Introduction

The Gualcamayo Mine is located in the Andes Mountains north of San Juan, Argentina (Figure 1). A property of Yamana Gold Inc, it declared commercial production in July 2009 and has a total mineral reserve and resource base of approximately 88,000 kg of gold. Crushing operations for the open-pit mine are located in a 13,500 m$^3$ underground cavern with a ceiling height of 22 m. More than 3,600 m of tunnels are used to access the cavern and convey the ore. The Project as described in this paper relates to the design and construction of the Main Cavern, Conveyor System Exit Tunnel, the Mechanical System Access Tunnels, and two 4.20 m diameter shafts (Ore Pass #1 and Ore Pass #2) as shown in Figure 2.

Preliminary engineering for the Project was performed by Hatch Chile. Rizzo Associates Argentina, S.A., a division of Paul C. Rizzo Associates, Inc (Rizzo) was contracted to provide geomechanical and geotechnical support for the construction of the access tunnel system and geomechanical design and construction supervision for the cavern and shafts.

Geologic Setting

The Gualcamayo Project is located along the eastern margin of the Precordillera of west central Argentina, immediately to the east of the Cordillera de Los Andes (Figure 3(A)). The Precordillera consists of a series of north-south trending ranges comprised of Cambrian-Early Ordovician marine platform carbonates (Albanesi et al. 2006) overlain by mid-Ordovician through Early Carboniferous marine clastics (Figure 3(B)), which are in turn overlain by late Carboniferous-Tertiary continental clastics. Permo-Triassic and Tertiary granitic complexes locally intrude all sediments (Simpson, 2004).

During the Tertiary Andean Orogeny, sedimentary blocks were shortened eastward into a high-level fold and thrust belt with crustal shortening of about 60-90%. The net effect is a series of N-S trending thrust faults, with a stratigraphic displacement of more than 100 km to the east, superimposing lower Paleozoic sediments over Tertiary and Permo-Triassic continental clastic red beds (Simpson, 2004).

The Gualcamayo Mine site contains a sediment-hosted disseminated gold occurrence known as “Quebrada del Diablo” (“QDD”) and two skarn-hosted gold deposits: Amelia Ines and Magdalena. As it is shown in Figure 4, the property is situated within a complex structural block of Cambrian/Ordovician carbonate sediments characterized by the Andean deformational east-west compression, which formed the Pre-cordillera (Simpson, 2004; Albanesi et al. 2006).

At QDD, gold mineralization is concentrated within stock work fractured carbonates, carbonate breccias and intrusive breccias. The mineralization can be described as low sulfide-bearing (<3%) and is in a low silica system. At Amelia Ines and Magdalena, gold mineralization is present in sulphide-bearing skarns that have developed at carbonate/intrusive contacts.

Skarns of igneous origin are classified as exoskarns or endoskarns. Exoskarns are formed when fluids left over from the crystallization of the granite are ejected from the mass at the waning stages of emplacement. When these fluids encounter reactive rocks, usually carbonates such as limestone or dolostone, the fluids react with them, producing alteration (metasomatism) (Theodore et al. 1991). However in a couplet where the exoskarn is a converted marble then it usually contains most or all the economic mineralization. The exoskarns at Gualcamayo are alterations of wall rocks and occur at and outside the granite, which produced them.

The Gualcamayo Project Area Stratigraphic Column and basic description of the rock units are described in Table 1.
Figure 1. Gualcamayo Project Location Map

Figure 2. 3D Rendering of the Project Site
For the central Andes, only a combination of stresses associated with Gravitational potential energy (GPE) and relative plate motions can account for the near N–S tensional stress observed in the Peruvian Andes and the margin–normal compressional stress along the eastern Cordillera and sub-Andean fold-and-thrust belt (Flesch and Kreemer, 2010).

In the Argentine Puna, the pre-Pleistocene stress field was WNW–ESE compressional. It has been shown that basal tractions alone could be sufficient to raise the Andes, and that the growth of the Andes would change the tectonic regime and rotate the stress orientations. Figure 3(A) shows the Gualcamayo Project location within the regional setting of central Andes and the direction of Nazca–South America convergence (Flesch and Kreemer, 2010).

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### Table 1. Gualcamayo Project Area Stratigraphic Column

<table>
<thead>
<tr>
<th>Age</th>
<th>Rock Unit</th>
<th>Basic Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tertiary</td>
<td>Red Beds</td>
<td>Typical clastic red beds.</td>
</tr>
<tr>
<td>Miocene</td>
<td>Quartz Diorite</td>
<td>Intrusive complex related to skarn and breccia gold mineralization.</td>
</tr>
<tr>
<td></td>
<td>Dacite Porphyry</td>
<td>Relatively recessive, clastic, red polymictic conglomerate sandstone, overlain by shale, white arkose and red sandstone</td>
</tr>
<tr>
<td>Ordovician</td>
<td>Fm. Trapiche</td>
<td>300 m sequence of thin-to thick bedded dark grey limestone. Becomes dominantly thin-bedded up section. Primary host for Quebrada del Diablo gold mineralization.</td>
</tr>
<tr>
<td></td>
<td>Fm. San Juan</td>
<td></td>
</tr>
<tr>
<td>Cambrian</td>
<td>Fm. La Flecha</td>
<td>Medium to thick – bedded rhythmically banded peritidal, shallowing upward dolostone.</td>
</tr>
</tbody>
</table>

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### Project Description

In order to optimize the flow of material during the mining process, the Project was designed such that the primary and secondary crushing operations are located in a cavern beneath the Open Pit. The mined material follows a workflow system whose regime is driven by the Primary Crusher. The linkage between Open Pit and the Cavern is a shaft that allows for the transportation of the ore by gravity towards lower levels and also functions as a material silo. An access tunnel, Target-11, was constructed prior to the start of the Project.

The Cavern was constructed in the Cerro Diablo massif. At the time of construction, the distance between the cavern ceiling and the bottom of the Open Pit was approximately 500 m. However, it is expected that this distance will be reduced to 120 m as the mine is developed. The cavern support design considered vibrations due to both the mining operations above as well as the crushing operations within the cavern.

### Geotechnical Investigation

At the outset of the Project, only general Geotechnical information from the area surrounding the Project site was available. Additionally, data from a single borehole approximately 65 m away from the center line of Ore Pass #1 reported 39% good rock, 22% fair rock, 20% poor rock, and 19% very poor rock, based on the total RMR ratings.

RIZZO performed a geological reconnaissance of the Project area as well as mapping within the Target-11 access tunnel and in the surface outcrops of the massif. This geologic reconnaissance sought to identify lithologies and main characteristics of the rock formation, fractures, discontinuities, weathering, and other important characteristic of the rock volume. During the geologic reconnaissance, different geological structures of dissimilar qualities were observed including a variety diaclases (flat, wavy, rough), earthy, and crushed rock. Failures or discontinuities ranged in thickness from tens of centimeters to several meters with regional orientation in the N-S direction indicating E-W compression.

Due to the limited access above the tunnel alignment, no additional borings were made.
Figure 3. (A) Tectonic Location of Project; (B) Ordovician Carbonates Geologic Map

Figure 4. (A) Gualcamayo Project location within the regional setting of central Andes (B) Model grid cells converted from World Stress Map database
The construction sequencing was as follows:

**Phase 1:**
- Extension of the Target-11 access tunnel to the Cavern location
- Construction of the Exit Conveyor Tunnel from the outside portal to the Cavern location

**Phase 2:**
- Construction of the Exit Conveyor Tunnel from the outside portal to the Cavern location (ongoing)
- Construction of the Cavern
- Construction of the Mechanical Access Tunnels
- Construction of Ore Pass #1

**Phase 3:**
- Construction of the Exit Conveyor Tunnel from the outside portal to the Cavern location (ongoing)
- Construction of the Exit Conveyor Tunnel from the cavern towards the outside portal

Both the Target-11 Access Tunnel Portal (Figure 6) and Conveyor Exit Tunnel were extended using steel structures. The tunnels and cavern were constructed during a two-shift operation (12 hr shifts) using drill and blast methods and advancing rates varied from 0.5 m per shift to 10 m per shift. The Conveyor Exit Tunnel, which was being advanced from both directions, met at approximately 400 m from the Cavern without any alignment issues. Final lining for the tunnels and Cavern was completed using shotcrete (Figure 7) and rock bolts with reinforced ribs as needed. Overall, the geological recognizance provided a good baseline for anticipating the conditions that would be encountered during the construction of the tunnels and cavern and for finite element modeling (Figure 8). However, the drill & blast excavation method did allow for some adaptability in choosing the support system based upon the specific conditions encountered.

Blasting at the site was done in either two or three steps based upon the geological conditions. In most instances, the perimeter of the horse-shoe shaped tunnel (5.4 m high x 4.6 m wide) was predrilled following the tunnel alignment. The holes were drilled to a depth of 3 m and spaced on 0.3 m centers. This perimeter drilling
was followed by the excavation of a round starter tunnel, 2.0 m - 2.5 m in diameter that was drilled and blasted with explosive specific load of 2 kg/m³. The explosive used in both cases are known locally as “Gelamón” 22 x 200 mm and VF 65%. For the starter tunnel, spacers were used as well as 5 gauge blasting wire. The explosives are activated with non-electric fuses with 25 ms of delay time. The design for each of the blasting steps was revised and approved prior to the drilling. Additional changes were permitted based on ongoing geological conditions found in the drilling. The design included the drilling pattern, length of borings, explosive loads, and delay times.

Once this starter tunnel was cleared and geotechnical description of the exposed rock was completed, construction followed with the drilling of borings in a 0.5 m perimeter around the starter tunnel. The blasting sequence then followed with same specifications as described in the paragraph above. The retrieval of the blasted material was always done after an in-situ analysis and tests were performed on the exposed rock. To reduce the likelihood of injury, the rocks were removed using telescopic retrievers. The final dimensions of the tunnel were always bigger than the design specifications in order to accommodate supporting structures and shotcrete application as needed.

Unlike the tunnels and cavern, the Ore Pass shaft was not lined. This proved to be troublesome during operation of the mine as described in the following section. A second shaft not included in the original plan, Ore Pass #2, was constructed to increase the flow of material to the crusher without further damaging Ore Pass #1.

**Challenges Encountered**

Overall, this was a very successful Project. The primary challenges encountered related to the construction and subsequent use of the Ore Pass #1 shaft. In order to reduce the likelihood of fracturing the rock in the area of the Open Pit, raise bore drilling was the method chosen for the mechanical excavation of the 330 m long, 2.5 m diameter shaft. A 0.3 m pilot hole was driven from the top of the Open Pit operations, with the main cavern as a target. The pilot hole landed 12 m away from the original target. It was later found that primary cause for the deviation was due to the presence of a faulted-sheared rock zone with soft to moderately hard gouge material located approximately halfway along the shaft. Because of the uncertainty of the areal distribution of the intercepted fault, a decision was made to alter the shape of the main cavern to accommodate the deviation and eliminate the need for a new pilot hole.

A second problem related to Ore Pass #1 was discovered after mining operations commenced at the site. The movement of material through the shaft was causing the walls of Ore Pass #1 to erode. A recommendation
was made to use drill & blast methods to increase the diameter from 2.5 m to 4.1 m, thus allowing for the installation of a 0.2 m thick concrete lining wall as well as providing additional space for material passage. However, in order to not impact the mining operation, an alternative solution was identified in the construction of Ore Pass #2. A gallery connecting the new Ore Pass #2 was excavated and a connecting conveyor system now allows for operation of both ore passes.

Conclusions

The raise bore excavated Ore Pass #1 proved to be slightly problematic to construct due to an unexpected fault zone. A more detailed geotechnical investigation program at the shaft site, construction using a drill & blast excavation method (if permissible), or increasing the final diameter of the shaft should be considered in similar formations. Additionally, wear of the shaft during mining operation was due to the shaft having too small of a diameter and not being lined.

Overall, this was a successful project. Although it was not feasible to conduct borings along the tunnel alignment, a thorough geological recognizance program provided a good baseline for construction of the tunnels and cavern. Drill & blast excavation allowed for some adaptability in choosing the support system based upon the specific conditions encountered.

References