TRANSITION FROM OPEN PIT TO UNDERGROUND MINING
AT CHUQUICAMATA, ANTOFAGASTA, CHILE

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ABSTRACT
The economical analyses of different Chuquicamata open pit mine planning scenarios, indicate that the pit closure should occur at latest in the year of 2017. However, about 60,000 m of drill holes have demonstrated that below the pit bottom there is a potential of 2.3 billion tons of ore. Hence, Division Codelco Norte developed the scoping engineering for a large underground panel caving operation, similar to El Teniente mine. This project considers the exploitation of a 2500 m 300 m footprint, with three 250 m lifts. The plan considers to initiate the construction in the year 2009, to begin the production in the year 2015 and achieve a production rate of 45 million tons per year in the year 2021.

A large-scale transition from open pit to underground mining like this one presents three main challenges: (1) to include the geotechnical aspects relevant for mine design and mine planning, (2) to define the proper surface and underground infrastructure, and (3) to fulfill the project deadlines and to achieve the production targets. This paper summarizes this transition project and discusses these three main challenges.

INTRODUCTION
Chuquicamata mine began open pit mining in the year 1915 and at the end of the year 2005 it had mined out about 2.6 billion tons of copper ore with a mean grade of 1.53%, reaching a pit depth of 850 m. The current mine plan considers to extract about 700 million tons in the period 2006-2014. At the end of the year 2014 the final pit condition will be reached with a depth of 1,100 m. The geological data from drill holes indicate that below the final pit bottom there are about 2.3 billion tons of ore with a mean copper grade of 0.81%, reaching a depth of 1,800 m, as shown in Figure 1.

Hence, Division Codelco Norte developed the scoping engineering for a large underground panel caving operation, similar to El Teniente mine. This project considers the exploitation of a 2500 m 300 m footprint, with three 250 m lifts. The plan considers to initiate the construction in the year 2009, to begin the production in the year 2014 and achieve a production rate of 45 million tons per year in the year 2020.
A large-scale transition from open pit to underground mining at Chuquicamata presents three main challenges: (1) to include the geotechnical aspects relevant for mine design and mine planning, (2) to define the proper surface and underground infrastructure, and (3) to fulfil the project deadlines and to achieve the production targets.

**GEOLOGICAL AND GEOTECHNICAL SETTING AT CHUQUICAMATA**

The Chuquicamata porphyry copper ore body is rectangular in plan, and dips vertically. The mineralization was controlled by the West Fault which is located at the toe of the West wall. From the fault to the West is waste and from the fault to the East is ore, as illustrated in Figure 1. About 2.6 billion tons of ore, averaging 1.53% Cu, have been mined out from the Chuquicamata ore body since 1915, and 700 million tons will be mined out from 2006 to 2014 (final pit). However, the ore body is open at depth, with geological resources estimated to be 2.3 billion tons with an average grade of 0.81% of Cu for the underground mine, as shown in Figure 1.

At Chuquicamata the predominant rock types are granodiorites and porphyries, whose western contact is defined by the West fault, a large regional fault with a NS trend, 4 to 6 m thick, and defining a 150 to 200 m wide shear zone on its western side. This shear zone has a poor to very poor geotechnical quality, and is located in the lower third part of the West Wall’s slopes. In the upper part of these slopes the rock is Fortuna granodiorite. On the eastern side of the West fault appears a massive quartz-sericitic rock, and beyond that porphyries with different types of alteration. Hence, from West to East the main rock mass types at Chuquicamata are:

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The engineering geology at Chuquicamata is such that twelve geotechnical units have been defined (Torres et al 2003), as shown in the plan view of Figure 2. The characteristics of the main geotechnical units in the sector of interest to the transition project are summarized in Table 1 (Flores et al 2004b).

Table 1
CHARACTERISTICS OF THE GEOTECHNICAL UNITS

<table>
<thead>
<tr>
<th>Geotechnical Unit</th>
<th>UCS (MPa)</th>
<th>FF (fract./m)</th>
<th>RMR&lt;sub&gt;L&lt;/sub&gt;</th>
<th>GSI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz-sericitic rock</td>
<td>20</td>
<td>1 to 5</td>
<td>55 to 65</td>
<td>70 to 85</td>
</tr>
<tr>
<td>Highly sericitic rock</td>
<td>10</td>
<td>&gt; 10</td>
<td>35 to 45</td>
<td>25 to 40</td>
</tr>
<tr>
<td>East porphyry with sericitic alteration</td>
<td>31</td>
<td>1 to 5</td>
<td>60 to 70</td>
<td>55 to 70</td>
</tr>
<tr>
<td>East porphyry with chloritic alteration</td>
<td>84</td>
<td>1 to 10</td>
<td>55 to 65</td>
<td>55 to 65</td>
</tr>
<tr>
<td>East porphyry with potassic alteration</td>
<td>85</td>
<td>1 to 10</td>
<td>55 to 70</td>
<td>55 to 75</td>
</tr>
</tbody>
</table>

UCS  Uniaxial compressive strength of the intact rock
FF  Fracture frequency (including weak veinlets)
RMR<sub>L</sub>  Laubscher’s rock mass rating
GSI  Geological strength index

The stress field at Chuquicamata has been measured using a hydrofracturing technique in deep vertical down holes. The in situ stress field is defined by a vertical stress proportional to the depth, with a magnitude ranging from 35 to 40 MPa at the elevation of a future undercut level (UCL). The horizontal stresses are defined by minimum and maximum stress ratios, K<sub>MIN</sub> and K<sub>MAX</sub>, respectively. K<sub>MIN</sub> ranges from 0.5 to 1.0, with a direction of N20ºE and K<sub>MAX</sub> varies from 1.0 to 1.7, with a direction of N70ºW (Torres et al 2003).
Figure 2: Geological units present in Chuquicamata (Torres et al 2003).
These values will be verified using the CSIRO hollow inclusion technique to perform stress measurements from the exploration tunnels which will be available below the final open pit shell at the beginning of the year 2006.

SCOPING ENGINEERING OUTCOME

The scoping engineering study carried out recently by Codelco Norte Division indicates that it is feasible to exploit the ore below the final open pit envelope using panel caving. Based on a combination of a series of preliminary analyses and other Codelco panel cave experiences, supplemented by a world benchmark on transition (Flores et al 2004a), the initial design proposed for the Chuquicamata panel cave are the ones summarized in Table 2 (from Arancibia & Flores (2004) and Adriasola & Olavarria (2005)).

PRE-FEASIBILITY ENGINEERING

Currently, the studies for the pre-feasibility engineering stage are being developed. These studies include the results of the scoping engineering and the new information from the last geological-geotechnical drilling campaigns (36,000 m), and also from the mapping of the exploration decline (3,250 m) and drainage drifts (2,500 m). The goal of this pre-feasibility engineering stage is to analyze and compare the different options, considering technical and economical aspects, in order to select the best one for underground mining at Chuquicamata.

It is important to note that the mine plan must consider the following issues:

- Optimization of the open pit.
- Open pit closure.
- Possible interaction between the open pit and underground mining.
- Underground mining.

Also, during the development of the pre-feasibility engineering studies (20 months) the geological-geotechnical exploration will continue. The exploration decline will be extended (about 6,460 m, including exploration drifts and a ventilation shaft) and additional boreholes will be drilled (57,000 m), as shown in Figure 3. The core drill samples will be used for additional laboratory testing, and some in situ testing will be done (direct shear tests and in situ stress measurements).

CHALLENGE 1: GEOTECHNICAL ISSUES

The planned transition from a large scale and deep open pit to underground cave mining at Chuquicamata is expected to face a number of unique geotechnical challenges, as illustrated in Figure 4. Given their potential impact to the transition project these need to be addressed during the early and subsequent design stages of the project. These main geotechnical challenges are:
### Table 2
#### PROJECT PARAMETERS (SCOPING ENGINEERING)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Scoping Engineering Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geological resources</td>
<td>2,300 million tonnes, with average grades of 0.810%, copper and 0.040%, molybdenum (see Figure 1)</td>
</tr>
<tr>
<td>Mining reserves</td>
<td>1,276 million tonnes, with average grades of 0.790%, copper and 0.051%, molybdenum (see Figure 1)</td>
</tr>
<tr>
<td>Mining method</td>
<td>Panel caving</td>
</tr>
<tr>
<td>Main accesses</td>
<td>2 declines (11.4 km, 12% gradient, 6 m – 5 m cross section), 1 service shaft and 4 ventilation shafts (1,800 m depth, 8 m diameter).</td>
</tr>
<tr>
<td>UCL depth from surface</td>
<td>1,300 m (Lift 1), 1,550 m (lift 2), and 1,800 m (Lift 3) (see Figure 5)</td>
</tr>
<tr>
<td>Block height</td>
<td>250 m (average)</td>
</tr>
<tr>
<td>Rib pillar (respect to West Fault)</td>
<td>60 m (minimum)</td>
</tr>
<tr>
<td>Crown pillar UCL-EXL</td>
<td>18 m</td>
</tr>
<tr>
<td>Measure(s) to facilitate the initiation of caving</td>
<td>Slot</td>
</tr>
<tr>
<td>Area for caving initiation</td>
<td>15,000 m² (with an square or rectangular shape)</td>
</tr>
<tr>
<td>Footprint</td>
<td>2,500 m (NS) – 300 m (EW) (average)</td>
</tr>
<tr>
<td>Mining sequence</td>
<td>The first lift initiates the undercutting just below the toe of the Northern and Southern pit slopes, then the undercutting will progress towards the North and the South, leaving a central pillar. One year later, the undercutting of the second lift will begin below the centre of the pit, 250 m below the first lift, then it will progress towards the North and the South. After the first lift mined out the undercutting of the third lift will begin below the centre of the pit, 250 m below the second lift, then it will progress towards the North and the South. This sequence allows maintaining always four production sectors (see Figures 5 and 6).</td>
</tr>
<tr>
<td>Cave front orientation</td>
<td>N85ºE</td>
</tr>
<tr>
<td>Undercutting rate</td>
<td>3,000 m³/month</td>
</tr>
<tr>
<td>Extraction layout</td>
<td>El Teniente, 208 m² (first lift) and 267 m² (second and third lifts) (see Figure 7)</td>
</tr>
<tr>
<td>Draw rate</td>
<td>0.17 t/m²/day (year 1), 0.33 t/m²/day (year 2), 0.66 t/m²/day (year 3, 4, 5 …)</td>
</tr>
<tr>
<td>Production rate increment</td>
<td>5,000 TPD (per year, per sector)</td>
</tr>
<tr>
<td>Maximum production rate</td>
<td>40,000 TPD (per sector)</td>
</tr>
<tr>
<td>Total production rate</td>
<td>125,000 TPD (45 million tonnes per year, whole mine) (see Figure 8)</td>
</tr>
<tr>
<td>Ramp-up period</td>
<td>7 years (see Figure 8)</td>
</tr>
<tr>
<td>Mining equipment</td>
<td>LHD Diesel 9 and 11 yd³, Jumbo and picking hammers, jaw crushers 47” – 63” (up to 2 m fragment sizes)</td>
</tr>
<tr>
<td>Subsidence</td>
<td>Angle of break: 60º (East) to 50º (West). Zone of influence: 125 m (East) to 250 m (West)</td>
</tr>
<tr>
<td>Construction</td>
<td>From year 2009 to year 2014.</td>
</tr>
<tr>
<td>Operation</td>
<td>Undercutting will begin the year 2015</td>
</tr>
<tr>
<td>Economical indicators</td>
<td>Capital cost: 1200 MUS$$, operational costs: 3 to 4 US$/tonne, NPV: 1,500 to 1,700 MUS$$, IRR: 20% to 26%.</td>
</tr>
</tbody>
</table>
Figure 3: Additional geological-geotechnical exploration to be done during the pre-feasibility engineering stage (from Adriasola & Olavarría, 2005).

Figure 4: Geotechnical challenges associated with a transition project at Chuquicamata.
Figure 5: Lifts considered for underground mining at Chuquicamata (from Adriasola & Olavarría, 2005).

Figure 6: Underground mining sequence at Chuquicamata. The Northern and Southern sectors of Lift 1 (Level 1900) will advance to the North and South, respectively, leaving a central pillar. Lifts 2 (Level 1700) and 3 (Level 1400) will initiate the caving below the central part, then the mining will progress towards the North and the South (from Adriasola & Olavarría, 2005).
Figure 7: El Teniente type extraction layout considered for the underground mine at Chuquicamata (from Adriasola & Olavarría, 2005).

Figure 8: Production target (125 KTPD), production plan and ramp-up period for the underground mining at Chuquicamata (from Adriasola & Olavarría, 2005).
(1) PRESENCE OF A LARGE DEEP OPEN PIT. The presence of the pit produces zones of stress concentrations and zones of low confinement. These induced stresses will likely affect the propagation of caving and must therefore be considered in evaluating the likelihood of caving propagation through the whole ore column to be caved.

(1) PRESENCE OF THE WEST FAULT AND SHEAR ZONES. The West fault forms an abrupt contact between the ore and the waste. The waste is a soft, weak and highly fractured rock mass which potentially could become a source of early dilution of the ore if the cavity reaches the West fault before connecting with the pit bottom. Hence, a rib pillar is required between the West fault and the undercut area as illustrated in Figure 4. If this rib pillar is too thin it could fail and early dilution may occur. On the other hand, if it is too wide some high grade ore would not be mined.

(2) INDUCED SEISMICITY. When the final pit is reached in 2014, with a depth of 1,100 m, the undercut level of Lift 1 will be located at a depth of 1,350 m from surface. Therefore, the induced stresses are likely to be high and induced seismicity will be expected during underground mining, which eventually could generate rockbursts. Due to this, a seismic monitoring system is considered an absolute need, and it should be implemented when the initial developments of the underground mine begin.

(3) CAVE INITIATION AND PROPAGATION. The initial stage of the underground mining will be in a hard and massive rock mass, where cave initiation and propagation may be difficult. As the cave propagation approaches the pit bottom the rock mass above the cave back would be affected by the higher stresses associated with the presence of the open pit, which may affect the rate of the caving propagation by either accelerating or arresting the process. It also becomes important to define and implement an instrumentation system to monitor the development of the cave. Considering the experience at El Teniente (Rojas et al 2000) and Palabora mines (Glazer & Hepworth 2004), this system would include seismic instrumentation, TDR’s and borehole camera observations.

(4) SUBSIDENCE. Once the caving connects to the pit bottom the pit will become a subsidence crater with a zone of influence extending beyond the pit perimeter. Of course, this condition will evolve through time; and due to slope failures and the extension of the undercut area, this crater will grow. The geometry of a subsidence crater at Chuquicamata will be defined by the crater depth, H, and the angle of break, $\alpha$, which is the angle between the edge of the undercut level and the start of discontinuous deformations (large tension cracks). The influence zone adjacent to the crater perimeter is defined in terms of the influence width, $d_{IZ}$. The $\alpha$ and $d_{IZ}$ terms depend on the rock mass quality and the presence of major geological structures. The relevance of these parameters is due to the requirement to determine the location of the main accesses to the underground mining and the location of the underground infrastructure which must be outside of the influence zone. In addition, it is necessary to know if this subsidence will affect the current surface infrastructure related to the open pit operations.
(5) SIMULTANEOUS OPEN PIT AND UNDERGROUND MINE OPERATIONS. The economic and business requirements of Chuquicamata are such that a period of simultaneous open pit and underground mining would be required. Hence, at least for a certain period, a stable crown pillar must be maintained between the cave back and the pit bottom. This period must be defined considering the stability of the crown pillar and the fact that its thickness is reducing due to the ore draw from the underground mine. A longer period of simultaneity requires a larger block height. A low block height would lead to a very short period of simultaneous operation, which could be non practical. Once the period of simultaneity has been established it is possible to define when the underground mining should begin.

CHALLENGE 2: SURFACE AND UNDERGROUND INFRASTRUCTURE

A deep underground mining by panel caving at Chuquicamata requires an important amount of surface and underground infrastructure. Here the main issues are:

(1) MAIN ACCESSES. There are three options to access a deep mine: shafts, declines, or a combination of both. Currently, as a result of the scoping engineering studies, the project considers one access decline (11.4 km, 12% gradient, 6 m 5 m cross section), and one service shaft (1,600 m initial depth (Lifts 1 and 2) and 1,800 m final depth (Lift 3), and 8 m diameter).

(2) VENTILATION SYSTEMS. Currently, as a result of the scoping engineering studies, the project considers the construction of eight ventilation shafts (each with a 1,600 m initial depth (Lifts 1 and 2) and 1,800 m final depth (Lift 3), and 8 m diameter).

(3) MAIN MATERIAL HANDLING SYSTEM. Currently, as a result of the scoping engineering studies, the project considers the construction of one conveyor decline (11.4 km, 12% gradient, 6 m 5 m cross section). However, this is being reviewed and compared with a hoisting system.

(4) UNDERGROUND INFRASTRUCTURE. A large underground mine requires underground infrastructure: crusher chambers, silos, magazines, workshops, refuelling stations, refuge bays, offices, ablution facilities, etc. The location and geometry of this infrastructure must be adequately defined in order to allow an efficient operation and, at the same time, not to interfere with the mining.

(5) UNDERGROUND SERVICES. A large underground mine requires several services: electrical distribution and stations, control and communication systems, fire detection and suppression systems, water supply, compressed air supply, mine dewatering systems, etc. These services must be reliable and efficient to allow an efficient operation.

(6) SURFACE INFRASTRUCTURE. Also some surface infrastructure is needed: offices, workshops, change houses, roads and parking areas, etc.
All these issues are being reviewed and they will be definitively defined at the end of the pre-feasibility engineering stage. Indeed, in a case like Chuquicamata’s transition from open pit to underground mining, where the limits of technology and mining practice are being reached due to the depth and production targets for a panel cave mining in massive rock, a high quality pre-feasibility engineering is of fundamental importance to achieve a successful project outcome in terms of safety, cost, performance and timing.

**CHALLENGE 3: DEADLINES FULFILMENT AND GOALS ACHIEVEMENT**

The decision to make the transition from open pit to an underground operation is often based on a simple determination of the net present value (NPV) of the next feasible open pit pushback. Underground mining is only considered when a further pushback proves to be uneconomic. However, any decision to go underground also requires consideration of a wide range of technical factors, and careful planning, which means a significant amount of time for achieving underground mining (up to 20 years has been suggested by Stacey & Terbrugge, 2000). This is in addition to the thorough assessment of the potential geotechnical hazards associated underground mining by caving methods, and its interaction with the open pit and the surrounding infrastructure.

The milestones of the current plan are the following:

**DEADLINES:**

- Pre-feasibility engineering studies: January 2006 to December 2007
- Pit optimization: January 2008 to December 2014
- Feasibility engineering studies: January 2008 to December 2008
- Construction initiation: January 2009
- Construction period: January 2009 to December 2014
- Pit closure: December 2014
- Production initiation: January 2015
- Ramp-up period: January 2015 to December 2021
- Full production stage: December 2021 to December 2051

**PRODUCTION TARGETS:**

- Initiation Sectors North and South, Lift 1: January 2015
- Initiation Sectors North and South, Lift 2: January 2016
- Production increment: 5,000 TPD per year per sector
- Full production: 125,000 TPD (45 million tons per year)

This program is summarized in the chronogram of Figure 9. The fulfilment of these deadlines is very important for the mine business, because any delay will affect the production plan and the economical indicators of the project.
CONCLUSIONS

Chuquicamata’s transition from open pit to underground mining will be a major challenge for the Chilean mining engineering due to its magnitude and characteristics: panel caving in a massive rock mass, at depths of 1,300 m to 1,800 m, and high production rates.

There are important geotechnical aspects to be considered: the presence of a large and deep open pit, the presence of a major regional fault and a shear zone defining the boundary between ore and waste rock, potential for induced seismicity, potential problems associated with cave propagation, unavoidable subsidence and a possible simultaneous operation of the open pit and underground mine.

Important infrastructure requirements must be satisfied, including the accesses, material handling and ventilation systems. The right location and design of this infrastructure is of paramount importance to achieve a safe and efficient mine operation.

All these issues are being reviewed and they will be definitively defined at the end of the pre-feasibility engineering stage. Indeed, in a case like Chuquicamata’s transition from open pit to underground mining, where the limits of technology and mining practice are being reached due to the depth and production targets for a panel cave mining in massive rock, a high quality pre-feasibility engineering is of fundamental importance to achieve a successful project outcome in terms of safety, cost, performance and timing.
Also this project has deadlines that must be fulfilled, and production targets that must be achieved.

Hence, a successful transition from open pit to underground mining at Chuquicamata requires high quality engineering, which allows a successful project outcome in terms of safety, cost, performance and timing.

REFERENCES


