Rock Slope Management at Sossego Mine

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Abstract

The stability of rock slopes in high strength rock masses is normally controlled by discontinuities. However, when only drill core is available it is not easy to characterize the discontinuities because of scale considerations and the difficulty of assessing such characteristics as continuity that can play an important role in the slope stability.

When mining commences, the discontinuities and rock mass can be better evaluated and characterized to improve the geomechanical model of the pit slopes. On the other hand, the performance of blasting can decrease the rock mass quality and start to become a significant factor in the stability of the slopes. Blasting can induce new fractures and open the existing discontinuities, reducing the rock mass strength and creating major rockfall hazards.

At Sossego Mine, despite a good geomechanical model at the design stage, the opening of Sequeirinho pit has illustrated the difficulties in achieving the slope designs due to poor blasting practices and the presence of local discontinuities that govern the behavior of the slopes in local areas.

To address these issues Vale contracted a review of the geomechanical model and an overall review to confirm the good quality of the rock masses and the need to improve controlled blasting, particularly near the final slopes.

In addition, studies have been undertaken at Sossego Mine to improve the blasting, particularly the controlled blasting. These studies have included both a detailed review of the entire blasting process and the adoption of a system to evaluate the results.

INTRODUCTION

The aim of any open pit mine is to provide an optimal excavation configuration in the context of safety, ore recovery and financial return. Large open pit mines depend on economies of scale to meet their business targets. Consequently, the trend in large open pit mining has been towards high energy blasting to increase in-pit comminution and thereby improve excavation performance, coupled with large equipment that is capable of high levels of productivity (Sjoberg, 1999).

Another important aspect is to mine in phases to maximize the ore recover and minimize the excavation of waste to pay the CAPEX of the mine as fast as possible. This practice can lead to mining both at the top and in the bottom of the same slope with blastover filling the berms between two.

For the slopes in large open pit mines, it is essential that a high degree of stability is assured to minimize the risks related both to the safety of operating personnel and equipment, and also to reduce economic risks to the reserves. In open pit mines, slope instability is one of the major sources of risk.

Controlled blasting strategies driven by technical issues are required to ensure that the walls are not damaged by blasting in the open pits. The geological characteristics of the region adjacent to the blast and further up the slope dictate the potential for blast induced damage. As with slope design, it is important to consider the hardness and structure of the rockmass when developing efficient wall control blast designs.

The rock masses at Sossego Mine are strong to very strong with very good to good geomechanical characteristics, and it is therefore necessary to use a high powder factor (550g/ton) for efficient production excavation. This high energy input can affect the walls and introduce slope stability problems both at the immediate bench scale and at a larger scale through to the reduction of rock mass cohesion.

To avoid this problem the Sossego Mine geotechnical staff is working with operations staff to determine a distance from the walls that controlled blasting must be used. Bothe pre-split and post-split blasting practices are used at Sossego Mine. In this regard, a key factor has been found to be the quality of the explosive and initiation products.

Sossego Mine

Sossego Mine is a copper mine located at Carajás mineral province in the southeast of Para State, Brazil. It is located approximately 80km from Carajás Iron Mine and 800km from Belem, the capital of Pará State (Figure 1).

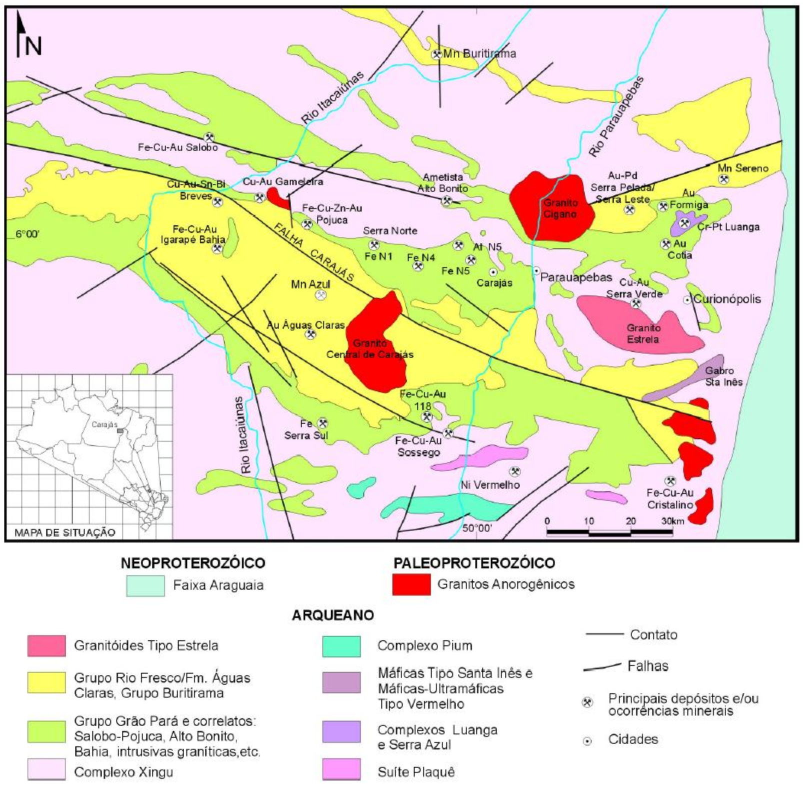

Figure 1 *- Carajás Mineral Province Map and Location of Sossego Mine.*

The mine has two main open pits, Sossego and Sequeirinho, which will eventually reach ultimate depths of 250m and 480m, respectively. The mine is owned and operated by Vale, and a combined total of 17 Mt of ore is mined annually. The copper mineralization occurs as disseminated veins of chalcopyrite and bornite. Average ore grade is approximately 0.94% Cu and some 320,000 tonnes of concentrate are produced from the plant each year. Figure 2 shows the general layout of Sossego Mine with the pits, waste dumps, plant and tailings dam.

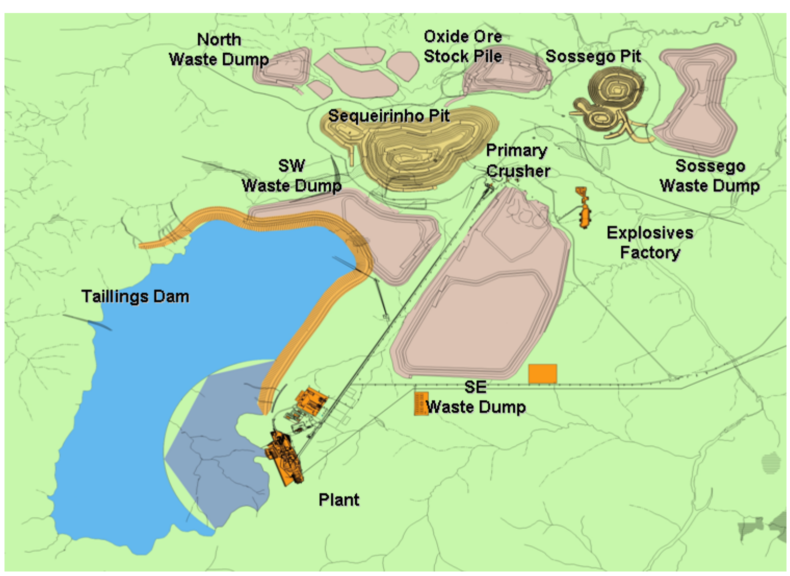

Figure 2 *- Sossego Mine Master Plan.*

The Sequeirinho and Sossego orebodies are different. The Sossego orebody is vertical and pipe-like, with radial joints and veins. At Sequeirinho, the orebody strikes WNW-ESE and dips between 40 to 50° to the south; it is approximately 2,000m long and 50m wide (Figure 3).

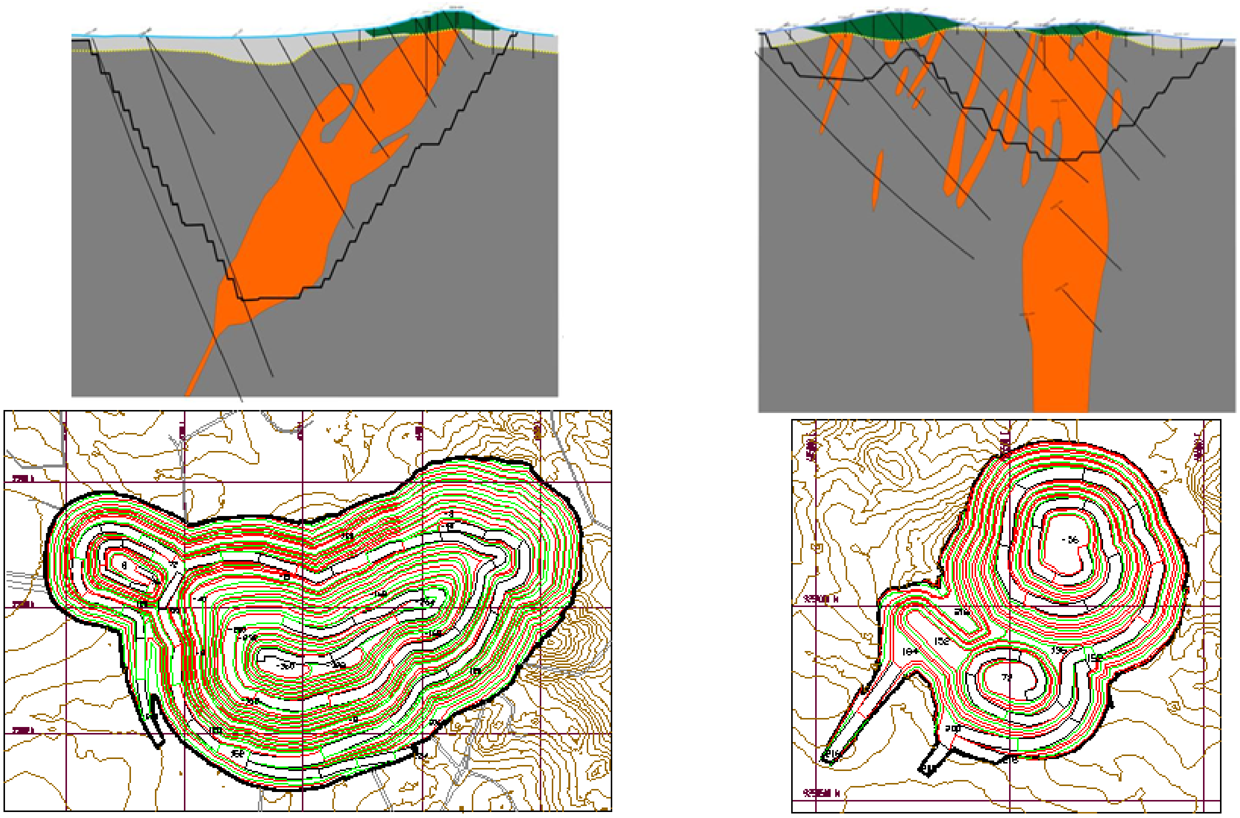

Figure 3 *- Sequeirinho and Sossego Pits at Sossego Mine.*

The current overall stability conditions of the slopes are generally good and there is no sign of large scale instabilities. In the north footwall at Sequeirinho pit there are several plane shear failures and a few bench scale wedge failures. All of the failures have occurred along well defined discontinuities, rarely exceeding one bench in height, and there have been no mining operation interruptions because of this.

Figure 4 shows a cross section through Sequeirinho Pit. The footwall of the ore zone is associated with a shear zone that dips to the south. Consequently, as the mining depth is increased to expose the orebody, a greater amount of waste rock must be removed from the hangingwall. This results in a requirement to establish steep, but stable slopes on the hangingwall in each mining phase.

The present Sequeirinho pit depth is around 200m, but current mining plans call for a final pit depth of around 480m. Today stability problems are confined to small failures along the benches and rockfall hazard, and there is no evidence of larger scale instability.

In the Sossego pit the Phase 1 cut has been completed and the larger, Phase 2 cut has been started and will eventually have a depth of about 250 m. Because of the pipe-like configuration of the orebody the steepest possible slopes are required on all walls to minimize stripping.

While the discussions that follow apply to both pits, they will focus on the Sequeirinho pit, which is the largest and geologically most complex.

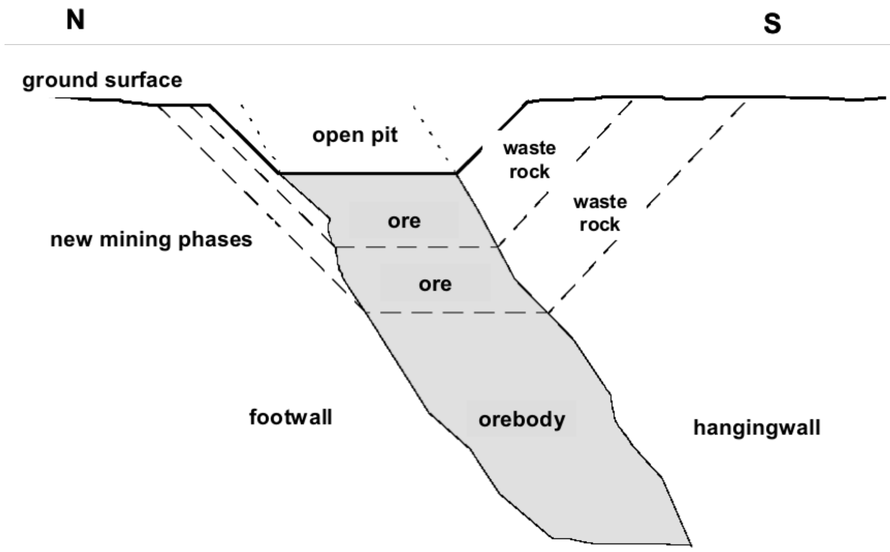

Figure 4 *- Schematic of Sequeirinho Pit Mining in Phases.*

ROCK MASS CHARACTERISTICS

Sossego Mine is located in the mineral province of Carajás in Pará state. The area around the mine consists of metamorphosed plutonic, volcanic and sedimentary rocks of Precambrian age.

The Itacaiúnas Belt of the highly mineralized Carajás Mineral Province comprises ca. 2.75 Ga volcanic rocks overlain by sedimentary sequences of ca. 2.68 Ga age, that represent an intracratonic basin rather than a greenstone belt. Rocks are generally at low strain and low metamorphic grade, but are often highly deformed and at amphibolite facies grade adjacent to the Cinzento Strike Slip System.

The Province has long been recognized for its giant enriched iron and manganese deposits, but over the past 20 years has been increasingly acknowledged as one of the most important Cu–Au and Au–PGE provinces globally, with deposits extending along an approximately 150 km long WNW-trending zone about 60 km wide centred on the Carajás Fault. The larger deposits (approx. 200–1000 Mt @ 0.95–1.4% Cu and 0.3–0.85 g/t Au) are classic Fe-oxide Cu–Au deposits that include Salobo, Igarapé Bahia-Alemão, Cristalino and Sossego. They are largely hosted in the lower volcanic sequences and basement gneisses as pipe- or ring-like mineralized, generally breccia bodies that are strongly Fe- and LREE-enriched (light rare earth elements), commonly with anomalous Co and U, and quartz- and sulfur-deficient. Iron oxides and Fe-rich carbonates and/or silicates are invariably present. Rhenium–Os dating of molybdenite at Salobo and SHRIMP Pb–Pb dating of hydrothermal monazite at Igarapé-Bahia indicate ages of ca. 2.57 Ga for mineralization, indistinguishable from ages of poorly-exposed Archean alkalic and A-type intrusions in the Itacaiúnas Belt, strongly suggesting a deep magmatic connection (Grainger et al, 2007)

The mapping in the open pits showed several lithologies exposed in the walls (Figures 5 and 6). The primary igneous and sedimentary features have been completely destroyed by metamorphism and it is not easy to identify the lithology. For geomechanical studies only the most important lithologies have been adopted, based on the block model and the mapping.

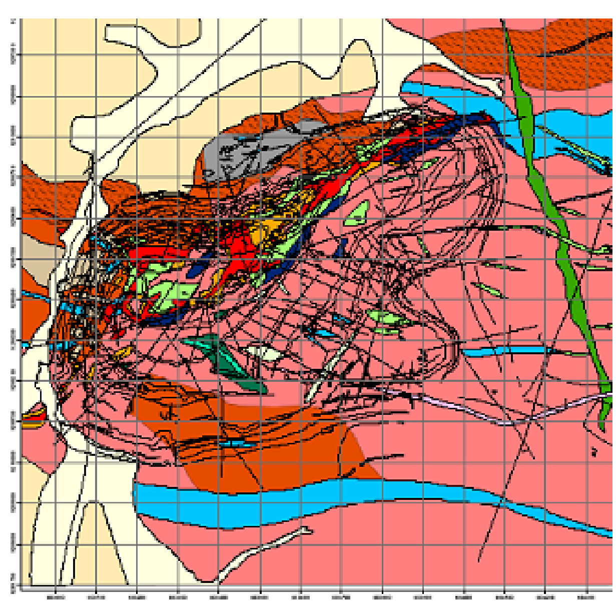

Figure 5 *- Geological Map of Sossego Mine. Sequeirinho Pit.*

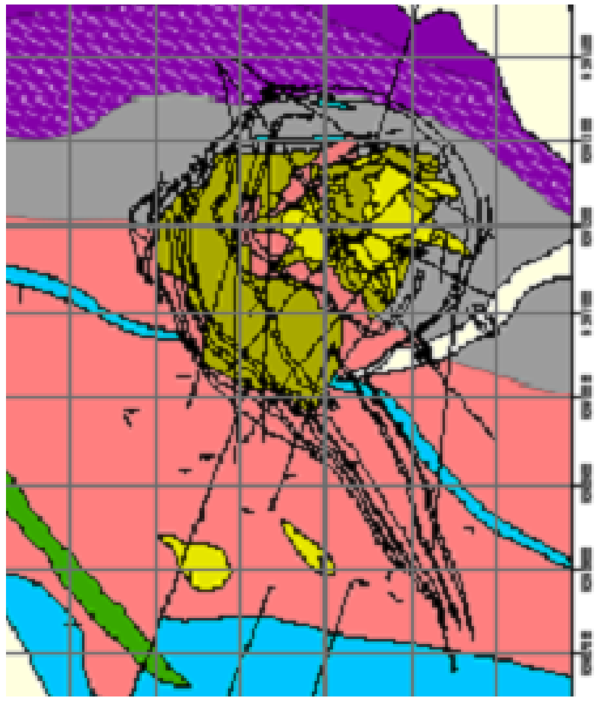

Figure 6 *- Geological Map of Sossego Mine. Sossego Pit.*

Geologic Model

The lithologies considered in the geomechanical model (BVP, 2007) are:

Metavolcanic acid rock (MVA)

These rocks, which have a hydrothermal origin with several stages, are located in the north portion of Sequeirinho pit. The boundaries with the shear structure are not very clear. Some veins of sulfide occur, but the rocks are waste.

Granite (GR)

Granite is very common in both Sequeirinho and Sossego pits and there is a great variation in mineral assemblage and magma composition. It is the most common waste lithology at Sossego Mine. The texture is sometimes massive, but there are small shear zones and some dikes up to a few meters wide. There are also some lenses of gabbro.

The granite in Sequeirinho pit occurs on the hangingwall of the shear zone that forms the orebody. In the Sossego pit it is the host rock of the mineralized pipe.

Biotite Schist (BIX)

Biotite schist is a heavily foliated and fine grain rock that occurs in the north and west portions of the Sequeirinho pit. It is waste rock in the north, but has some veins of sulfide ore in the west. The lens structure may have developed during the first stage of shearing, after the first mineralization of the orebody.

In some places the hydrothermal fluids have weathered the schist, giving it a similar appearance to the metamorphic acid volcanic rocks; in this case it is termed "hydrothermalite".

Breccia

The mineralization in both the Sequeirinho and Sossego pits is associated with hydrothermal fluids that changed the rock to a breccia composed of angular or sub-angular grains in a finer grained matrix. The mineralization is composed quartz, actinolite, carbonate, sulphide (mainly chalcopyrite and bornite) and oxide minerals.

In Sequeirinho pit the breccia is located between the metavolcanic and granite rocks that respectively form the footwall and hangingwall of the orebody. In Sossego pit the breccia occurs as veins in the host rock.

Structural Model

Sequeirinho

The main geological structures identified in the Sequeirinho pit are foliation, brittle-ductile shear zones, fractures, faults and joints.

Foliation is very well developed in the biotite-schists in the NW portion of Sequeirinho pit as schistosity and banding. However, it is less evident in the granite, where it is generally represented by a weak foliation, giving the rock a gneissic texture. The foliation strikes WNW-ESSE with vertical dip and appears to be related to regional ductile shear zones.

One such shear zone is located in the north wall, where it results in plane shear failures, making it the main geological structure in terms of slope stability at Sequeirinho pit. The shear zone strikes ENE-WSW and dips at a high angle to SE, although there is some undulation.

The lineations on the structure planes suggest a general genesis related to strike-slip (transcurrent) faulting. There are two different movements, the first associated with the foliation with strike WNW-ESSE and low dip, showing ductile transcurrent movement. The second one is related to the shear zone planes with a WSW strike and low dip, showing ductile-brittle strike-slip movement.

The faults are mainly shear zones, typically with low thickness (centimeters to meters), but with a persistence of at least tens of meters. They are generally parallel to the foliation and cross the shear zone. There is a specific fault (Fault T) with an orientation N10ºE/60°SE (strike and dip) and a width of about 10m that crosses the main shear zone in the center of the north wall at Sequeirinho pit (Figure 7).

There are several joint sets in the rock mass, generally three to five sets in any specific face in the pit. The geological mapping has identified about eleven sets. The structural model, based on the types and geometry of these sets, can be defined, in a chronological sequence of events, as:

- regional strike-slip faults, ductile, with sinistral movement in big shear zones, a WNW-ESSE strike and subvertical dip that generate foliation depending on the lithology and controlled the sulphide mineralization;
- local strike-slip faults, brittle-ductile, probably with sinistral movement, that generated the shear zone in the north wall of the Sequeirinho pit and controls the breccia in the granite, with a strike ENE-WSW and a dip of 55° to 65° to the SE;
- faults parallel to foliation and crossing the shear zone were probably formed at the end of the brittle-ductile shear movement;
- formation of the joint sets in brittle events, without movement of the blocks;
- faults related to the young tectonism (friction striae planes) described in the Golder Associates report (2004a).

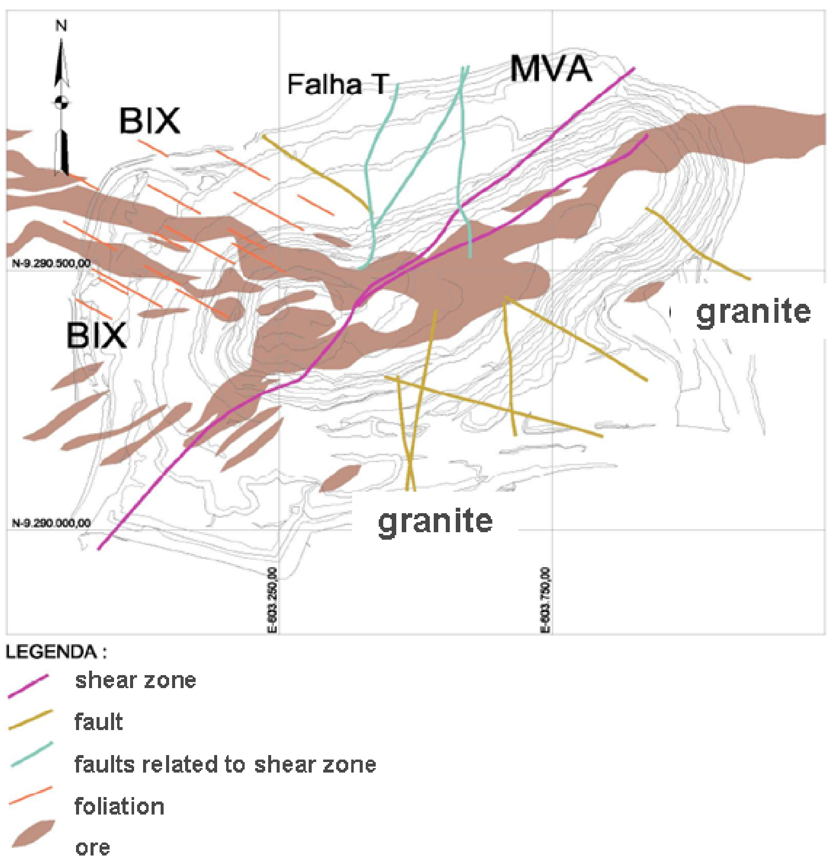

Figure 7 *- Structural Map of Sequeirinho Pit.*

Sossego Pit

In the Sossego Pit Phase 1 cut, the prevalent lithology is the granite, and the geological structures identified in the field mapping were joint sets and faults. There is evidence of brittle movement at this rock mass. The orebody, which is in the form of a pipe, is controlled by the jointing of the rock mass. These faults are not as large as those identified in the Sequeirinho pit; they also are typically narrow (centimeters to meters), but very persistent (in the order of at least several tens of meters).

Foliation related to the regional ductile shear zones is the geological structure that controls the mineralization at Sossego Mine orebody.

Sossego pit Phase 2, on the other hand, the mineralization occurs as a shear zone contact between granite and metavolcanic rocks with cross faults. This structural geology model is similar to Sequeirinho pit.

Geomechanical Model

The initial (feasibility study) geomechanical classification of the rock mass was made based on the borehole log. Using this information some cross sections were made for both the Sequeirinho and Sossego pits. Figure 8 (Golder, 2004c) shows the typical geomechanical section and details of the main divisions.

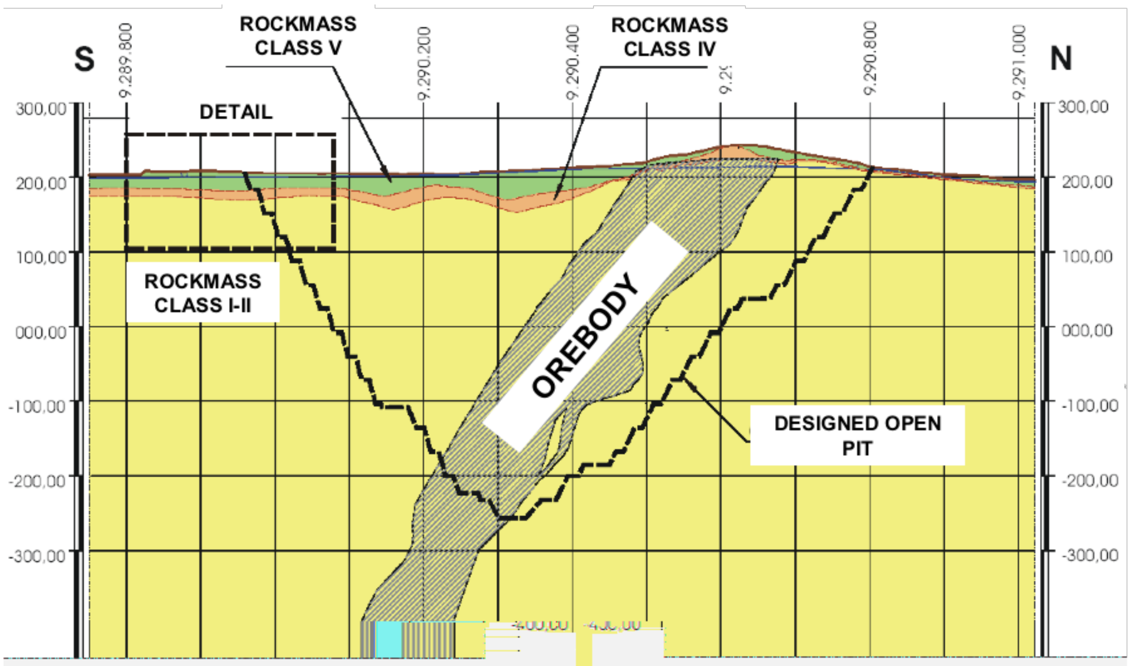

Figure 8a *- Sequeirinho Pit Geomechanical Cross-Section.*

Figure 8b *- Detail of the Geomechanical Layers.*

The classification was based on the ISRM ("International Society for Rock Mechanics") methodology and the rock mass classification based on Bieniawski (1989) and Barton et al (1974) classification systems.

Three main geomechanical layers can be described at Sossego Mine (Figure 8):

- Overburden, geomechanical Class V (very poor), is formed by soil / saprolite with a thickness of 1m to 50m. The thicker soil is located in the SW portion of the Sequeirinho pit;

- Weathered/Jointed rock, Class IV (fair to poor) between 1m and 30m thick;
- Fresh rock Class I-II (very good to good) extending to the bottom of both pits. This is a sound and weakly jointed rock mass with intact strengths higher than 100MPa.

The granites, gabbros and actinolites of rock mass Class I-II have a geomechanical behavior somewhat better than the biotite schist and metavolcanic rocks.

In these rock masses three types of slope failure can occur in the walls of the pits: circular in the saprolite, and planar and wedge failures in weathered and fresh rock classes.

Geotechnical Parameters

The strength characteristics of the rock mass were defined from laboratory testing and core logging (Golder, 2004a), with some modification based upon the experience of the geotechnical team. The input parameters are shown in Table 1:

	c MPa	f	g tf/m^3
Granites (GRA)	1,93	64,5º	2,7
Biotite-Schists (BIX)	1,48	56,2º	2,9
Metavolcanic rocks (MVA)	1,09	52º	2,9
Discontinuities	0	35º (basic friction angle and roughness increment)	

Table 1 *– Input parameters to granites and biotite schists.*

Rockmass strengths were determined using the Hoek-Brown criterion as shown in Table 2.

	Q'	GSI	D	s	a	mi	mb	σci(MPa)	σcm(MPa)
GR	13,4	67,4	1	0,004	0,51	32	3,11	150	9,36
BIX	15,5	68,7	1	0,005	0,51	12	1,28	117	8,2
MVA	10	64,7	1	0,003	0,51	12	0,97	76	3,74

Table 2 *– Input parameters to granites and biotite schists.*

The strength parameters for the shear zone were based upon the Barton-Bandis criterion as shown in Table 3.

	JRC	JCS (MPa)	f(°)
ZC	8.7	52.4	30

Table 3 *– Input parameters to the shear zone (Barton-Bandis criterion)*

Groundwater Model (Golder, 2004b)

The fresh rock (Class I-II) has a low hydraulic conductivity and limited groundwater flow. The overburden and weathered rock (Class IV) are the most permeable strata in both pits at Sossego Mine.

For the groundwater model four units have been adopted, namely:

- Overburden (residual soil and saprolite) with 20m thickness and a permeability around $K=1x10^{-3}$cm/s;
- Weathered rock, very jointed with a thickness up to 30 m and a permeability of $K=5x10^{-4}$cm/s;
- The upper 150 m of fresh rock, jointed a permeability $K=5x10^{-5}$cm/s; and
- Deeper fresh rock, massive or less jointed, with a permeability of $K=1x10^{-7}$cm/s

Groundwater flow is mainly related to the upper 50 m thickness of the sequence (overburden and weathered and jointed rock mass) where there is higher hydraulic conductivity and recharge.

There are some packer and pumping tests that confirm this hydrogeological model for the rock mass at Sossego Mine. Even the shear zones and the faults indicated in Figure 7 showed low permeability. The geological mapping in both pits also confirms this groundwater behavior.

There is no evidence that the faults and shear zones in the rock mass have a different hydraulic conductivity from the surrounding rocks.

Some sheet joints were identified in Sequeirinho Pit with water flowing (Figure 9). These joints can decrease the water pressure in the walls and groundwater is not the main feature of the rock mass to take into account to the slope stability.

Piezometric levels around the pits show that the fluctuation of the water level is related to the hydrologic cycle, there is no correlation among the instruments and the hydraulic gradient is low. It is necessary to construct more piezometers to determine the real hydraulic gradient in the sound and massive rock mass to confirm these data.

Figure 9 *– Sheet Joint with Groundwater Flowing in 120 Level Sequeirinho Pit. schists.*

There are major concerns regarding the natural reduction of the water table in the walls as the pits are excavated. The low permeability of the rocks below the weathered and jointed zones could leave the groundwater table close to the walls, resulting in high pressures. Figure 10 shows the water table modeled by Golder (2004c) for the final of Sequeirinho Pit. Because of the potential impact on slope stability, it is proposed to install additional piezometers and some exploratory drains.

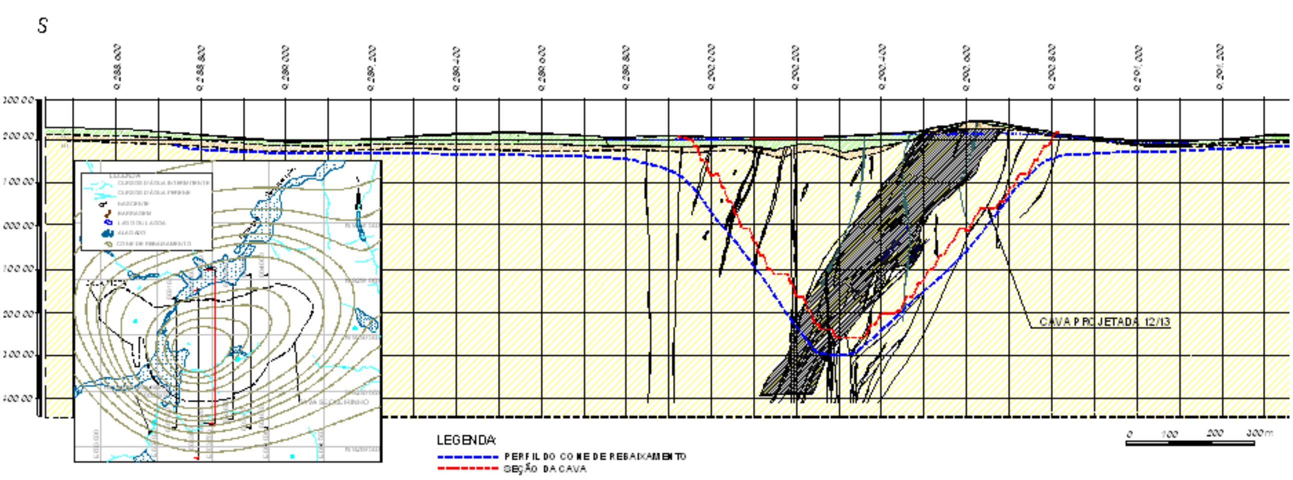

Figure 10 *- Water Table at Sequeirinho Pit after 13 years of Mining Operation.*

Design Review

After two years of operation a review of the geomechanical model was developed for Sossego Mine. The resulting updated model comprised a detail description of joint sets and structures, mechanical properties of intact rock and joints and the geohydrological conditions. The virgin stress state was assumed to be low because of the shear zone and jointed rock mass. From this, representative design cross sections and parameter values were established and used as input to stability analyses of the pit slopes.

The revised model formed the basis for the current recommended inter-ramp angles, which are based on 16m high operating benches, with double-benching of slopes where possible. A catch bench is left for every double bench.

The slope design report is entitled "Revisão dos Modelos Geológico-Estrutural e Geomecânico e do Projeto dos Taludes da Mina do Sossego", dated September 5th, 2007 by BVP (Brito, Vector, Piteau). The BVP study was based upon field mapping, geotechnical drilling and laboratory testing. The hydrogeological model was based upon an earlier study by Golder Associates.

The following basic points pertain to the slope designs in the pits:

- The rocks exposed in both pits are strong to very strong.
- Because of the rock strengths the slope designs will, in large part, be a function of:
  - Structural control of the bench faces
  - Implementation methods (controlled blasting, excavation, etc.)
- Slope depressurization may occur naturally as the pit is deepened. However, if required, pumping wells and/or horizontal drain holes should be able to control water pressures in the slopes.

The slope designs proposed by BVP are summarized in the following table 4 from the report (BVP Engenharia, 2007).

	structural dip	Face angle	Back break (m)	berm	operational berm	adopted berm	inter-ramp angle
MVA ZC	60	65	2,2	3,5	8	8	46
BIX	47	47	0	0	8	8	34,9
BIX	69	90	4,1	9,3	15	13,4	60,6
GRA	72	90	3,5	8,6	15	12,1	60,6
Sossego pit	81	90	1,7	6	15	7,7	60,6

Table 4 *– Inter-Ramp Angles at the Sossego Mine*

Stability analyses are routinely performed in order to assess the safe and functional design of the excavated slopes at Sossego Mine. The analysis technique chosen depends on both site conditions and the potential mode of failure.

Stereographic and kinematic analyses were performed to evaluate critical orientations and the failure modes (planar, wedge, toppling, etc) to the slopes. Computational analyses for the failure modes and rockfall simulations were also performed to determine the design of slopes geometry and safety factors.

The results of stability analyses show that it has been possible to simulate the main failure mechanisms at Sossego Mine, in particular circular shear as a global (rock mass) failure of the slopes, and large scaling toppling failure related to a shear zone in the north wall of Sequeirinho Pit. In all cases the indicated Factor of Safety values are well above acceptance criteria for overall and inter-ramp stability suggesting that the bench design is the main control.

The topographic survey of the slopes after blasting showed the final effective bench face angle is flatter than the design. This occurred because of the undercut of some portions and backbreak of others that formed a final wall different from the design. This is a problem because the mass to excavate is bigger than that designed and the safety of the wall and access to the berm is dangerous because of lost width.

Slope Performance

An independent review of slope conditions after the first 5 years of mining (Stacey, 2007) resulted in the following comments and recommendations:

- The geotechnical model developed during the feasibility stage and updated as part of the BVP design review was generally confirmed and provided a sound basis for the proposed slope design revisions.
- While there were no overall stability issues in the pits, both of which were at an early stage of development, blast damage was a major issue on all walls, creating severe rockfall hazards and precluding achievement of the proposed designs, see Figure 11.

Figure 11 *- Blast Damage in Sossego Pit*

- The proposed slope inter-ramp angles for the MVAC and BIX Plano rock types in the north wall of the Sequeirinho pit were based upon single benched configurations, as shown in Figure 12. While this was appropriate for the current operating procedures, with improved controlled blasting it may be possible to adopt a double-benched configuration, particularly for the MVAC, where the fabric is relatively steep. This would permit somewhat steeper inter-ramp slopes, even with a wider bench allowance.

Figure 12 *- Blast Damage in MVAC in North Wall of Sequeirinho Pit*

- In the materials with steep fabric (BIX Foliação and granite in Sequeirinho and granite in Sossego) the blast damage was precluding the achievement of the proposed slope designs, which were based upon double benching, see Figure 13. In particular, the vertical bench face angles that formed part of the design were not being achieved due to excessive backbreak caused by the blasting. In consequence a flatter inter-ramp angle was proposed until slope performance could be improved.

Figure 13 *- Granite Slope on the South Wall of the Sequeirinho Pit*

In summary, in both pits the geotechnical models, confirmed by field observations, indicated potential slope designs that were not being achieved due to blast damage.

At the time of the 2007 review controlled blasting in the form of presplit blasting was being applied, locally with some success, although in general ineffectively.

IMPROVEMENTS

In an attempt to improve slope performance, the blast designs and performance were reviewed by an external consultant and a program of blast optimization was established. At the same time, Sossego Mine geotechnical staff started working with operation staff to determine a distance from the walls to use control blasts.

Blast Technology

A review of the blast designs for the Sossego Mine operations was commenced during April 2008 (Crosby 2008 and 2009) and indicating several potential problems. These were addressed systematically in an overall program of blast optimization. This being summarized from the various visit reports in this section.

A first major problem found at Sossego Mine was the incidence of numerous misfires both in the production blasts and in presplit holes. Many misfires were located, but many more would have been dug out without the knowledge of the excavator equipment operators. Proper handling of these misfires needed immediate attention to ensure mine safety. A new protocol to handle the misfire problem was introduced which helped to reduce the number of misfires experienced, as did changes to other operating practices.

At the same time, reduction of the misfire frequency was also addressed through a program which included assessment of the presplit hole charging technique with a view to introducing design modifications.

The accuracy of the detonating relays was also identified as a possible contribution to the misfire frequency. One potential solution considered was the exclusive use of electronic delays. However, after a few electronic blasts, one large shot produced a complete row of misfires.

This prompted even more intense scrutiny of the delay accuracy: after multiple tests, it was found that a relatively large number of the detonating relays were delaying the detonation by as little as 1ms, whereas the nominal delay time might have been 30ms, 50ms or even 150ms. Naturally such differences between the nominal and actual delay times could have caused many rows of holes to fire out of sequence producing poor fragmentation, while increasing the potential to generate misfires being the result. A detonating relay manufacturing defect was discovered and corrected.

Even the electronic delays were found to have a considerable scatter if short delay periods were selected (up to 11.5%) and it was therefore decided not to employ the electronic system with a delay of less than 100ms.

During the review it was also identified that the mining GPS system was not providing accurate hole positioning, particularly near pit walls, which is vital for wall control blast preparation. A number of tests were conducted on drilling accuracy, and it was found that both hole position and hole depth determination were frequently in error. The hole position inaccuracy was clearly a problem, but so was the erratic blast hole depth determinations. Inaccurate depths (amongst other things) introduced overbreak at the bench toe throughout the pits. As regards wall control, this meant that berm crests automatically sloughed off with the excavation of the wall control blast. After attempts to correct the problem, eventually the use of the GPS control on the drills was discontinued, and now all blasts are again staked by surveyors.

As regards the wall control blasts themselves, at the start of the study period, all presplits and main wall control blasts were fired together. Indeed, while the rear row of holes was designed as, and called, a presplit line, commonly it was being fired after the rest of the blast. It was therefore being shot as a postsplit rather than a presplit, i.e. it was being shot after most of the final wall damage from the main wall control blast had taken place. Accordingly, to ensure that the presplit line had been correctly sequenced and was fully formed before the main wall control blast was shot, the presplit holes are now drilled, charged and shot ahead of time, even before the main blast was drilled. The introduction of this change quickly brought to light the drill GPS control problem, as it was found that some buffer row holes ended up very close to the presplit. Such occurrences did not happen before as all of the holes were being drilled together, thus making any drilling errors clearly visible in the field and in turn readily corrected.

All of the early wall control work was conducted without the use of a presplit drill; only production drills of 251mm (9 7/8 in) or 311mm (12 1/4 in) were employed. It was originally planned to have a suitable 165mm (6 1/2 in) drill on site during August 2008, but in fact, the machine was only available in February 2009, at which time the first proper angled presplit blast was conducted. This naturally required the introduction of presplit cartridge explosive, which greatly improved the control and accuracy of charging as compared with the presplit tubes and bulk explosive in the large holes.

Modifications to both the products and the blast hole drilling are now starting to bear fruit with reasonable results from the controlled blasting being achieved, although there are still some ongoing deficiencies that are continually being improved including presplit drilling accuracy, record keeping accuracy, survey control, the need to survey the exact position of all holes as drilled, etc.

Future plans call for an accelerated program involving the introduction of 20° (from the vertical) angled presplits, if not 25° angles in special cases, and drilling the full double bench height walls rather than single benches. All of this angled work is initially planned for the very difficult structural conditions of the north wall in Sequeirinho Pit.

Elsewhere, where rock conditions are easier, wall control blasts continue to be conducted using production drills producing both 251mm and 311mm diameter holes. Full height double bench presplit holes are being introduced where appropriate using 251mm vertical holes. Presplit hole charging no longer uses tubes and emulsion, but rather a cartridge explosive product or toe loads for better loading control. There is also a plan to use a T4 drill with 203mm (8in) hole diameter as a first step, followed by a further reduction to 165mm diameter holes.

Blast Designs

Presplit and post-split blasting are now used on a regular basis in the Sossego Mine excavation process as part of trim blasts along final and phase walls. The most appropriate blast designs are determined jointly by geotechnical staff working with operations and short term planning to establish each blast design according to the field conditions and the production plan. The short term planning staff of the mine is ultimately responsible for the control of the blasthole depth and position. An example of a typical design layout is illustrated in Figure 14.

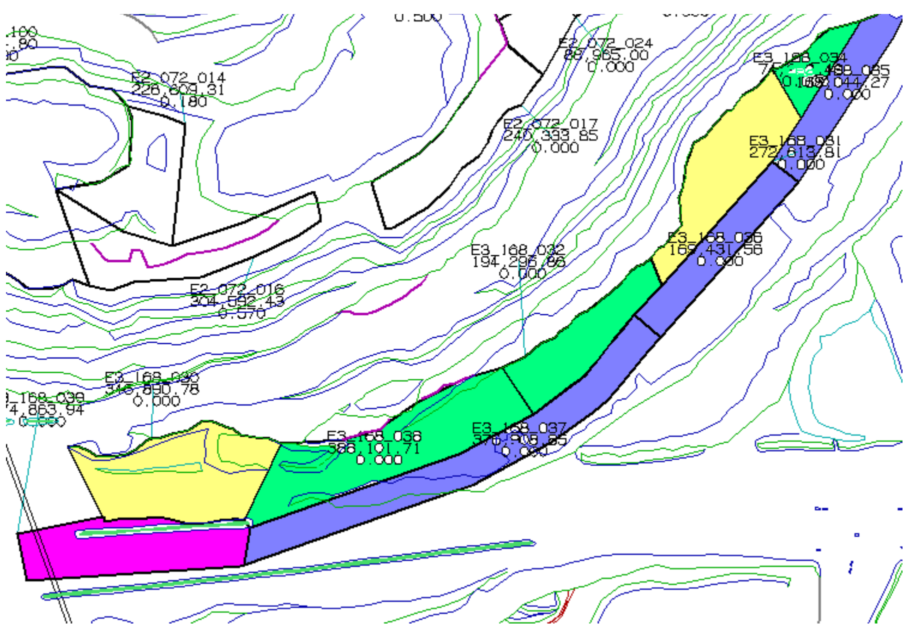

Figure 14 *-Typical Planning of Blasts at Sossego Mine. The Blue Space indicates the region where trim blasting was used (typically 25m from the toe). The other areas are production blasts.*

After each blast the results are reviewed and excavation and scaling are planned. The scaling is performed with an excavator, which sometimes uses the muck pile as a base for cleaning the upper regions of the wall. This approach has led to further improvements in wall conditions.

SLOPE DESIGN IMPLEMENTATION AND EVALUATION

Implementation Procedures

As a result of the various studies, a procedure has been developed at the Sossego operations for ensuring optimized slope configurations. This procedure involves a team drawn from geotechnical, long term planning, short term planning and mine operation and involves the following approach:

- Establishing the area for controlled blasting;
- Joint planning of the blast design by mine operations and geotechnical staff;
- Close monitoring of the drilling, with modifications in the blast pattern as required;
- Evaluation of the blast both after detonation and after excavation;
- Joint review of the results in comparison with the geomechanical zones of the pit as a basis for further improvements.

Evaluation System

As part of the evaluation procedure, subsequent to the excavation and scaling of the slope, the Sossego Mine geotechnical staff evaluates the bench using a modified version of a system developed at Chuquicamata for assessing face conditions. This system, which takes the form of a matrix, assesses both the achieved configuration (Df) after clean-up and the condition of the bench face (Fc). As such, it incorporates blasting, excavation and scaling results.

The components for each of these two sets of parameters are as follows, together with the respective ranges of values that are applied in the matrix:

Component (Weighting)	Assigned Values	Rating	Comments
Bench Face Angle (50%)	≥ Design Design –3° Design –5° Design –10°	50 25 10 0	Achieved overall bench face angle relative to design
Bench Width (40%)	≥ Design Design –1 m Design –2 m Design –3 m Design –5 m	40 35 25 15 0	Achieved average bench width relative to design
Toe Position (10%)	On design Design –1 m Design – 2 m Design –3 m	10 8 5 0	Whether design toe is being achieved

Design Achievement (Df)

Component (Weighting)	Assigned Values	Rating	Comments
Half Barrels Visible (20%)	≥80% 70-80% 60-70% 50-60% 30-50% 10-30% < 10%	20 15 12 8 5 2 0	If half barrels only visible in lower part of bench reduce by 5 to 10 points
Intact rock breakage (15%)	< 1/m³ > 5/ m³	15 0	Subjective evaluation, interpolate between 0 and 15
Open Joints (10%)	All closed Many moved	10 0	Subjective evaluation, interpolate between 0 and 10
Loose Material on face (20%)	No blocks Few small blocks Large blocks Many blocks	20 15 10 0	Assess in terms of rockfall hazard
Face Profile (20%)	Straight Hard toe Overhang crest Irregular face	20 10 5 0	Shape of face and basis for variations
Crest Condition (15%)	Achieved < 1 m loss 1 m – 2 m loss 2 m- 3 m loss > 3 m loss	15 12 10 5 0	For loose rock on crest deduct 0 to 5 points more

Face Condition (Fc)

The total of assigned values for each component in the two factors should be reduced to a factor between 0 and 1 and plotted in the matrix shown in Figure 15.

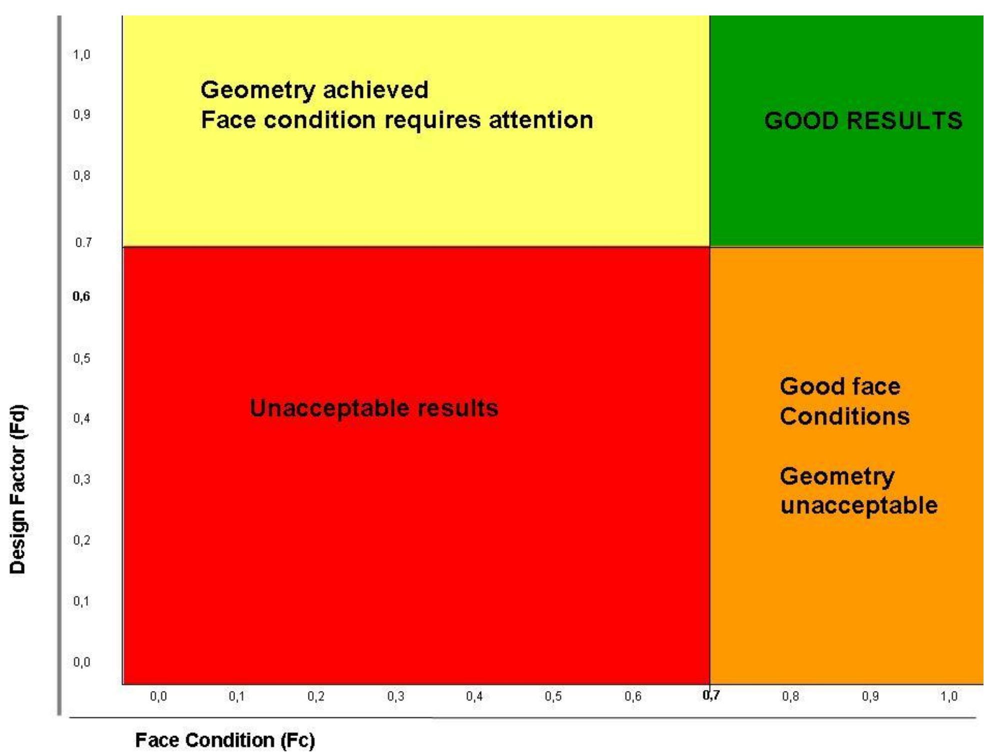

Figure 15 *- Acceptability Criteria Chart for Bench Conditions.*

The results are discussed in a weekly meeting, and changes are made as required with the aim of consistently achieving bench conditions in the green area (Df > 70% and Fc > 70%).

Results

Once the issues with the explosive products had been resolved, significant improvements in the condition of the bench faces were noted. Other improvements were noted as follows:

- The use of a small diameter blast hole rig, which has the capability of drilling inclined holes close to the design bench face angle, provides better results than the larger diameter vertical blast hole rigs, in part due to the reduction of backbreak at the bench crest. This is illustrated by comparative evaluations in Figure 20.
- The use of cartridge explosive has a better control than emulsion in a PVC tube.

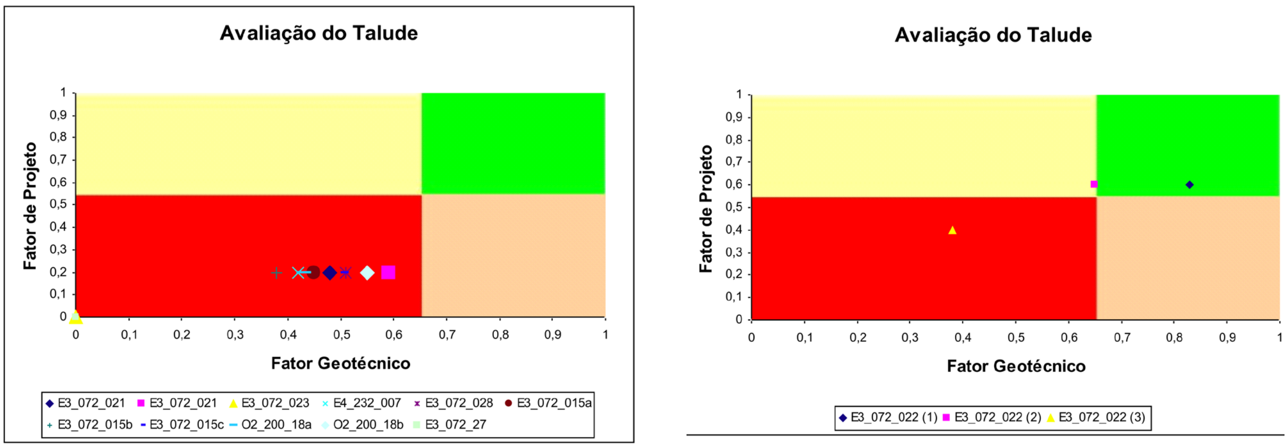

Figure 16 *- Evaluation Chart from the Slopes at Sossego Mine. a) 251mm and 311mm vertical presplit holes compared with b) inclined 165mm pre-shear holes*

Other examples of the results of controlled blast trials are shown in Figures 17 to 20.

Figure 17 *- Smooth Blasting of a Granite Face in Sequeirinho Pit. Note the Joints intercepting the Half Barrels and forming Rock Blocks.*

Figure 18 *- Sequeirinho Pit North Wall (shear zone). Note the surface of the shear zone and the consequent effect on the blast results.*

Figure 19 *- Sequeirinho NW Wall in Schist. Note the loose blocks at the crest; half barrels are present along most of the wall.*

Figure 20 *- Sossego Pit Phase 2. Note the jointing pattern and weathering variation of the rock mass. Vertical 311mm blast holes were used for the controlled blast.*

CONCLUSIONS

Sossego Mine slope designs at the feasibility level were based on the best evaluation of rock types and their characteristics, structural geology and groundwater conditions. With the excavation of the pits and exposure of the rockmass a review was made of the geomechanical model to ensure the most stable geometry for the slopes. Local variations in geology and hydrogeological conditions and structural geology became known and better understood. These data were incorporated into revised designs, and a routine program of monitoring and slope evaluation was initiated. This is important to determine the hazard areas of the pits and to avoid slope instability.

The overall slope stability at the mine has been good, which is to be expected due to the strong nature of the rock and the decoupling of the slopes to date. However, local bench-scale failures have occurred, particularly on the north wall, and rockfall hazards have been a significant issue, even though a controlled blasting program was in place. The main issue with the slopes is to determine the major structural conditions and the mechanisms and size of potential failures in order to avoid ruptures and instabilities. Rock fall are another important issue mainly to the push back of the pit with a new phase of the mine.

An evaluation of the slopes in 2007 resulted in a recommendation that the controlled blasting program be reviewed by a specialist. This review indicated several factors contributing to the poor controlled blasting results, notably inaccurate delays and poor control of the drilling in terms of pattern layout, as well as hole orientation and depths. Once these issues were resolved an improvement in bench conditions became apparent.

Subsequent improvements to the controlled blast results are expected with the introduction of a smaller diameter drill capable of drilling inclined presplit holes combined with the use of cartridge explosives instead of emulsion in pvc tubes. Further work is also required on bench scaling to reduce the rockfall hazards. Continual monitoring of the blast design, the drilling pattern, the explosive's quality and blast timing have all identified as some of the essential elements necessary to ensure good wall control blast results.

Another important issue for mine slope management is to have a slope evaluation system that can show the blasting, excavation and scaling results in the slopes and to indicate the procedures that can be changed to improve the results. This latter indication has also improved safety conditions in the pits and allowed the development of appropriate production plans for the mine. This wall evaluation procedure also helps to identify the blasting factors that can be modified in order to produce continual improvement in the wall results not just to assess slope conditions at the mine (i.e. good or bad slopes).

The controlled blasting program at the operation is the responsibility of a team drawn from geotechnical, mine planning and operations. Evaluation of the results involves a matrix system, which is helping Sossego Mine staff to achieve better slopes.

REFERENCES

1. Barton, N, Lien, R. and Lunde, J. 1974. Engineering Classifications of Rock Masses for the Design of Tunnel Support. Rock Mech. Vol. 6.6, pp.189-236.

2. Bieniawski, Z.T. 1989. Engineering Rock Mass Classifications. John Wiley & Sons p. 251

3. Golder Associates Brasil - 2004a- Projeto Sossego - Relatório RT-PR-CT047-MI-1000-91-0180-01-J - Caracterização Geológico-Geotécnica;

4. Golder Associates Brasil - 2004b - Projeto Sossego - Relatório RT-PR-CT047-MI-1000-93-0001-00-J - Caracterização Hidrogeológica;

5. Golder Associates Brasil - 2004c - Projeto Sossego - Relatório RT-PR-CT047-MI-1101-91-0039-01-J - Relatório Final - Talude das Cavas

6. BVP Engenharia - 2007 - Mina do Sossego - Relatório 072-E-CA-RT-11-019 - Revisão dos Modelos Geológico-Estrutural e Geomecânico e do Projeto dos Taludes da Mina do Sossego.

7. Crosby, W. A. - A summary of some of the findings obtained under Sossego Mine Technical Services Agreement #814223

8. Stacey, P. - Sossego LR 01-07- Mining Geotechnical Review - October 2007.

9. Stacey, P. - DIOC LR 01-09 - Mining Geotechnical Review of Sossego and Salobo Projects - March 2009.

10. Sjoberg, P. - 1999 - Anlysis of Large Scale Rock Slopes. Doctoral Thesis. Division of Rock Mechanics. Lulea University of Technology. Sweden.

11. LOP Project, Design Guidelines Text.

12. Grainger, C. J.; Groves, D. I.; Tallarico, F.H.B.; Fletcher, I.R. - Metallogenesis of the Carajás Mineral Province, Southern Amazon Craton, Brazil: Varying styles of Archean through Paleoproterozoic to Neoproterozoic base- and precious-metal mineralisation. Ore Geology Reviews (2007), Elsevier.com