Geomechanics considerations in the Grasberg pit to block cave transition

E.C. Wellman *Call & Nicholas, Inc., Tucson, Arizona, USA*

D.E. Nicholas *Call & Nicholas, Inc., Tucson, Arizona, USA*

C.A. Brannon *Freeport McMoran Copper and Gold, Phoenix, Arizona, USA*

Abstract

The Grasberg Pit currently produces approximately 200,000 tpd of ore. In about 2017, PTFI will fully transition the Grasberg deposit to block caving operations with planned production of approximately 160,000 tpd. In the geomechanics analysis there are several factors that are considered. First and foremost, the geology, major structure, and in-situ stresses have significant influence on the engineering assumptions and analyses related to the prediction of deformations and instability in the pit and underground openings. With rate of mining—planned and in progress—the schedule and sequence have impacts on the stress conditions predicted within the deposit. The geomechanics analysis of the transition from pit to block cave needs to be able to evaluate these conditions with respect to varying mining schedules, therefore a geotechnical model is developed that is used and updated for that purpose.

A number of tools and methods are used in the construction of a geotechnical model and the geomechanical analyses of the pit, underground workings, and the interaction between the two. The geotechnical model incorporates the geology and geomechanics data provided by PTFI, rock-strength testing, rock-mass strength estimates, and in-situ stress measurements. The geotechnical model is the basis for numerical analyses of stability of the pit and underground with respect to the mining sequence of the deposit. Sensitivity analyses are run to mining schedules (both pit and underground) to predict instability. The results of these analyses are then utilized to re-evaluate mining sequences with regard to the potential for slope instability within the pit, stability of underground openings, dilution of ore, and timing and location of crack limits. In this process, the geotechnical model is updated with geomechanics recommendations that are utilized by mine planners in optimizing the mine plan and in transitioning from open-pit to underground production.

1 Introduction

The mines of the Ertsberg District, in the province of West Papua in Indonesia, are operated by P.T. Freeport Indonesia (PTFI) under contract to the Republic of Indonesia. The Grasberg Mine is located in the Ertsberg Mineral District within the Sudirman mountain range of West Papua, Indonesia, at approximately 4 degrees south latitude and 137 degrees east longitude, as illustrated on Figure 1. The terrain is very rough and the relief is extreme with elevations ranging from 2900 to 4500 meters.

Two mines are currently producing from the Ertsberg District currently, the Grasberg Pit, and DOZ-ESZ block cave mine. The Big Gossan open stope mine is currently under development construction. Planned mines include the MLZ and DMLZ block cave in the East Ertsberg Stockwork Zone (EESS), and the Kucing Liar Block Cave (KLBC), located southwest of GBC. The locations of these active and planned mines with respect to the Grasberg Pit and block cave are illustrated on Figure 2.

As a part of the continuing engineering work there are many geotechnical issues to be considered in the mining transition. We will address the inputs and assumptions in the geomechanical analysis. The details of the mine design are discussed in detail in Brannon, et al. (2008). The final geometry of the Grasberg Pit, which is expected to have slope heights exceeding 1 km and 40-42-degree overall slope angles, has significant bearing on the initial state of stress for development of the block cave. As a part of the feasibility study, PTFI requested that sensitivity analysis be run to determine what impact different final pit geometries would have on mining the block cave. This sensitivity was run, in part, to determine the potential geotechnical advantages of various mining scenarios, and it was determined that the varying pit geometries were not critical to the success of the block cave.

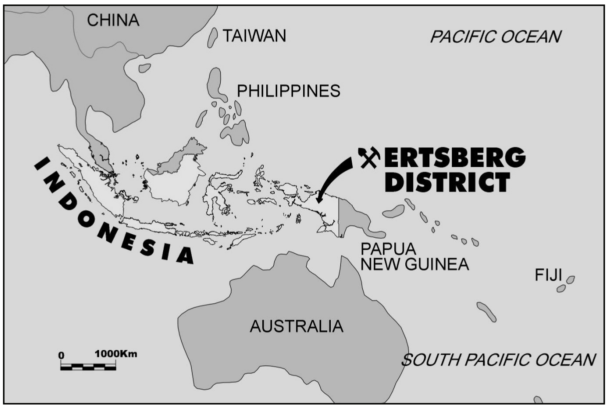

Figure 1 Location of PTFI's Mining Operations

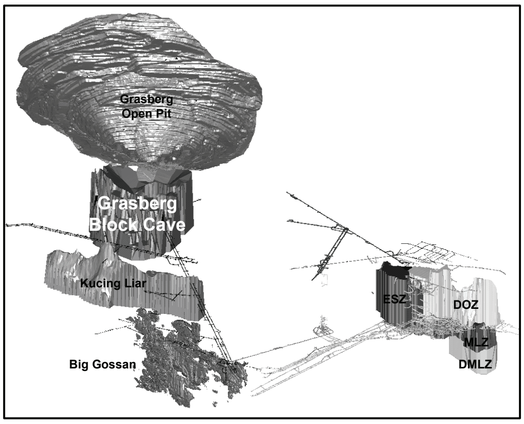

Figure 2 Grasberg Pit and Block Cave Locations with Respect to Other Ertsberg District Mines.

Once the pit is completed and caving commences, it is expected that there will be slope instabilities within the pit that will displace ore within the mineable reserve of the cave. A methodology and process for the geomechanical analysis was developed to incorporate various pit configurations and differing caving schedules that will have effect on the timing and location of these instabilities. This methodology was extended to incorporate the estimates of pit instability into the PCBC model (Diering, 2000), which included a sensitivity analysis to the dilution/displacement of ore for mine planning and scheduling.

CNI is working with PTFI to continue geomechanical analysis, incorporating additional geologic and geotechnical data. The goals of this work are to improve the schedule and to develop a mining sequence that reduces geotechnical risks in mining the GBC. The following is a discussion of the various inputs into the geotechnical model, a summary of the geomechanical analyses and results, and how the results of these analyses are re-input into the geotechnical model for use by the mine planning and engineering groups in making the transition from open pit to block cave.

2 Inputs to the Geomechanical Analysis – The Data

This section is subdivided to discuss key observations and inputs to the geotechnical analysis, including: geology, major structure, rock fabric, rock-strength-testing summary, rock-mass strength estimates, and in-situ stress measurements. The geotechnical model is discussed, as is the primary means of transmitting data for input into the analysis, and later in Section 3, how the model is used to transmit conclusions for use in mine planning and scheduling.

2.1 Geology of the Grasberg Block Cave

The Grasberg Ore Body is located within the Papuan Fold Belt. The fold belt consists of Paleozoic and Triassic granite and metamorphic basement rocks that are overlain by Mesozoic and Cenozoic sedimentary rocks. In the Ertsberg District, Plio-Pleistocene quartz monzonite intruded these strata and resulted in Cu-Au skarn and porphyry type mineralization.

2.1.1 Lithologies

The Grasberg Igneous Complex (GIC) intrusives make up the bulk of the ore-grade material in the deposit. These GIC units consist of the fine-grained Dalam Trachyandesite, coarser-grained Dalam Fragmental, and dioritic intrusion of the Main Grasberg Intrusive (MGI) rock type.

The GIC is fringed by the Heavy Sulfide Zone (HSZ), which consists of greater than 50 percent pyrite. Outside of the HSZ, the deposit is hosted in folded sedimentary rocks of the New Guinea Limestone Group. For the sake of brevity, the term *sediments* is used to describe the Kais (Tk), Faumai (Tf), Waripi (Tw), and Sirga (Ts) formations.

2.1.2 Major Structure

The dominate structure in the Ertsberg District is the Yellow Valley Syncline, which is a broad, open, upright synclinorium with a vertical axial surface and no apparent plunge. The syncline axis trends approximately N60°W. The Yellow Valley Syncline separates the two geologic structure domains in the limestone. All the limestone to the northeast of the fold axis is the North Geologic Domain and all limestone southwest of the fold axis is the South Geologic Domain.

There are several sets of regional faults found within the vicinity of the Grasberg Deposit. The Grasberg Fault trends approximately N60°E and intersects and offsets the axis of the Yellow Valley Syncline. The most common regional faults strike northeast and are sub-parallel to the Grasberg Fault. The rock types and selected major structures, as projected to the Final Pit, are illustrated on Figure 3.

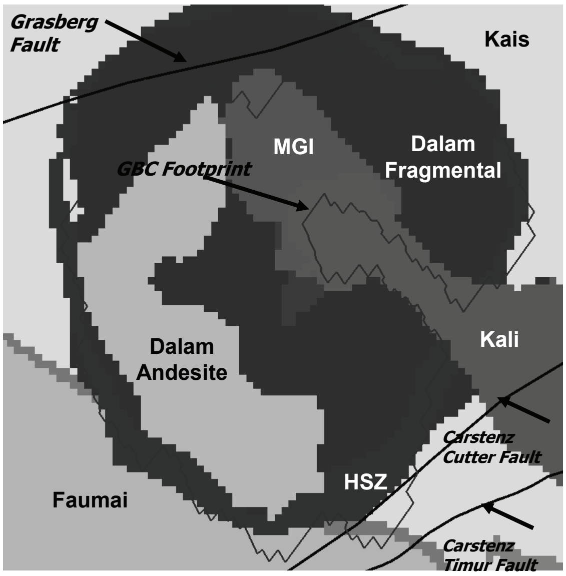

Figure 3 Geology and Major Structures

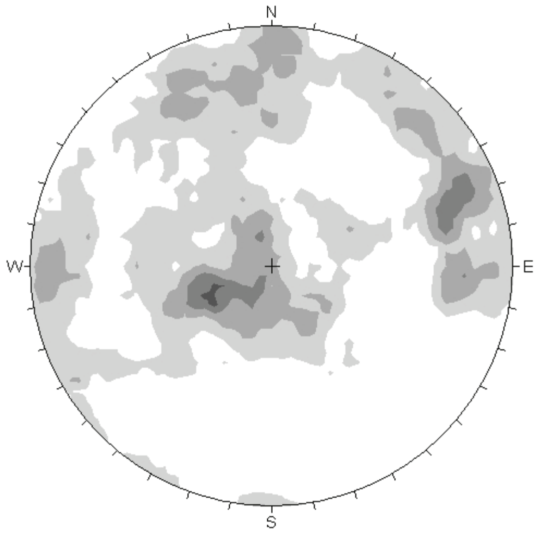

Figure 4 Rock Fabric in the Dalam Andesite

2.1.3 Rock Fabric

Jointing and rock-fabric data was collected from cell-mapping and oriented drill-core data. Cell-mapping was done in the Amole Drift which cuts through the GBC at the 3000 level (approximately 180 meters above the 2815 extraction level). Cell Mapping, and obtaining rock fabric data is an areal-mapping technique, discussed in Nicholas & Sims (2000). Oriented-core holes were also drilled from this level to ascertain rock fabric in the vicinity of the proposed facilities. The rock-fabric data, joint orientation, length, and spacing, were used to determine the preferred orientation of the extraction level panel drifts at 035 degrees. The rock-fabric data is a key input to the fragmentation analysis and is used in the ground support design. Figure 4 illustrates a contour plot of the rock fabric used in the Dalam Andesite from the 2006 oriented data. Joint lengths were determined from the 2002 cell-mapping of the Amole Drift.

2.2 Geotechnical Rock Types

The Block Cave Geotechnical Rock Types (BCGRT) are determined based on the geology of the unit, alteration, and by the Rock Quality Designation (RQD) estimate for the block. Block Cave Geotechnical Rock Types (BCGRT) are assigned as a function of the geologic unit and modelled RQD value, as illustrated on Table 1. BCGRT's ending in 2 are high RQD rock types in the range of 70 to 100, and BCGRT's ending in 0 are low RQD rock types with RQD typically less than zero. The use of BCGRT's with RQD as the primary parameter, allows for the delineation of poor ground – without the smoothing and averaging effects that have been observed using RMR classification only. There are 66 different geotechnical rock types utilized in the GBC geotechnical model.

Table 1 Determination of BCGRT

•Block Cave Geotechnical Rock Types

•Rock Types	•RQD ID	•RQD %
•Igneous	•ii •0	•0-40
	•ii •1	•40-60
	•ii •2	•60-90
	•ii •3	•>90
•Sedimentary	•s •0	•0-40
	•s •1	•40-70
	•s •2	•>70

•Where ii is the igneous rock formation and s is the sedimetary rock formation name.

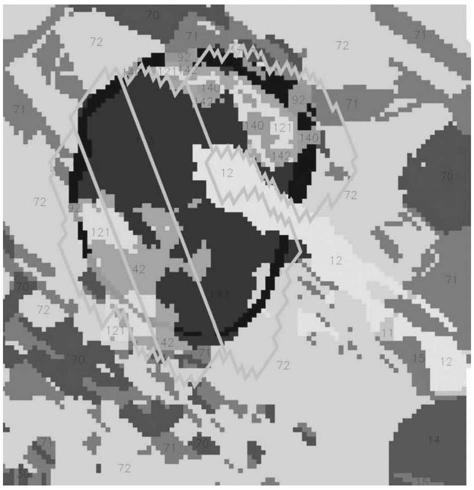

Figure 5 BCGRT's Projected on the 2815 Extraction Level

2.3 Rock Mass Properties

Rock-mass properties and strengths are based on the Block Cave Geotechnical Rock Type (BCGRT). Geotechnical rock types are broken down from the various igneous and sedimentary lithologies as a function of RQD.

2.3.1 Geomechanical Testing Program

As part of the GBC Geotechnical Feasibility Study, rock-strength testing was performed on a number of samples. In the Feasibility Study, various tests were completed to characterize rock strengths near the undercut and extraction levels. Intact material properties results are listed in Table 2 for selected igneous and sedimentary rock types.

In addition to these test results, all available rock-strength-testing data from the Grasberg Deposit was considered in the calculation of the intact and fracture-strength properties for the different lithologies. Results from the 1992 Grasberg Pit Slope Feasibility Design provided additional rock-testing data on key igneous units, and the results from the 1997-98 Limestone and Intrusive Slope Design were also used (Call and Nicholas, 1992-1998).

2.3.1 Rock Mass Strength Estimation

The calculation method for determination of the rock-mass properties, from the intact and fracture-shear testing data is described in detail in Call, et al. (2000). The rock-mass strengths are calculated based on the geomechanical test results. The rock-mass strengths for each BCGRT are computed as a function of the RQD.

Table 2 Selected Intact Strength Properties.

Rock Type	UCS (MPa)	Density (tonnes/m^3)	Young's Modulus (GPa)	Poisson's Ratio
Kali	**123**	**2.63**	**45.0**	**0.28**
Trachy Andesite	**88**	**2.68**	**41.2**	**0.24**
HSZ	**110**	**3.44**	**49.6**	**0.28**
Sirga	**49**	**2.59**	**31.6**	**0.25**
Kais	**89**	**2.73**	**51.8**	**0.30**

The rock-mass strength is calculated as both a linear and a power law relationship. The power law relationship is the preferred method because linear strength estimates overestimate the strength at high-normal stress. Computational limitations of the FLAC3D code and other stability analysis tools require the use of bi-linear strength. The bi-linear strength was estimated from the power-strength curve. The linear estimate is used for low-normals, a break point is determined, and a "best fit" is determined to fit the second half of the bi-linear curve out to approximately 100 MPa, so that the highest expected stress magnitude is within the range of estimation.

The sensitivity of the rock-mass strength to the RQD is illustrated by an example of the Dalam Trachy Andesite at four different RQD's, as illustrated on Figure 6. High RQD's have the highest strength, and low RQD's have strengths that approach the fracture strengths. The strengths are bounded on the upper end by the intact strength and on the lower end by the fracture strength illustrated by the dashed line.

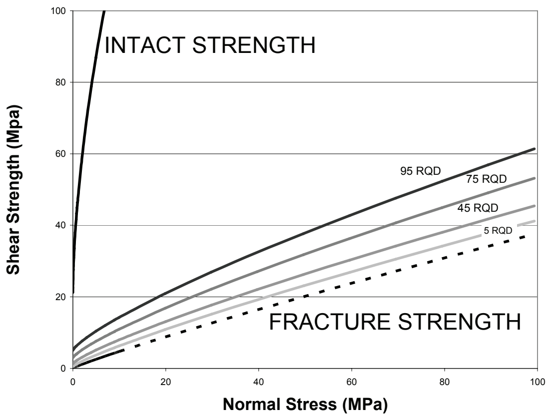

Figure 6 Trachyandesite Rock Mass Strengths.

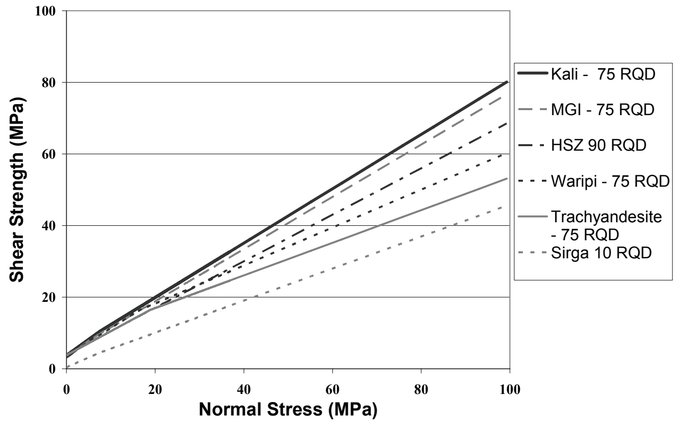

Figure 7 Comparison of Selected Rock Mass Strengths.

An example of select rock-mass strengths used in the analysis is illustrated on Figure 7. This shear strength verses normal stress plot illustrates the comparative strength between key igneous and sedimentary rock-mass material properties used in the feasibility study.

2.4 In Situ Stress Measurements

Two *in situ* measurements were taken in the Amole Drift using the CSIRO-HI Cell by ES&S of Australia, for the feasibility study done in 2006. The results of measurements in the intrusive can be summarized as follows:

- Sigma 1 and Sigma 2 are roughly equivalent (within the error of the measurements).
- Sigma 3 is oriented to the NW and is 0.6 to 0.7 times Sigma 1 (Maximum principal stress).
- Magnitudes of the principal stresses were on the order of 20 MPa, when the measurements were taken at depths ranging from 350 to 550 meters below the Grasberg Pit bottom.

The results of the stress measurements in the GIC indicate that the intrusive sites are closer to a hydrostatic loading condition where all principal stresses are equal. The regional stress field is based on approximately 13 *in situ* measurements made in the Ertsberg District. The maximum principal stress S1 in the sediments is oriented in the horizontal plane in the NE/SW direction. This stress configuration would seem to match regional tectonic stresses that cause severe folding in the sediments. The ratio of S1 to the vertical stress is approximately 1.5:1. Both the intrusive and sedimentary stress conditions are considered in the geomechanical analyses.

3 Geotechnical Model – The Repository for Data and Results

The geotechnical model is the repository for all geologic, rock-fabric, and geomechanical data used in the analyses for the GBC. Following analyses work and review, recommendations and tools for use in mine planning are loaded back into the model for use by mine planning engineers and schedulers.

PTFI provides the drill-hole data, geologic models, and RQD model. CNI inputs rock-fabric data from oriented core, cell mapping, rock-strength database, and rock-mass strength estimates. These are, in turn, used in the geomechanical analyses and to determine appropriate recommendations. Key input elements of the GBC Geotechnical Model and their input format include.

- Block Model—Geology BCGRT's based on RQD (Minesight®)
- Drill Hole Data (acquire database)
- Bucketized Drill Hole Data (Microsoft Access)
- Rock Strength Testing Database (Microsoft Access)

3.1 Geomechanical Results for Mine Planning and Scheduling

Geotechnical engineers use the various input models as the basis for the engineering analyses. The results of these analyses and studies are provided back to the mine planners and schedulers in formats (as part of the geotechnical model) that are readily useable for their slope and underground design and scheduling work.

3.1.1 Slope Angle Model (SA Model)

As PTFI updates its geology model, CNI periodically reviews the updates and generates the SA model. The SA model incorporates all of the slope stability recommendations for the Grasberg Pit slope. The SA recommendation model is based on the results of stability analyses, including rock fabric (backbreak and interramp analysis), numerical models (FLAC, FLAC3D, stability analysis, using Spencer's Method of Slices (i.e. Slope/W), and also using three-dimensional analyses, including CLARA. CNI transmits the results of these analyses in the SA model that is used for updating the open pit mining plan as required. The SA model is generally transmitted as a Minesight® block model.

3.1.2 Ground Condition Model

For scheduling and development drifting of the GBC, a ground condition model was developed to estimate ground support requirements and heading advance rates for development. This model was based on the adjusted RMR values utilizing RMR, RQD and geotechnical rock-type values. The ground condition model is transmitted as a three-dimensional Minesight® solid, which can be exported as an AutoCAD dxf file for use in other software packages. This model is updated as additional drilling and geotechnical data is obtained and analysed.

3.1.3 Fragmentation Model and Estimate for Simulation

CNI utilizes the primary and secondary fragmentation estimates from the Core2Frag analysis, and the mining schedule to estimate fragmentation for mining simulation years. One of the primary goals is to estimate mining equipment requirements for hang-ups and secondary breakage. Mine engineering and mill groups are, in turn, using these results to estimate crushing requirements for the project. At present, CNI transmits the fragmentation estimates as distributions in a database format. The fragmentation is estimated by both primary and secondary as a function of draw height, and by rock type, alteration type, and mill material zone.

There is still significant work that needs to be done to better understand, measure, and then estimate fragmentation for block caves. Through future work, a goal of improved fragmentation estimation is to develop the model to a resolution for use in estimating input fragmentation at the mill.

3.1.4 Cave and Crack Limits / Pit Slope Failures and Dilution Models

One of the principal findings and considerations in the feasibility of the GBC is determining the effect of pit slope failures on the ore recovery and dilutions. The timing and location of pit slope failures is of critical importance. Failure geometries are determined from the stability analysis results, and are coded as three-dimensional solids. The response of the Grasberg Pit slopes to caving is expected to be generally controlled by the undercutting and draw sequence, the orientation of the cave face relative to the HSZ and pit wall orientation, structural controls – faults and bedding, and material properties of the various rock units.

The grade of these failure solids is determined, and the locations of where the pit slope failures slide towards, is determined, along with a bulking factor. From the resultant failure geometry, bulking, and translation, a solid is constructed with the expected grade to establish resultant final pit geometry and grade location, which is used in the PCBC simulation for caving. The three-dimensional solid model of failure geometries and expected final post-failure resultant geometries are typically provided as a Minesight® model or AutoCAD dxf files. An example of these pit slope failures is illustrated on Figure 8, and the conceptual model for input to PCBC is illustrated on Figure 9.

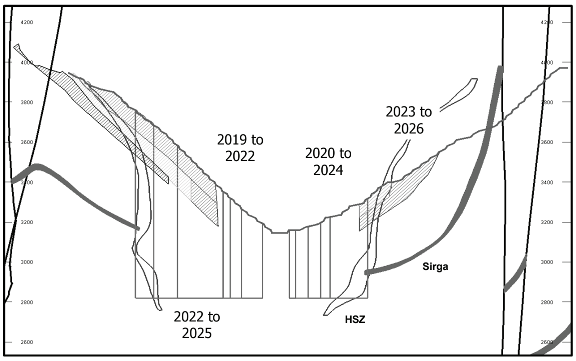

Figure 8 Estimated Failure Geometries Along Section 50-230 Looking West.

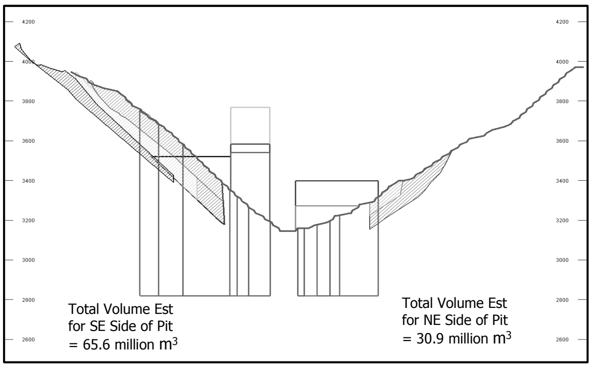

Figure 9 Conceptual Bulked Failure Geometries. Input to PCBC.

4 Geomechanical Analyses – The Methodology

A summary of the geotechnical analyses and results of numerical analyses are discussed.

4.1 Cavability

The Grasberg Block Cave (GBC) is cavable. Each of the mining production blocks has sufficient hydraulic radius to initiate and sustain caving as an independent cave. Cavability was determined with Laubscher's Caving Stability Graph (after Laubscher, 2001) as illustrated on Figure 2-10. Eighty percent of the Rock Mass Rating (RMR) values are less than 60, and this was chosen as the design value for the GBC analysis.

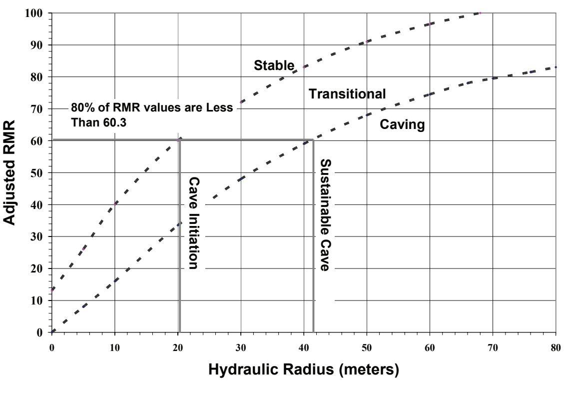

Figure 10 Laubscher's Caving Stability Graph.

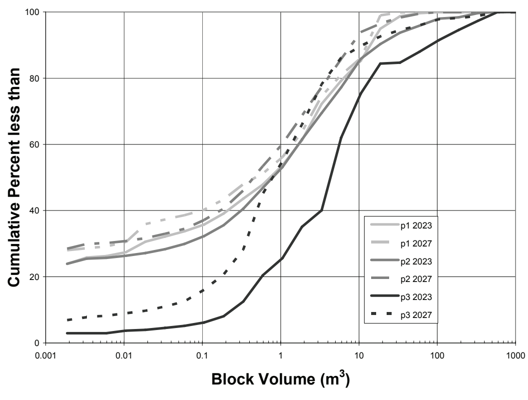

Figure 11 Core2Frag Fragmentation Estimate.

4.2 Fragmentation

The Core2Frag Analysis (Nicholas & Srikant, 2004) was used to estimate fragmentation for the GBC. Primary and secondary fragmentation was estimated for each rock type and material zone. The estimates for both primary and secondary were done for each production block and each 60-meter elevation range of the mineable shape. The initial estimation of primary and secondary fragmentation is made, utilizing cell mapping on the 3000-meter level from the existing Amole Drift and all drill holes that had geomechanical data. The annual fragmentation estimates for each production block are illustrated on Figure 11. These fragmentation estimates are based on the primary and secondary results, and were developed using the mining schedule provided by PTFI.

A couple of key observations from the mining simulation fragmentation estimate for years 2023 and 2027 are that Production Blocks 1 and 2 are fairly mature at the simulation years, with average draw heights in excess of 200 meters. Production Block 3 is just initiating caving at year 2023, and the fragmentation estimate for that year is essentially primary fragmentation for the block. As Production Block 3 is developed into year 2027 with draw heights now in the 120-meter to 200-meter range, the fragmentation is finer.

These fragmentation estimates are the basis used by the mine planning groups to estimate secondary breakage and hang-up estimates. These are also used to determine drawpoint spacing and to estimate crushing requirements. Further discussion of the fragmentation analysis can be found in the above referenced papers.

4.3 Ground Support

The rock-mass ratings (RMRs) are generally fair-to-good for the GBC undercut, extraction, and haulage levels. It should be noted that zones of poor and very poor ground conditions are expected in Production Block 1. CNI has developed an adjusted RMR Model that has been used to estimate the ground support requirements. The construction of the adjusted RMR/Ground Condition Model, using RQD, BCGRT, and Composited RMR values within 25 meters of the area being analysed, is shown on Figure 12. The adjusted RMR is factored based on the geotechnical rock type and RQD estimates; the borehole RMR estimates were not adequate to define the limits of the poor ground based on the limitations of the RMR method.

The ground support recommendations are based on the use of friction bolts, mesh, threadbar anchors, and shotcrete. Additionally, reinforced concrete and steel sets are recommended for specific openings (i.e. ore passes at the rail haulage level). Ground support is generally based on existing practices at the DOZ, except that bolt lengths have been increased to accommodate the larger drift dimensions. The ground support scheme is designed for rock bursting conditions that are expected to occur based on numerical modelling results.

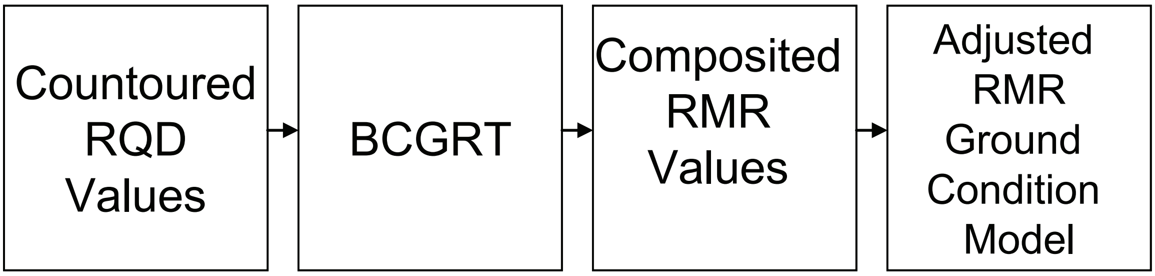

Figure 12 Construction of the Adjusted RMR Ground Support Model from Drill Hole RQD/RMR and Geotech Rock Type

4.4 Cave and Crack Limit Estimation

Cave and crack limits were estimated based on several methodologies, including FLAC3D analysis results, pit slope stability analysis, and engineering judgement. Pit slope stability analyses and failure geometries were estimated based on experience and the results of previous and continuing slope-stability studies and analysis of Grasberg Pit geometries. The timing and location of these failures is based on the caving sequence.

4.5 Stress and Numerical Analyses

Stress is initialized in the FLAC3D Model utilizing the Stress Alteration Method (Killian, et al 2008). *In situ* stress measurements in the intrusive indicate maximum principal stress on the order of 20 MPa, in 2006, However, forward modelling of the stress conditions indicate that the maximum principal stress expected at the initiation of undercutting of the cave is closer to 40 to 50 MPa, based on the hoop stresses that are expected to develop around the final Grasberg Pit geometry. The orientation of the maximum stress is approaching the horizontal.

The FLAC3D analysis, using Itasca's software, is performed using Version 3.10. The model resolution in the fine mesh is approximately 15-meter cubed blocks that extend from 75 meters below the 2775 haulage level to the final pit surface. Time scale is 1 year, based on the schedule provided by PTFI. The limits on FLAC3D Model resolution are the block model geology provided by PTFI using 15-meter blocks, and also the limitations of running the 3D analysis on 64-bit computers.

Figure 13 illustrates the maximum principal stress for the extraction level. White areas within the cave footprint illustrate the areas that have been or are actively caving in year 2023. Higher stress contours on the order of 50 to 70 MPa are observed in the advancing cave front to the southeast. There is a zone of high stress in excess of 70 MPa north of the footprint due to the high RQD in that area and the hoop stress under the pit. Additional geologic delineation is required to determine if the ground conditions are as interpreted, but, at this time, the high stress in this area is acceptable, as no workings are planned in that area of the extraction level.

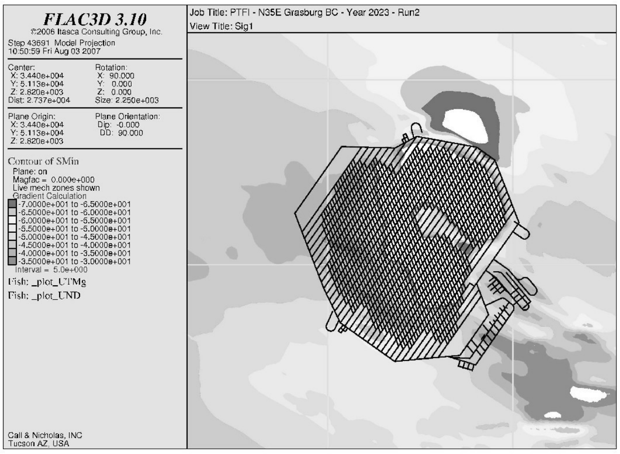

Figure 13 **Example FLAC3D Stress Results illustrating the Maximum Principal Stress for Year 2023.**

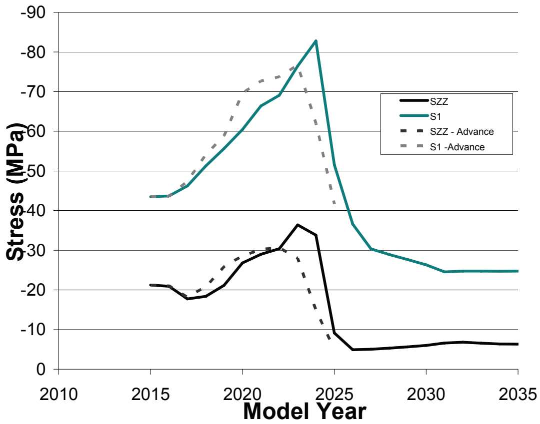

Figure 14 **Cave Front Stress Evaluation for the Advance Undercut.**

Figure 14 illustrates a history point and how using an advance undercut reduces stresses on the extraction and haulage levels as compared to a conventional undercut. As indicated by the stress history point on the haulage level, the maximum principal stress is reduced from 82 MPa to approximately 77 MPa. The advance undercut results are illustrated with dashed lines. The maximum vertical stress is reduced as well. A key goal of the numerical analyses and continuing studies is to determine if there are preferred caving sequences that minimize stresses in advance of the cave front.

5 Conclusions

The development of a working geotechnical model allows for engineering sensitivity analyses with input from the geotechnical consultant, mine engineering, planning, and operations staff.

Geology, rock fabric, and major structure are critical inputs into the geotechnical model.

Large open pits have significant impact on the initial state of stress before caving. Hoop stresses develop under the large pits. The stress measurement and forward analysis predicting the stress have significant impacts on the forward caving analysis, and, in turn, the conclusions and determining cavability and stresses expected on the working levels of the mine. The caving schedule and the use of advance undercutting techniques also have impact on the stress field that is observed in numerical modelling of the cave front.

The use of the geotechnical rock types in the model allows for the ready identification of good ground for facilities, and is also able, through the use of numerical models, to determine areas of high stress, with respect to time for planning and scheduling.

The transmission of the geotechnical model with ground conditions allows mine planners and schedulers to improve upon mine scheduling. This also may allow for improved safety with respect to modifying schedules and development to avoid working in areas with rock-burst potential.

Detailed geologic and geomechanical observations from large caves, and large caves underneath large open pits, are required to improve both quantitative and empirical analyses methods. These observations include, but are not limited to, measurement of *in situ* stresses at various locations within the cave and cave front, fragmentation, and mapping of observed ground conditions, with respect to predictions based on drilling data.

There are uncertainties in the analysis of large caves. The methodology of using the geotechnical model, allows for sensitivity analyses to be run holding parameters constant that allow the engineers to bracket and determine the critical parameters for successful caving.

Acknowledgements

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