

Slope Design for Maricunga Mine in Chile.

E. Hormazabal *SRK Consulting, Chile*

C. Almarza *Kinross Gold Corp., Chile*

E. Pizarro *SRK Consulting, Chile*

Abstract

Kinross Gold Corporation has several porphyry/epithermal gold properties in Maricunga gold belt in northern Chile. The Maricunga site comprises the operating Verde pit and the Pancho deposit, currently under development. Currently active operations are all open pits mines of a medium scale, and have experienced varying degrees of geotechnical difficulties due to the highly altered and fractured nature of the rock mass. Kinross is currently conducting, at a feasibility engineering level, the Maricunga Mine Slope Optimization. A geomechanical assessment is being carried out to evaluate the wall stability of the final open pits at Verde and Pancho. To evaluate the mechanical stability of the open pits, a series of field work and geomechanical studies have been performed. These studies involved, among others, slope stability analyses based on limit equilibrium methods and numerical modeling. This paper describes the analysis methodology for the slope design applied to the optimization project.

1 Introduction

The Maricunga property, which consists of the Pancho and Verde deposits, is located in the Andes Mountain Range, close to the Chile-Argentina border in a region noted for numerous volcanic centres. The Maricunga District is elongated in a north-south orientation between latitudes 26° to 28°S. It extends for approximately 200 km in length and 50 km in width. The Maricunga site is structurally controlled gold deposit located approximately 120 Km east of Copiapo and is between 4,200 to 4,600 masl (see Figure 1).

Kinross is currently conducting at a feasibility engineering level the Maricunga Mine Slope Optimization. A geomechanical assessment is being carried out to evaluate the wall stability of the final open pits at both Verde and Pancho. To evaluate the mechanical stability of the open pits, a series of field assessments were performed by Golder (2003); AKL (2007) and SRK (2009 & 2010). Geotechnical information used in the study was comprised of wall mapping data carried out on the exposed benches and core logging of exploration boreholes. A structural model was defined for this purpose and groundwater investigations carried out.

2 Engineering geology

The regional geology is dominated by Miocene to Pliocene volcanics and portions of an exposed Paleozoic-Triassic basement (see Figure 2). The Pancho and Verde deposits are part of the Maricunga Metallogenic District. The older basement of Paleozoic and Mesozoic igneous and sedimentary rocks is unconformably overlain by the Miocene volcanic rocks. The volcanics are related to a series of large calc-alkaline stratovolcanoes. The volcanics have been subdivided into two sub-belts using K-Ar dating into western early Miocene (24 Ma to 20 Ma) and eastern middle Miocene (14 Ma to 13 Ma) sub-belts. High angle reverse faults caused by regional compression have juxtaposed these two volcanic belts. The same compressional event resulted in low angle thrusting in areas west and north of the property.

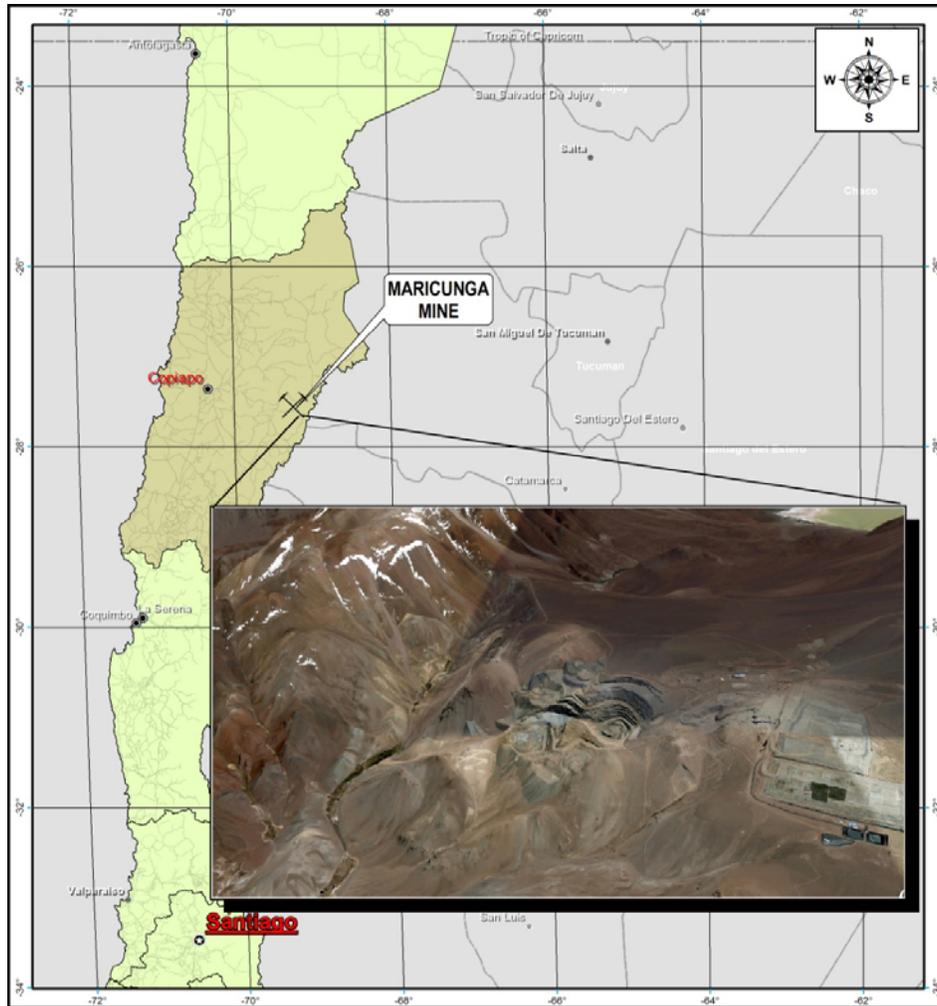


Figure 1. ‘Maricunga’ mine location.

Fourteen deposits or mineralized zones have been identified in this district including intrusion-hosted porphyry type precious metal deposits such as Lobo, Marte, Vally, Escondido, Cerro Casale, Maricunga, Amalia, and Santa Cecilia, and several volcanic-hosted high sulphidation, acid-sulphate type epithermal deposits (such as La Pepa).

The composite porphyry stocks in the eastern belt are dioritic, and in the western belt the volcanics are quartz dioritic. Microdiorite, intrusion breccias, and inter- to late-mineralization hydrothermal breccias are noted within the stocks.

Gold mineralization at Maricunga has been interpreted to be porphyry style gold systems. At Verde West, gold mineralization is centered about an elliptical porphyry plug measuring 175 m by 100 m and oriented at N30°W. At Verde East, the porphyry plug measures 130 m by 80 m and is oriented at N35°E. The porphyries occur within a sequence of intermediate tuffs, porphyries, and breccias that are the host rocks to the gold mineralization. Lithological interpretation at Verde has identified four main lithologic units. These are: Dacite Porphyry, Diorite Porphyry, Verde Breccia (Intrusive) and Laguna Tuff.

The gold mineralization at Pancho is also described as porphyry style mineralization. It occurs within a sequence of intermediate tuffs, porphyries, and breccias that are the host rocks to the gold mineralization. Lithological interpretation has identified six major lithologic units. These are described below from older to younger rocks: Dacite Porphyry, Diorite Porphyry, Verde Breccia (Intrusive) and Volcanic Breccia.

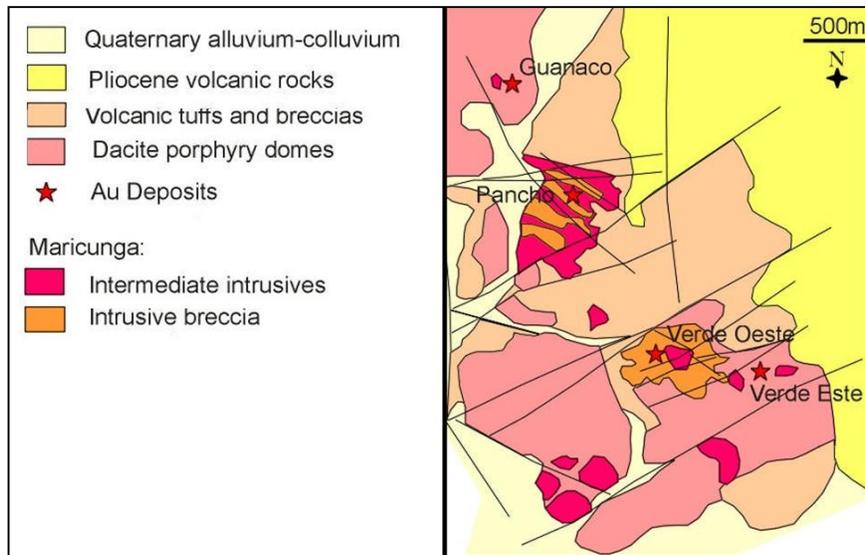


Figure 2. District geology of Verde and Pancho deposit.

Alteration assemblages observed at Verde and Pancho are generally supportive of porphyry style mineralization but the intensity of the alteration fabric tends to be weak. Potassic alteration has been observed at Verde but generally tends to be rare. Silicification is local and patchy. Propylitic alteration, although variable on the small scale, appears ubiquitous on the mine scale and in global terms does not change laterally or vertically.

Supergene alteration, which directly affects gold recovery, occurs deeper within fracture and fault zones. Sericite and chlorite are replaced by clay minerals, magnetite by hematite and pyrite by jarosite. The oxidation and leaching by meteoric waters has penetrated to variable depths within the deposits depending on the fracture intensity and faulting. The supergene alteration is accompanied by the deposition of limonite, manganese oxides, clay, sericite, and jarosite along with gypsum in the argillic altered zones.

According to the geotechnical information provided by surface mapping and geotechnical logging of several campaigns in the past (Golder, 2003, SRK 2009 & 2010), 6 structural domains can be defined at Verde pit (domains A, B, C, D, E & F) and 3 structural domains at Pancho pit (domains A, B & C). Figures 5 and 6 show these structural domains in the current Verde and Pancho pits.

At Verde, the main structural trends observed are major E-W subvertical faults, and secondary structures in NE-SW and NW-SE orientations. The latter two orientations are those associated with the presence of gold-bearing veinlets. Previous models have shown the E-W fault zones as continuous faults, crossing both the Verde and Pancho pits, however inspection of the map data and pit exposures, indicates that the E-W fault zones are composed of a number of *en echelon* sections, which have right-stepping offset, with subsidiary zones of NW-SE and NE-SW faulting concentrated around the termination and offset of the E-W faults. This is consistent with observations in the pit of intense fracturing and veining where faults of WNW-ESE and NW-SE trend intersect. These secondary faults are those that contain the gold-bearing veins, and therefore, there is a close relationship between the fault offsets and concentrations in gold grade (Goodman, 2010).

At Pancho, the main structural trends observed are major E-W subvertical faults, and secondary structures in NW-SE orientations. The lack of NE-SW faults observed at Pancho may be a result of the available outcrop lying on a NE-SW trending slope, which is close to the strike of such structures.

The groundwater level is below the bottom of the final pit at Verde pit. At Pancho, borehole loggings indicated that the phreatic table is located about 100 to 150 m below the current topography. This required a hydrogeology conceptual model to be developed to identify the groundwater conditions and the potential effect on the stability of the different mining phases.

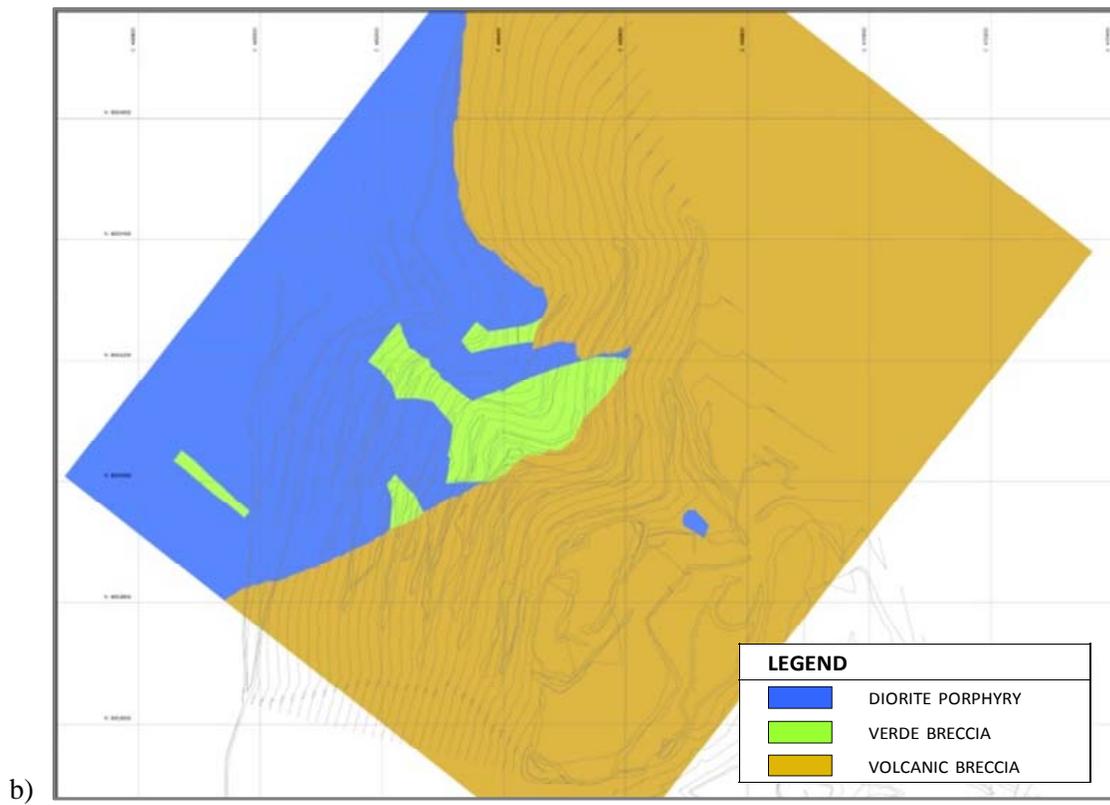
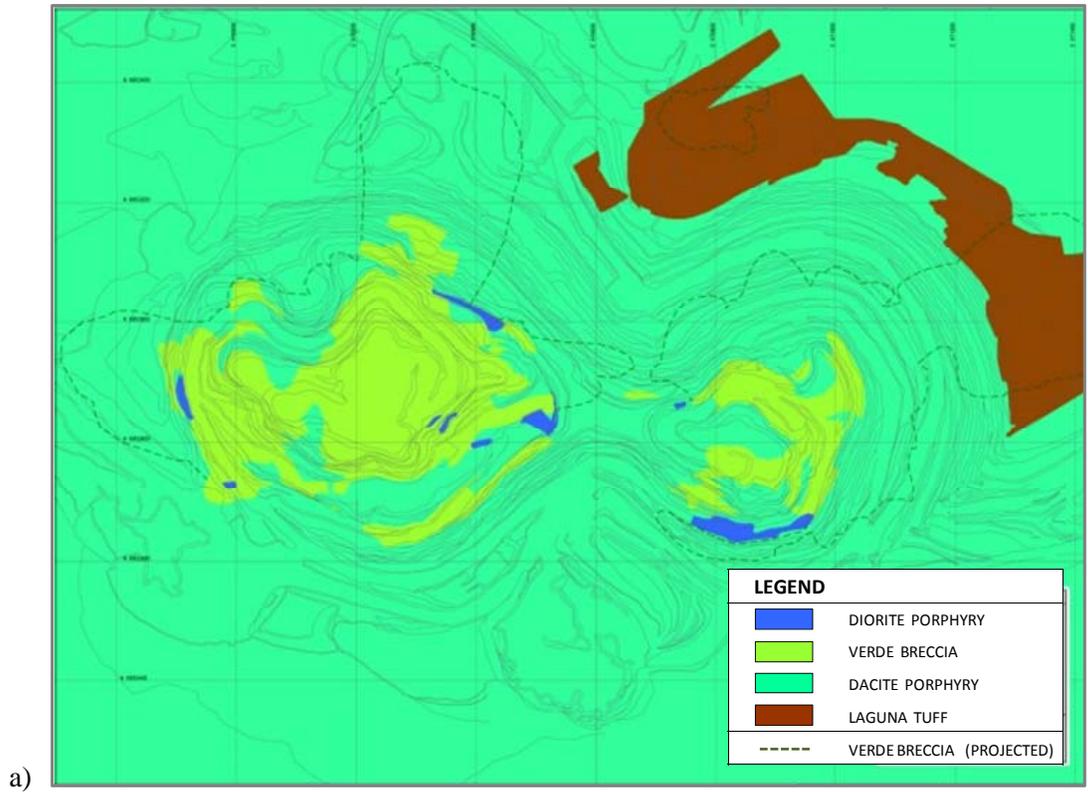


Figure 3. Lithologic units at a) Verde Pit, and b) Pancho Pit.

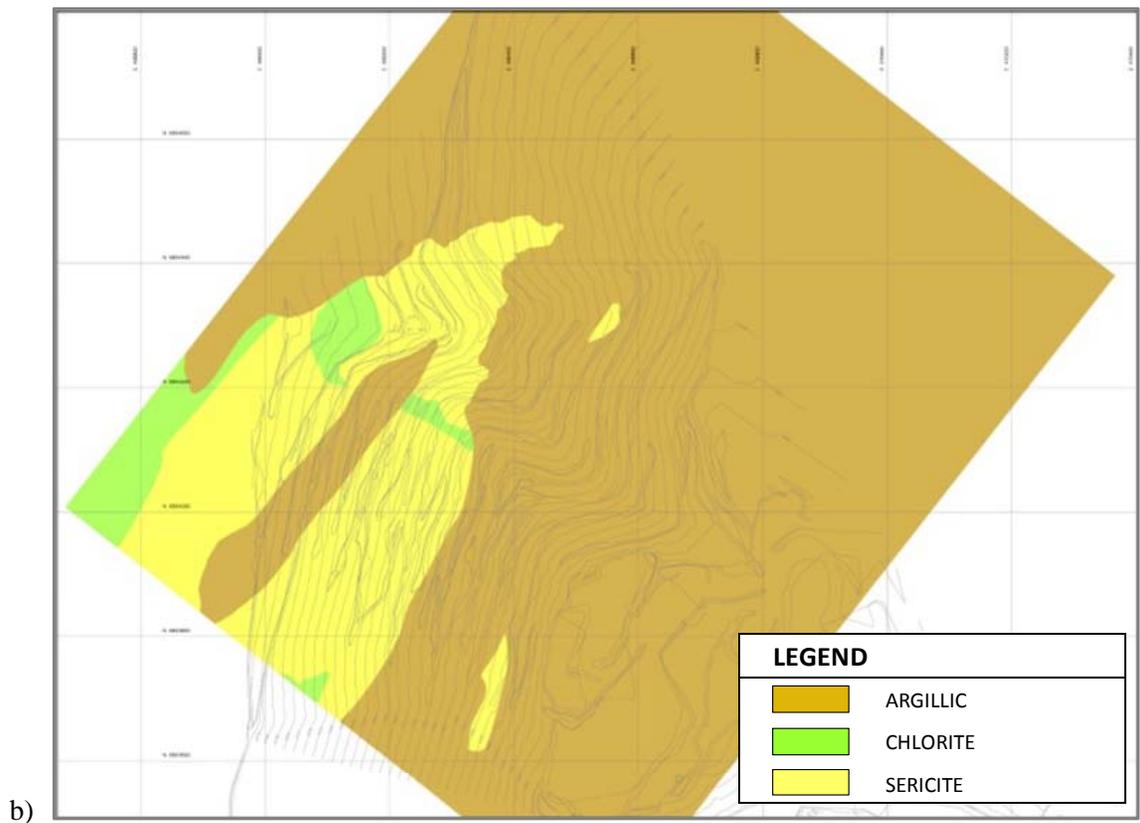
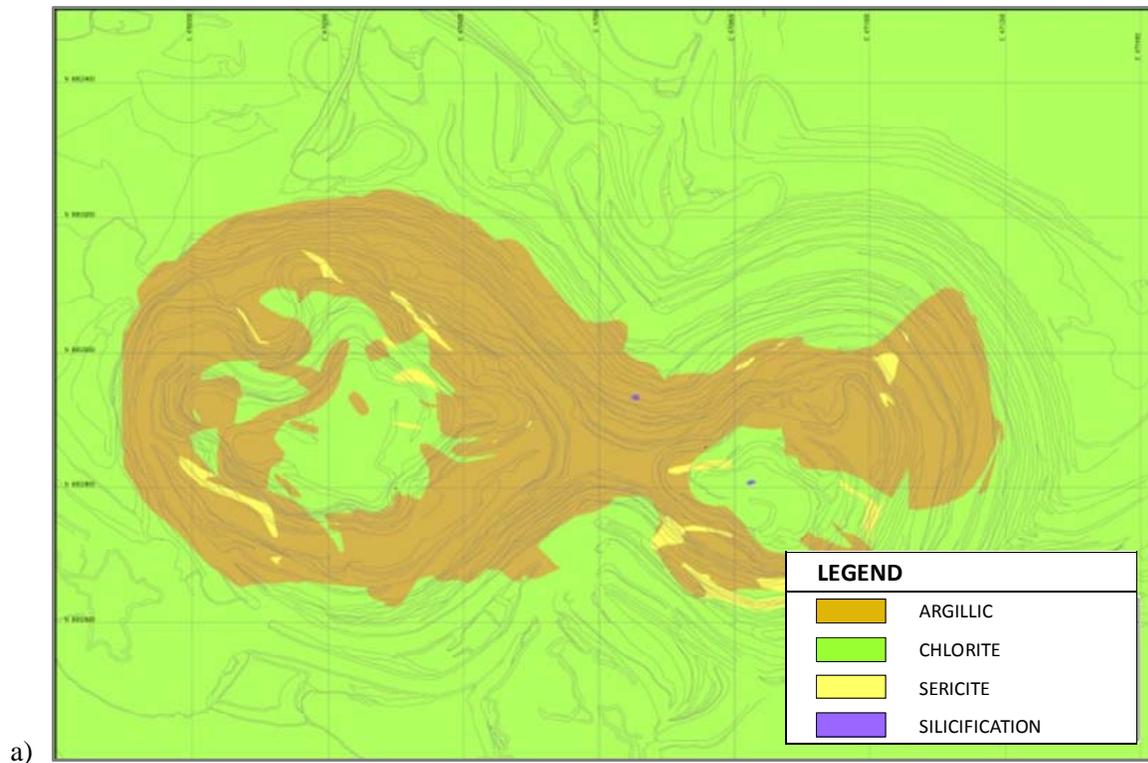


Figure 4. Alteration types at a) Verde Pit, and b) Pancho Pit.

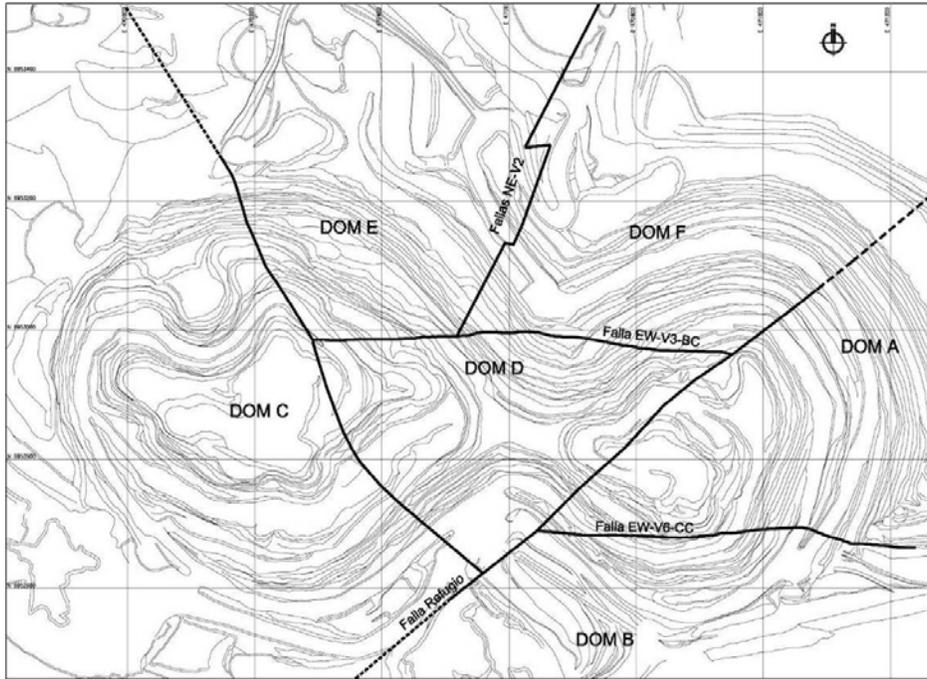


Figure 5. Structural domains in the current Verde Pit.

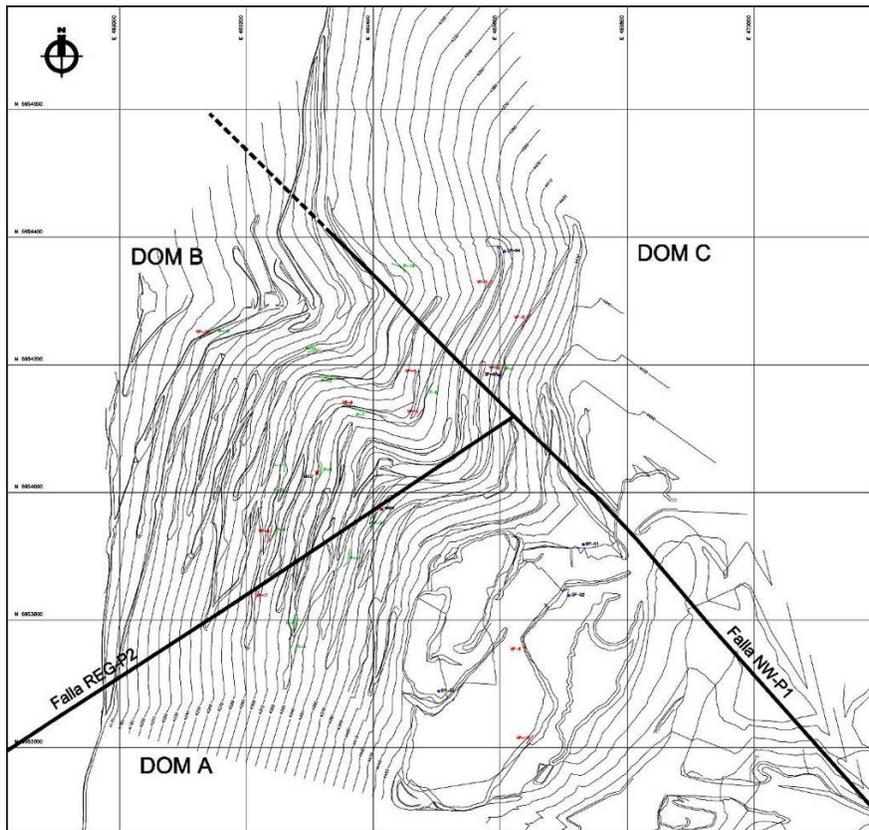


Figure 6 Structural domains in the current Pancho Pit.

3 Geotechnical characterization

Geotechnical characterization is based on geological-geotechnical borehole logging and surface mapping. The quality of the rock mass was rated using the Rock Mass Rating (RMR_B) defined by Bieniawski (1976). With this information geotechnical sections were developed, which include geotechnical parameters such as RMR_B or RQD (Deere, 1967).

The rock mass properties of the geotechnical units were evaluated using the Hoek-Brown criterion (Hoek et al, 2002), results of laboratory testing, and the geotechnical sections. The uncertainty of the geotechnical data was assessed using Monte Carlo simulations, based on recommendations from Harr (1987), Hoek (1998) and Steffen & Contreras (2007). These simulations were run using Crystal Ball, a stochastic software available from Oracle. Table 1 summarizes the geotechnical properties of the rock mass.

4 Slope analyses and design

Slope design process is based on the following sequence:

- a) Establish the geotechnical domains in terms of lithology, alteration, structural patterns and weathering boundaries.
- b) Define the critical sections within each domain for analysis of different slope orientations.
- c) For each section, determine the safety margins for different overall slope angles in terms of Factor of Safety (FOS) and Probability of Failure (POF) based on the surface response methods (see Steffen et al. 2008). Given potential slope heights and the quality of the rock mass, the standard limit equilibrium models would be appropriate with structures being the controlling factor in determining the failure mode.
- d) From the proposed mine plans, evaluate the inter-ramp slope angles, in terms of FOS and POF.
- e) From the inter-ramp angles, determine the bench/berm configuration in terms of FOS & POF.
- f) For the critical sections (highest wall and/or poor rock mass/structural conditions) run numerical models to identify other potential failure mechanisms controlled by major faults.

To evaluate the stability of the open pit, a series of studies have been performed. These studies included, bench berm designs, slope stability analyses using on limit equilibrium methods and finite difference numerical models. The acceptability criteria adopted for the feasibility study stage are the following:

- Bench Scale: FOS > 1.1 & POF < 30%
- Interramp Scale: FOS > 1.2 & POF < 10%
- Global Scale: FOS > 1.3 & POF < 5%

FOS: Factor of Safety.

POF: Probability of Failure.

These criteria are based on the minimum risk to personnel and equipment, continuous remote monitoring systems, safe double access and exit from the pit.

Table 1. Geotechnical properties of the rock mass.

Geotechnical Units				γ (kg/m ³)	σ_{ci} (MPa)	m_i	RMR _{B76}	E (GPa)	ν	c (kPa)	ϕ
Code	Litho	Alter	Min Zone								
BX_ARG_OX/MX	BRECCIA	Argillic	Secondary	2100	31.7	7.2	20-40	0.95	0.29	300	20°
BX_ARG_SUL			Primary	2150	35.1	10.1	20-40	0.60	0.29	360	22°
BX_CLO_OX/MX		Cloritic	Secondary	2270	44.4	9.5	20-40	1.07	0.28	535	24°
BX_CLO_SUL			Primary	2010	86.0	18.0	40-60	4.54	0.25	1340	40°
BX_SER_SUL		Sericite		2260	66.3	12.5	40-60	4.27	0.25	1035	36°
PDA_ARG_OX/MX	DIORITE PORPHYRY	Argillic	Secondary	2040	38.7	14.4	20-40	0.24	0.29	480	24°
PDA_CLO_OX/MX				2590	69.0	10.5	40-60	5.15	0.25	1080	33°
PDA_CLO_SUL		Cloritic	Primary	2500	89.8	17.5	40-60	3.99	0.25	1375	40°
LAGUNA TUFF				1900				0.05	0.40	60	38°
FAULTS ZONES				2200				0.05	0.40	150	25°

γ	Density	σ_{ci}	Intact rock unconfined compressive strength.
m_i	Hoek-Brown 'm' parameter for intact rock.	GSI	Geological Strength Index (Hoek, 1994).
E	Young's modulus.	ν	Poisson's ratio.
c	Cohesion of the rock mass	ϕ	Friction angle of the rock mass.

The bench berm design considers a bench height of 10 m from the operational perspective; and a double bench design was selected (20 m total height). The expected bench face inclination was defined as 65° for the oxide zone and 70° for the primary zone. Structurally controlled bench instabilities (i.e planar and wedges) were analyzed for all slope orientations and domains. The analyses were performed using the software DIPS, ROCPLANE and SWEDGE (available from www.rocscience.com). The berm width required was computed based on recommendations provided by Gibson et al., 2006, and acceptability criteria suggested. According to this reference, the minimum berm width required for doubles benches ranges from 8.0 to 10.5 m for Verde pit and 8.5 m to 13.0 m for Pancho pit.

For interramp and global design, limit equilibrium models were used to analyze structurally controlled stability problems. To assess the stability of interramp and overall slopes in Verde Pit, 11 cross sections were defined as shown in Figure 7a. For Pancho pit, 7 cross sections were defined as shown in Figure 7b.

Each section was analyzed with the Generalized Limit Equilibrium (GLE) method using SLIDE software (available from www.roscience.com). The stability analyses were done according to the following:

- To include the effect of rock bridges, probabilistic analyses were performed to define a directional strength. These probabilistic analyses were run using STPSIM program, considering the mean and the standard deviation for the strength of geotechnical units and the structures for the different domains. Also, length, dip and spacing of the structures were considered in a similar way to the one described by Baczynski (2000).
- In each section all the possible failure combinations were considered: lower and upper interramp, more than one interramp, overall slope and lithological contacts.
- Fully saturated tension cracks were utilized to simulate snow conditions
- A path search technique was used to find the most critical failure surface in each case. For the most critical failure surface the probability of failure was computed using the surface response method (Steffen, 2008). Basically, the uncertainty was associated to the cohesion, friction angle, structures dip and phreatic surface position only for Pancho Pit (It was assumed a correlation coefficient equal to zero between cohesion and friction angle).
- The results and interpretation of slope stability analyses indicate that the slopes are stables (FOS > 1.4 and POF < 5% in all cases). Table 2 shows the results for all cases analyzed. Figure 9 shows typical results from these slope stability analyses.

Table 2. Results of the slope stability analyses.

Pit	Section	H ₀ (m)	α ₀	α _{IRA}	FS ₀	PF ₀	W (KTON/m)
VERDE EAST	V1	240	44°	50° - 53°	2.56	< 0.1%	62.1
	V2	257	44°		2.44	< 0.1%	83.0
	V3	270	42°	38° - 53°	2.63	< 0.1%	45.8
	V4	213	44°	48° - 49°	1.60	< 0.1%	23.0
	V5	244	41°		2.19	< 0.1%	29.7
	V6	263	43°	48° - 53°	2.42	< 0.1%	56.7
VERDE WEST	V7	340	42°	50°	1.78	0.8 %	81.5
	V8	349	34°	38° - 50°	1.93	< 0.1%	108.2
	V9	178	48°	53°	1.54	3.1%	13.8
	V10	229	45°	50°	1.83	< 0.1%	43.9
	V11	271	47°	47° - 53°	1.86	1.0%	56.6
PANCHO PHASE 3	P1	490	46°	47° - 49°	1.97	< 0.1%	202.4
	P2	510	46°		2.21	< 0.1%	226.6
	P3	501	46°		2.30	< 0.1%	177.4
	P4	482	46°	48° - 52°	1.55	0.9 %	145.9
	P5	473	47		2.41	< 0.1%	250.9
	P6	470	46°		1.47	1.2%	151.0
	P7	150	34°		54°	3.48	< 0.1%

H₀ Potential Failure Surface Height α₀ Overall Angle. α_{IRA} Interramp Angle.
 FS₀ Factor of Safety (Overall Slope) PF₀ Probability of Failure (Overall Slope).
 W Tonnage per lineal metre of potential failure surface.

Additionally to the equilibrium limit method, a numerical analysis was performed for cross section V7 (Verde West pit), using software FLAC v 5.0 (available from www.itasca.com) and for cross section P4 (Phase 3 of Pancho pit), using software UDEC v 4.0 (available from www.itasca.com). These cross sections were selected to assess the rock mass behavior for Verde West pit and major faults for the highest slope and lower FS at Pancho Pit. The numerical analysis was done according to the following:

- In situ stresses were assumed as follows:
 - A gravitational vertical stress.
 - Horizontal stresses in the EW direction, $K_{EW} = 1.2$ and NS direction, $K_{NS} = 0.6$.
- To include the effects of structures, ubiquitous joints were considered for Verde West pit. For Pancho pit explicit faults were considered.
- Same strength properties, structural domains and phreatic surface were considered for limit equilibrium and numerical models.
- The FOS was computed according to the shear strength reduction technique.

The results of these numerical analyses for Verde pit, indicated that:

- Maximum horizontal displacements occur locally in the lower benches corresponding to the fault zone and Breccia Secondary Unit and do not exceed 1.25 m. Hence, if the ratio between the slope crest's horizontal displacements and the slope height is smaller than 1.0% ($1.25/340 \approx 0.4\%$). Hoek & Karzulovic (2000) suggested that slopes begin to show signs of instability when the ratio is greater than 2%.
- Large deformations are observed at the toe of the slope due to fault zones (poor rock mass quality).
- The plasticity indicators (failure through the rock mass by shear and/or tension, slippage along ubiquitous joints) indicated that tensile failures occur in the lower slope.
- The factor of safety computed with the strength reduction technique is 1.63 and the failure surface reach 340 m of height (see Figure 8). The FS obtained from limit equilibrium method was 1.78.

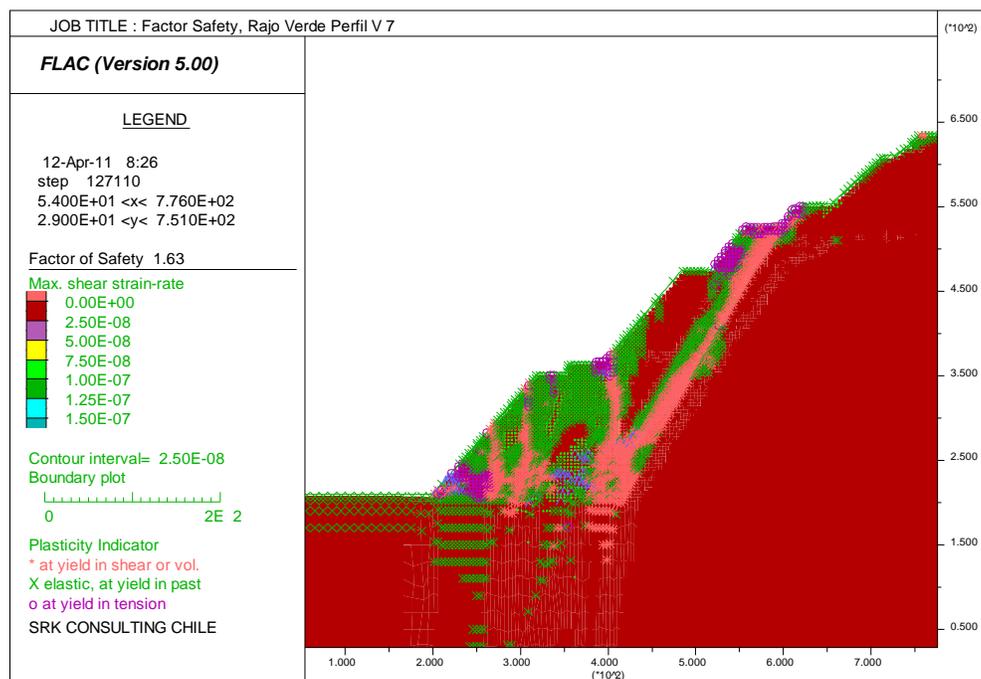


Figure 8. Plasticity indicators concentrated in fault zones in cross section V7 of Verde Pit Phase 4. Factor of Safety FOS = 1.63.

The results of these numerical analyses for Pancho pit, indicated that:

- Maximum horizontal displacements occur locally in the lower benches corresponding to fault zone and Breccia Secondary Unit and do not exceed 0.2 m. Hence, if the ratio between the slope crest's horizontal displacements and the slope height is smaller than 1.0% ($0.2/480 \approx 0.1\%$). Hoek & Karzulovic (2000) suggested that slopes begin to show signs of instability when the ratio is greater than 2%.
- Large deformations are observed at the toe of the slope due to the water table effect.
- The plasticity indicators (failure through the rock mass by shear and/or tension, slippage along ubiquitous joints) indicated that tensile failures occur in the lower slope.
- The factor of safety computed with the strength reduction technique is 1.37 and the failure surface reach 480 m of height (see Figure 9). The FS obtained from limit equilibrium method was 1.55.

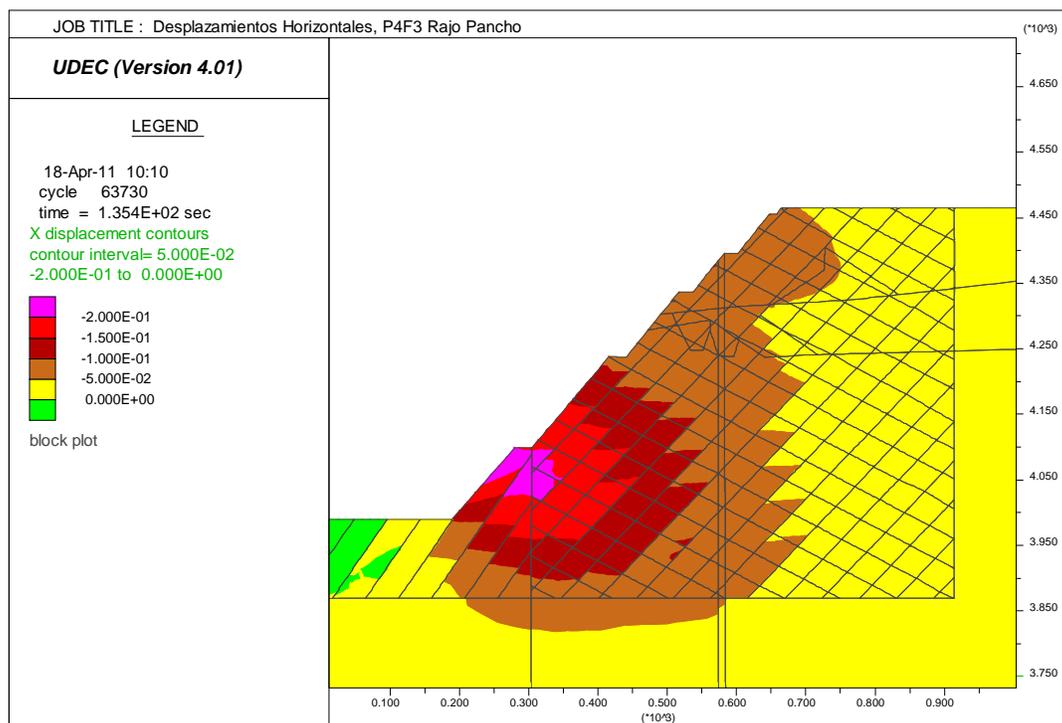


Figure 9. Horizontal displacements at section P4 of Phase 3 of Pancho pit.

5 Blasting considerations

It is clear from Figure 9 that the benches of Verde pit in general were in a very poor state with virtually no catch berms available and rubble filling whatever berms that did exist. Multiple bench failures have occurred at several locations around the pit perimeter ranging from rock mass failure to structural induced failure mechanisms. The slope failures experienced resulted partly from design but mostly from poor blasting control.

It is clear that blast damage of the slope faces is excessive in terms of modern practice and standards of house-keeping. Poor blasting practices are a major cause for berm loss and screed development. It should be noted that the high degree of fracturing in the rock mass requires special care in blasting practices to avoid damage and berm loss. While it is not expected that pre-split blasting of these bench faces would result in perfectly smooth bench faces, it would avoid the excessive damage to the bench faces and retain intact berms for rock fall retention. The fundamental reasons for the blast damage in Verde pit were:

- It is a hard rock pit and there are no shovels in the pit that can dig the muck pile, only rubber tired loaders are used for loading, and are not capable of digging.
- For this reason, blasts were designed to fragment the rock finely to improve the productive capacity of the loaders.
- Powder factors greater than 500 gr of explosives / removed tonnage, for poor to regular rock mass quality.



Figure 9. View of the North face taken from Verde West pit.

During 2010 and 2011, an extensive blasting program had been carried out including trial blasting for different units, vibration measurements, alternative types of explosives, and drillholes diameters (Rock Blast Design Ltda., 2011). The results can be seen in Figures 10 and 11, which indicates the current blasting practices for double benches (20 m) of a 70° bench angle using controlled blasting can be observed.



Figure 10. Double benches achieved using controlled blasting (6×6×10 m, Ø 9 7/8“and pre-shearing Ø 5 1/2“) in Pancho pit.



Figure 11. View of the current North wall of Pancho pit. Detail of the well groomed double benches achieved using controlled blasting ($6 \times 6 \times 10$ m, $\varnothing 9 \frac{7}{8}$ " and pre-shearing $\varnothing 5 \frac{1}{2}$ ").

6 Conclusions

A summary of the field work and analyses for the feasibility engineering stage has been presented to provide an example of geotechnical design in very difficult conditions. Based on geotechnical and structural characterization limit equilibrium and numerical methods were used to assess slope stability at the Maricunga Mine (Verde and Pancho pits).

Based on the results of all analyses performed, the geotechnical characterization must be improved with more laboratory tests for the main geotechnical units. Also, a hydrogeology conceptual model needs to be incorporated for Pancho pit.

The overall slope design is controlled by the stability of interramp stack, so any optimization in the overall angle needs to be verified at interramp level.

The recommended slope design requires good operational and blasting practices, and also efficient slope instrumentation and monitoring system. Currently, the quality of blasting allows achieving well groomed 20 m double benches, with 70° bench face inclinations, and the pits walls are under continuous monitoring by a robotic Leica APS-Win system and one Reutech radar system (model MSR-300). The use of radar monitoring equipment provides excellent coverage for the safety of personnel and equipment and is essential in the current situation and should be continued into the future final phases. It is important that a suitable evacuation procedure be developed and integrated into the monitoring system for risk management.

Back analyses of the existing failures are an important benchmark for the future design program of the final pit. Design criteria for the final slopes should be based on the value vs risk trade off, provided that the monitoring system is effective.

7 Acknowledgements

The authors would like to thank KINROSS - CHILE, Technical Services Kinross Copiapo, and specially, the Maricunga General Manager Mr. Cleres Sampaio for their permission and authorization to share the mining experience and practices provided in this paper.

8 References

- AKL (2007). Revisión Geotécnica de Estabilidad de Taludes – Pit Final Rajo Verde. Report CMM-2007.01 de AKL, submitted on April to Compañía Minera Maricunga.
- Baczynski, N. (2000). Stepsim4 “Step-path” methods for slope risks. In *GeoEng 2000 Proceeding of the International Conference on Geotechnical and Geological Engineering*. Melbourne, 6pp.

- Bieniawski, Z. T. (1976). Rock mass classification in rock engineering. In *Proceedings of Symposium on Exploration for Rock Engineering*. Balkema, Rotterdam, vol. 1, pp. 97-106.
- Decisioneering (2004). CRYSTAL BALL v. 7.0. Risk Analysis Program. USA.
- Gibson, W., Bruyn, I., Walter, D. (2006). Considerations in the optimization of bench face angle and berm width geometries for open pit mines. *International Symposium on Stability of Rock Slopes in Open Pit Mining and Civil Engineering, Cape Town*. The South African Institute of Mining and Metallurgy.
- Golder Associates (2003). Report On. Feasibility Slope Design Criteria for the Verde Este and Verde Oeste Pits. Refugio Mine.
- Hoek, E., Carranza, C., Corkum B. (2002). Hoek-Brown failure criterion 2002 edition. In Hammah et al. (eds.), *Proc. 5th North American Rock Mechanics Symposium & 17th Tunneling Association of Canada Conference, Toronto*. University of Toronto Press, Toronto, vol 1, pp. 267-273.
- Hoek, E. , Diederichs M.S. (2005). Empirical estimation of rock mass modulus. *Int J Rock Mech Min Sci* 43: 203-215.
- Hoek, E. , Karzulovic, A. (2000). Rock mass properties for surface mines. In Hustrulid et al. (eds.), *Slope Stability in Surface Mining*. Society for Mining, Metallurgical and Exploration (SME), Littleton, pp. 59-70.
- Itasca (2005). FLAC. FAST LAGRAGIAN ANALYSIS OF CONTINUA. Ver. 5.0, Itasca Consulting Group, Inc.
- Itasca (2004). UDEC. UNIVERSAL DISTINT ELEMENT CODE. Ver. 4.0, Itasca Consulting Group, Inc.
- Kinross Gold Corporation (2007). Technical Report for the Maricunga Gold Mine.
- Read. J., Stacey, P. (2009). *Guidelines for Open Pit Slope Design*. CRC Press. USA.
- Rocscience (2005). SLIDE v 5.0. Limit Equilibrium Slope Stability for Soil and Rock Slopes. Canada.
- Rocscience (2005). SWEDGE v. 5.0. 3D Surface Wedge Analysis for Slopes. Canada.
- Rocscience (2006). ROCPLANE v. 2.0. Planar Sliding Stability Analysis for Rock Slopes. Canada.
- RockBlast Design Ltda. (2011). Optimización de los actuales diseños de perforación y tronadura implementados en Rajo Pancho. Report submitted in April to Compañía Minera Maricunga.
- SRK Consulting (Canada) Inc. (2010). Structural Model of Pancho and Verde deposits, Maricunga Mine, Chile.
- SRK Consulting (Chile) S.A. (2010). Estudio Optimización de Taludes Maricunga. Feasibility Engineering Stage Report. January.
- Steffen, O., Contreras, L. (2007). Mine planning-its relationship to risk management. ACG, Perth, Western Australia.
- Steffen, O.K.H., Contreras, L.F., Terbrugge, P.J., Venter, J. (2008). A risk evaluation approach for pit slope design. In *Proceedings of the 42nd US Rock Mechanics Symposium and 2nd U.S.-Canada Rock Mechanics Symposium*. San Francisco, June 29-July 2.