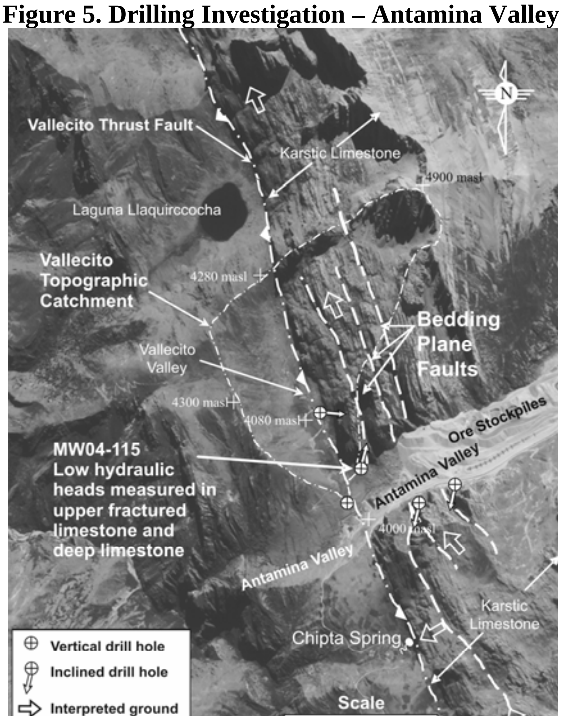


Figure 6. Hydrogeologic Section and Piezometric Level – North Side of Antamina Valley

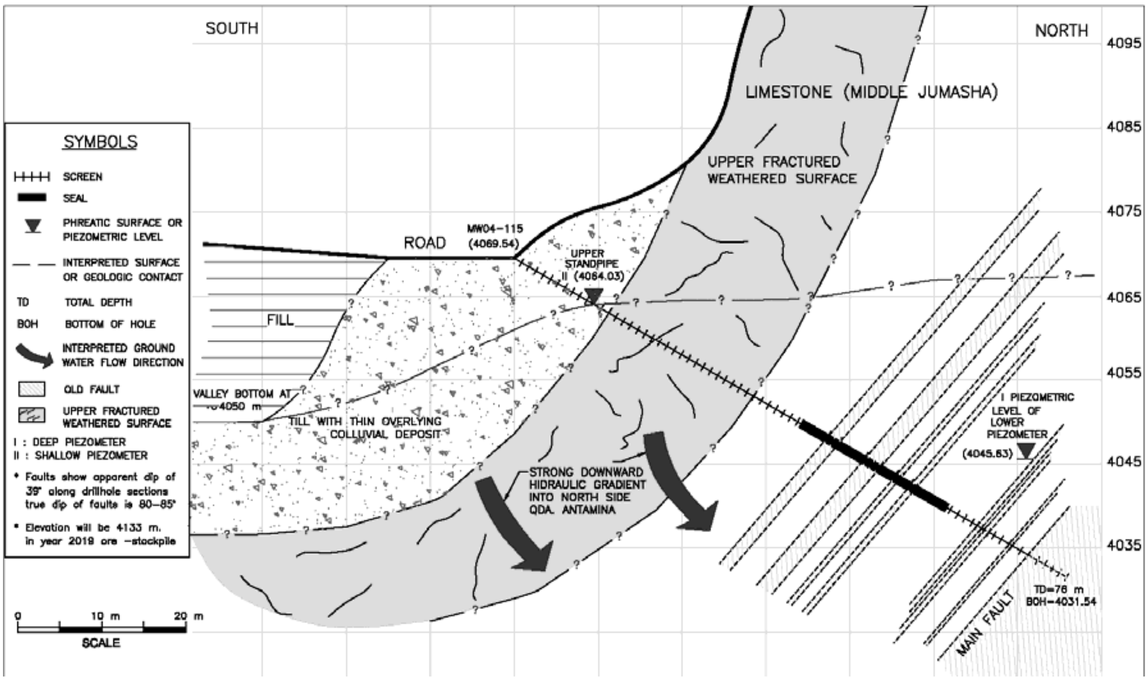


Figure 7: Water Levels from Piezometers installed in North Wall of Antamina Valley

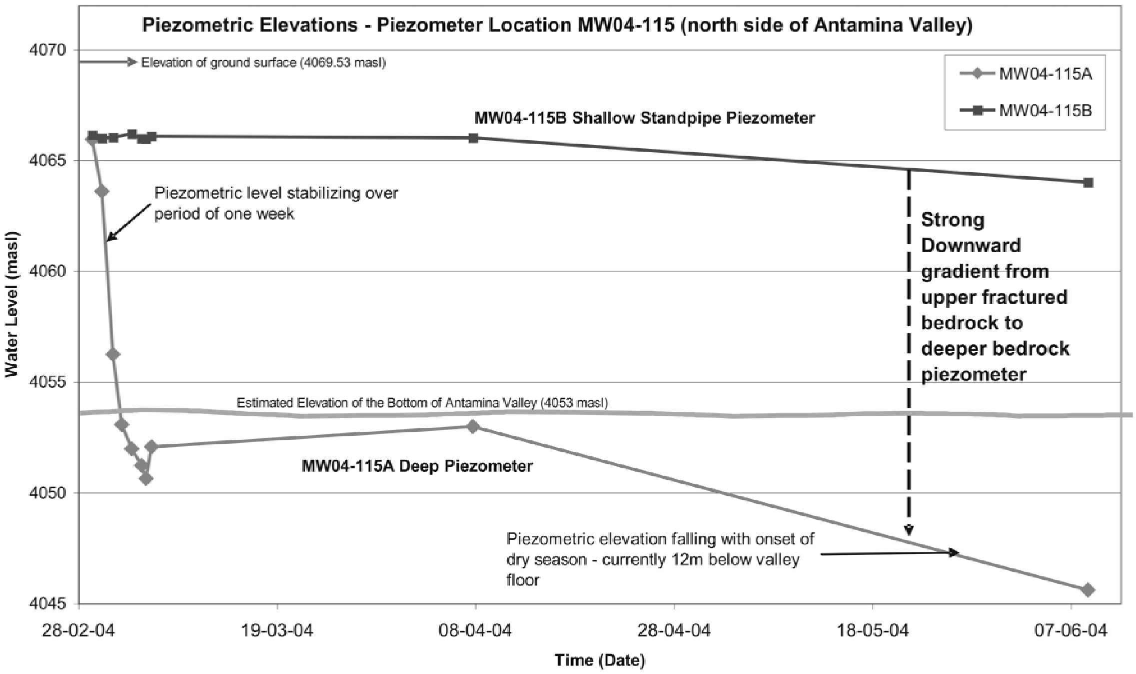
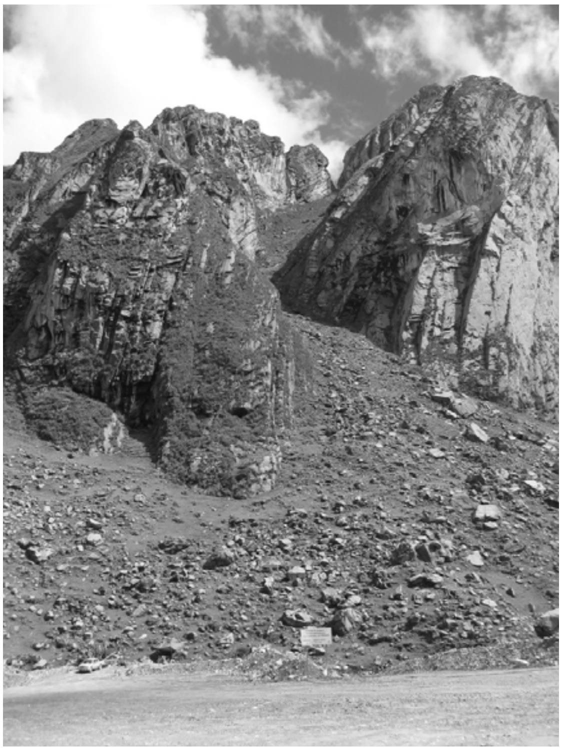


Photo 4. North View of Antamina Valley showing deep Gulley Formed along a Bedding Plane Fault



There are no apparent water quality impacts in the Callapo River due to ground water discharge from the karstic limestone aquifer indicating that seepage losses from the stockpiles via karst is minimal. To confirm this, event-based sampling of the Callapo River is necessary during base flow conditions as well as during and after rain events. Routine sampling (e.g. monthly or quarterly) is not recommended for karst terrain. Rainfall event-based sampling strategy is recommended since flushing of contaminants and leachate mobilization is more likely to occur during and after heavy precipitation.

Summary

Characterizing Karstic Hydrogeologic Watersheds

Antamina is a good example of how karstic hydrogeologic watersheds can be very different compared to topographic watersheds. Defining the boundaries of karstic hydrogeologic watersheds can be very challenging, often requiring extensive field programs. Drilling, piezometers installations and water level monitoring are commonly used to help define the ground water flow regime, however, these programs are very costly and often do not adequately characterize the flow regimes of karst aquifers. The phreatic surface can be extremely variable in karst, due to high permeability contrasts within the carbonate aquifer, and faulting generally adds more complexity to the flow system. Flow within a karst aquifer will be toward the deepest and best developed karstic conduits. Finding the conduits responsible for draining a karstic aquifer can be a bit like finding a needle in a haystack – even with sophisticated geophysical programs and other techniques. Care must be taken when interpreting piezometric levels collected from piezometers which do not intersect these conduits, but lie within massive to fractured limestone. Because of the problems associated with drilling in complex terrains, dye-tracer studies have proved to be very cost-effective in helping define the ground water flow regime surrounding the waste rock dumps and stockpiles at Antamina.

Implications for Waste Dump Designs

The original concept of the waste rock disposal facilities had approximately 30% of the Vallecito dump overlying karstic limestone and approximately 16% of the Tucush dump overlying karst features. Low grade ores, which produce poor quality drainage, were also originally planned to be stockpiled within the Vallecito valley. Following the hydrogeological characterization of the Antamina and Vallecito valleys, the configurations of the waste rock and stockpiles were changed, reducing the potential for uncontrolled seepage losses and environmental impact to water resources.

References

1. Aley, Thomas. 2002. The Ozark Underground Laboratory's groundwater tracing handbook. *Available from Ozark Underground Laboratory*, Protem, MO, USA 65733. 35p.
2. Aley, T. 1997. *Groundwater tracing in the epikarst.* Proceedings of Conference: 'The Engineering Geology and Hydrogeology of Karst Terranes. Eds: Barry F. Beck and J. Brad Stephenson. A.A. Balkema, Rotterdam. pp. 207-211.
3. Itasca. 2003. Antamina Mine, *Tucush Valley Hydrogeology Study*.
4. Ground Water International - Itasca. 2004. Antamina Mine, *Quebradas Vallecito and Antamina – Hydrogeology Study*.