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# Ground Support Design Using Three-Dimensional Numerical Modeling at Molycorp, Inc.'s, Block Caving Questa Mine

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## Abstract

*The Molycorp, Inc., Questa Mine, located in New Mexico, currently mines using a gravity-draw panel cave to extract molybdenum sulfide ore from the 600-m-deep D Orebody. Prior to initial development, geotechnical studies were undertaken to predict ground response for the design of entry support on the Grizzly and Haulage levels and in transfer raise connections. Heavy abutment pressures were anticipated ahead of the undercut, followed by significant stress relief as a consequence of a post-undercutting mining sequence. Detailed three-dimensional continuum modeling was conducted to predict changing stress states during the undercutting sequence and to evaluate the performance of various concrete and steel liner designs. Lithologic variation across the orebody was simulated and proved meaningful for identifying different stress transfer mechanisms and liner pressures in different types of squeezing ground. Recommendations for concrete liner thickness, concrete strength, reinforcement, and steel liner thickness were developed from modeling and, ultimately, were implemented during construction. Since the cave was initiated in October 2000, ground support has performed reliably, with only occasional compression cracking and minor tensile separation of the Grizzly Level liner in response to passing abutment loads. Observations to date corroborate model predictions and validate initial support design for the new deep orebody.*

## 1 INTRODUCTION

The Molycorp, Inc., Questa block caving mine is located near the northern New Mexico town of Questa, as shown in Figure 1. Molybdenum has been mined at Questa for over 80 years. Molycorp began large-scale open pit mining in 1965, but by the mid-1970s plans for underground mining were developed to combat high stripping ratios. By the end of 1976, a substantial high-grade deposit was delineated by exploratory drilling southwest of the open pit. A gravity block-caving method was selected because of the well-fractured nature of the rock mass and the size and shape of the deposit (Shoemaker 1981). Figure 2 shows the general layout of the Goathill and D orebodies and the current underground mine.

Underground mine development began in 1979, followed by initial production in 1983 from the Goathill Orebody. Production peaked in the mid-1980s, reaching 16,000 tonnes per day. By 1992, the mine was placed in stand-by mode in response to declining molybdenum prices. The mine was reactivated in 1995 and caving operations in the Goathill Orebody were converted from manual gravity draw to highly-mechanized load-haul-dump (LHD) draw.

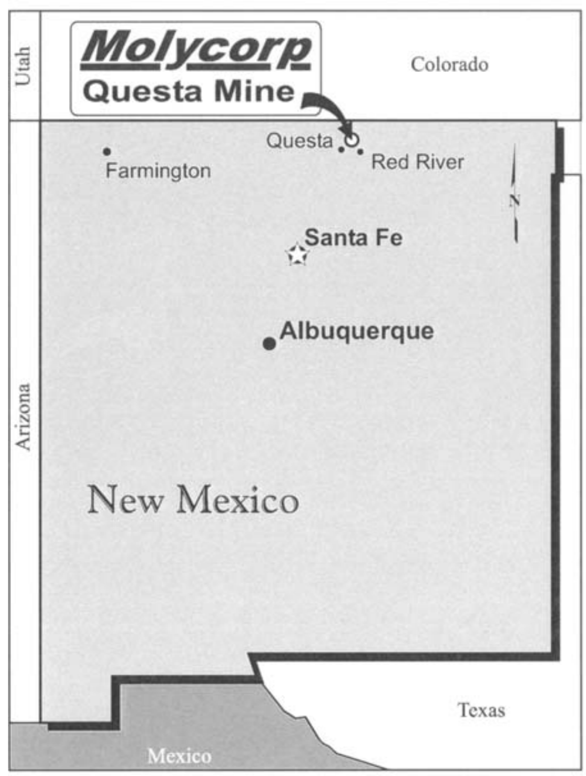


Figure 1: Location of Molycorp, Inc., Questa Mine

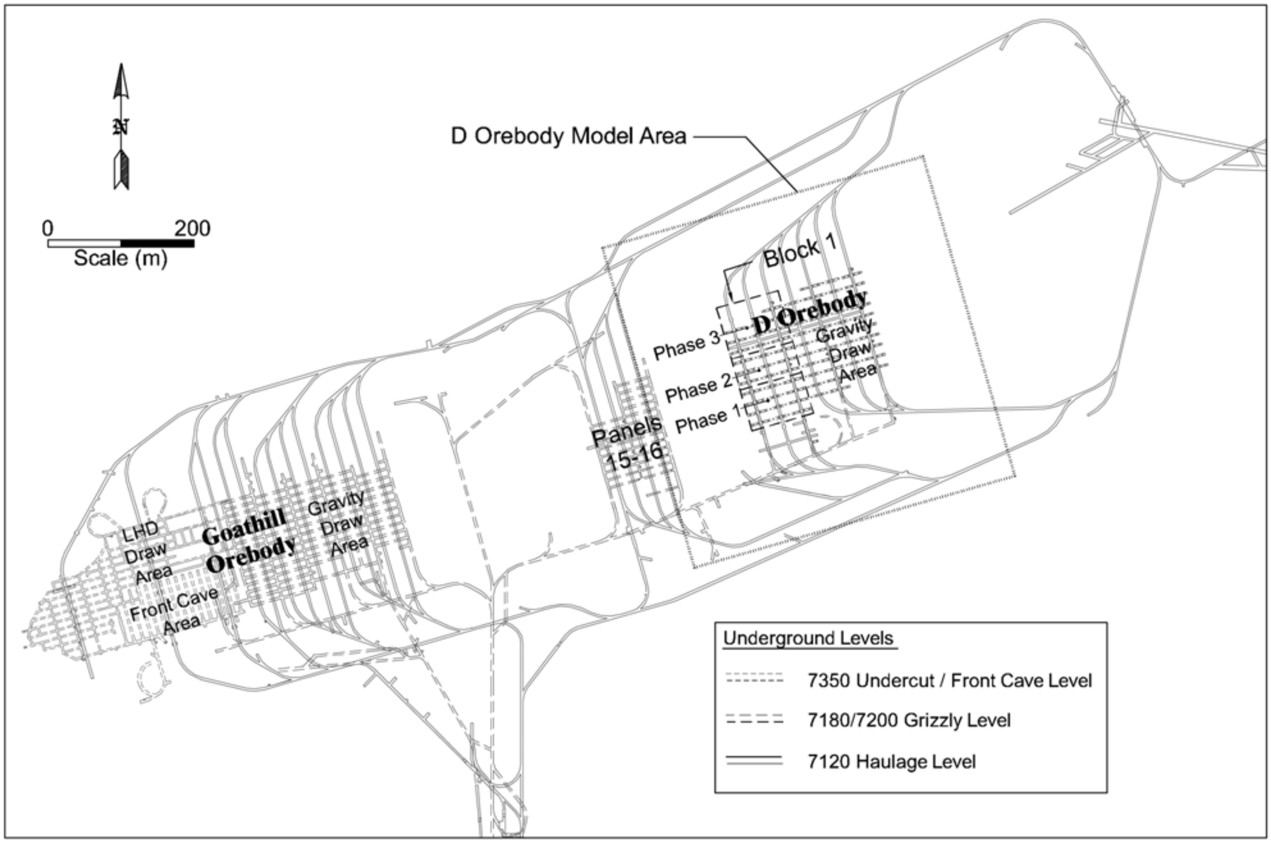


Figure 2. Plan View Mine Layout

Plans were developed to replace production from the Goathill Orebody with the new, deeper D Orebody to the east by the year 2000. However, at more than twice the depth of the Goathill Orebody (300 m deep), the D Orebody (600–800 m deep) posed unprecedented geotechnical challenges for mining at Questa. Experience with mining in weak ground at Goathill suggested that very heavy support would be required in the deeper orebody. With expectations of high ground pressures, Molycorp reverted to the original and proven gravity draw system in the D Orebody, which was considered the lower risk alternative to LHD draw. Gravity draw was also favored for better cave fragmentation and lower ventilation requirements. Molycorp's gravity draw mine system is illustrated in Figure 3.

Designs for ground support, comprising concrete and steel liners of various dimensions and strength, were developed in accordance with predicted high-abutment stress magnitudes. Changing abutment stress conditions and rock mass-support interaction were simulated per the planned caving sequence using detailed three-dimensional computer models. Ultimately, designs were adopted based on modeled performance and experience. Production from the D Orebody began in October 2000.

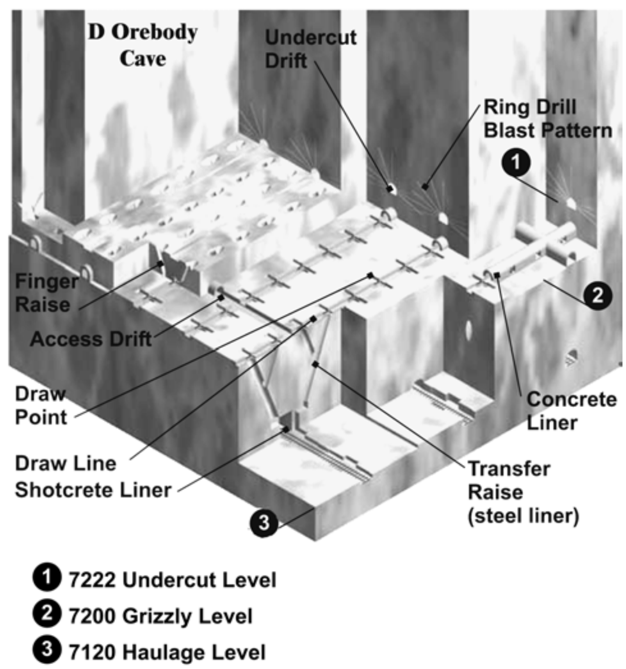


Figure 3: Gravity Draw System

## 2 GEOLOGY

The deposit occurs in a hydrothermally altered region associated with extensive faulting and fracturing in aplite-porphyry rocks which intruded a complex sequence of volcanic andesites and rhyolites. These rocks occur in a down-dropped trench developed in Precambrian metamorphic rocks consisting of gneisses, schists, and amphibolites. Structurally, the deposit is controlled by major shear systems that trend northeast, east-west, and north-south to northwest.

Hydrothermal solutions, rich in molybdenum, migrated upward from a deeply buried batholith through fractures, and formed the molybdenite ($MoS_2$) mineralization—the only ore mineral occurring in the deposit (Agapito and Shoemaker 1987). The individual orebodies comprising the deposit vary in width and height from 125 m to 250 m and are collectively about 1,500 m long.

## 3 ROCK MASS QUALITY

For engineering purposes, the complex geology of the D Orebody is simplified to four predominant rock types: strong and weak andesite, breccia, and aplite-porphyry rocks. Figure 4 shows the general geology on the 7200 Grizzly Level, located 6.7 m below the 7222 Undercut Level. The molybdenum ore occurs mostly in the breccia above the Grizzly Level and, to a lesser extent, in veins. Beneath the breccia, to the south, is a generally weak andesite and, to the north, a moderately competent intrusive aplite-porphyry, which also underlies the andesite.

The andesites in the 7120 Haulage Level are generally of better quality and exhibit less jointing and faulting than the andesites on the Grizzly Level. They are also of better-than-average quality than the andesites in the Goathill Orebody.

Rock quality is substantially affected by intense fracturing spaced as closely as 30 mm. The southern half of the orebody is generally weaker than the northern half due to large amounts of clay present in the highly fractured andesites and aplites. Fractures in the northern half of the orebody contain more quartz than clay, resulting in a significantly stronger rock mass. Extensive mapping and observations have shown a range in Q value (Barton et al. 1977) of 0.002 to 8, which rates the rock mass from exceptionally poor to fair.

Rock mass properties were estimated according to the Geological Strength Index (GSI) introduced by Hoek et al. (1995) and are summarized for the D Orebody in Table 1.

Caving operations were designed to proceed from south to north, so that the abutments from caving can be transferred away from the weaker andesites in the south to the stronger aplites in the north. Experience in the Goathill Orebody showed consistently better ground conditions when caving proceeded in a northward direction.

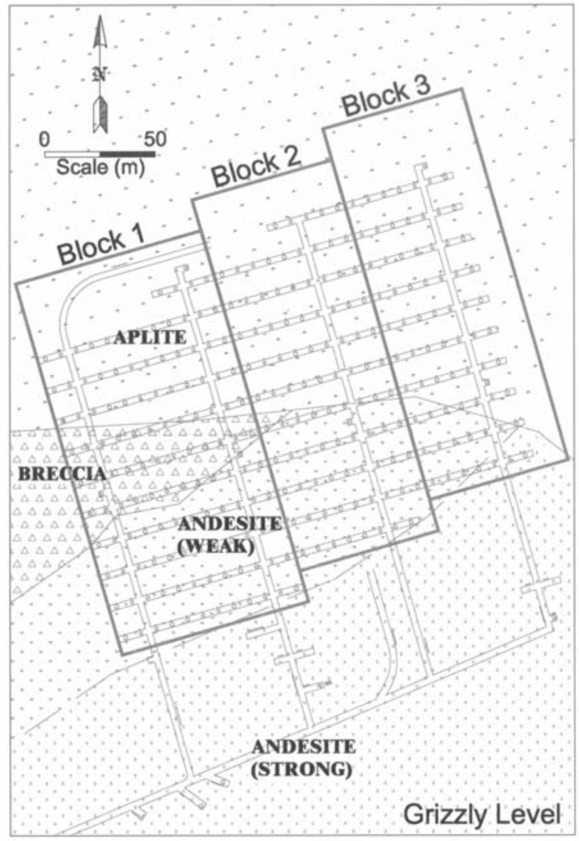


Figure 4: Predominant Rock Types on the Grizzly Level

**Table 1. Rock Mass Properties**

| | Andesite | | Breccia | Aplite |
|---|---|---|---|---|
| | Weak | Strong | | |
| **GSI** | 10 | 30 | 48 | 65 |
| **Q**† | 0.0023 | 0.021 | 0.16 | 1.03 |
| **Q Rating** | Exceptionally poor | Extremely poor | Very poor | Poor |
| **Elastic Modulus, *E* (MPa)** | 1,000 | 3,200 | 8,900 | 23,700 |
| **Poisson's Ratio, *v*** | 0.30 | 0.30 | 0.25 | 0.25 |
| **Unconfined Compressive Strength, $\sigma_c$ (MPa)** | 3.8 | 12.5 | 18.6 | 52.7 |
| **Cohesion, *c* (MPa)** | 1.1 | 3.1 | 4.1 | 9.2 |
| **Friction Angle, $\theta$** | 29° | 38° | 42° | 52° |

† Q = 0.10*Q' for D orebody conditions, where Q' = Modified Tunnelling Quality Index.

## 4 ABUTMENT STRESSES

From inception, heavy abutment stresses were anticipated on the production levels in the D Orebody. Because a post-undercutting sequence was required, newly developed lines were expected to be subjected to the greatest range of support pressures possible. Newly developed draw lines would be rapidly exposed to peak abutment loading followed by maximal relief to less-than-*in situ* stress conditions after passage of the overlying cave. Such extremes are normally avoided with a pre-undercutting sequence.

Detailed, three-dimensional continuum modeling was conducted with the finite-difference code FLAC$^{3D}$ (Itasca 1997) to predict changing stress conditions on the Grizzly and Haulage levels during the undercutting sequence in Block 1. Figure 5 shows the general model geometry and spatial relationship of the four predominant rock types.

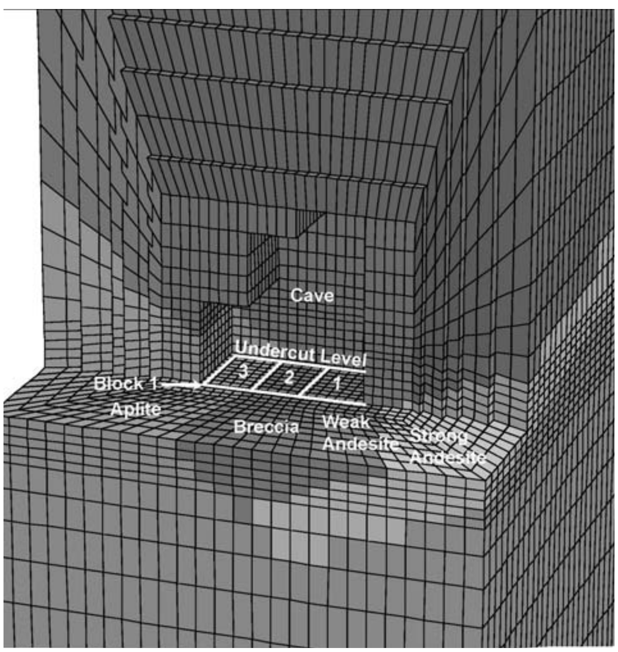


Figure 5: Block 1—D Orebody Abutment Stress Model Geometry and Rock Types

Peak abutment loads, calculated by elastic-only modeling, are summarized in Table 2 by rock type. Best estimates from modeling are that active ground pressures in the deeper D Orebody will range from 130% to 290% of those at Goathill, depending upon rock type.

Abutment stresses in the more competent aplite and, to a lesser extent, breccia rock masses were determined to reach their highest levels near the end of Block 1 mining. Figure 6 is a map of the major principal stress magnitude acting on the Grizzly Level near the end of Block 1 mining. Stresses were determined to peak at an earlier stage in the andesite.

Model results also suggest that abutment stresses will attenuate a short distance away from the cave. Abutment effects are expected to become largely unnoticeable by about 12 m laterally into Block 2 on the Grizzly Level. In the vertical direction, abutment stresses are expected to decrease from the Grizzly Level to the Haulage Level by as much as 25% in the weakest andesite and 50% in aplite.

**Table 2. Modeled Peak Abutment Stresses**

| | Nominal Pre-mining Stress (MPa) | Peak Abutment Stress (MPa) | |
|---|---|---|---|
| | | Grizzly Level | Haulage Level |
| **Goathill Orebody** | 8.0 | 17.2 | 12.9 |
| **D Orebody** | | | |
| Weak Andesite | | 23.0 | 17.1 |
| Strong Andesite | 15.1 | 24.7 | 18.0 |
| Breccia | | 40.1 | NA† |
| Aplite | | 49.6 | 24.0 |

†Breccia absent on Haulage Level.

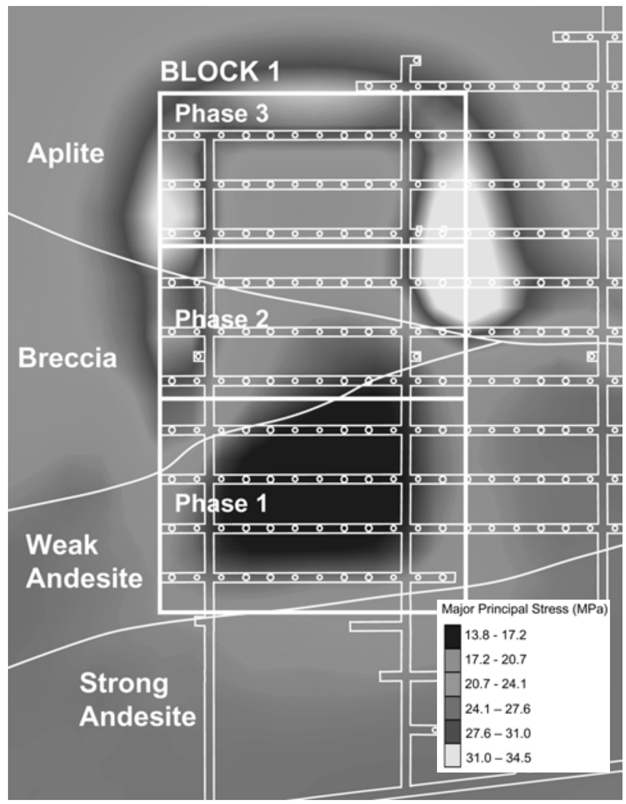


Figure 6: Peak Abutment Stress Map at the Final Stage of Undercutting—Grizzly Level, Block 1

## 5 GROUND SUPPORT

Original estimates for ground support at Goathill were based on ground-support interaction analyses, which relied upon the load-deformation characteristics of the rock mass and support (Agapito and Shoemaker 1987). For the D Orebody, the method was used for preliminary support design. Initial results indicated that a minimum of 46 cm of concrete would be required for lining the draw lines on the Grizzly Level and that approximately 15 cm of shotcrete would be required to stabilize the heaviest sections on the Haulage Level.

A 61- to 69-cm-thick cast concrete liner (46-cm-thick floor), using 21 MPa strength concrete, was initially proposed for secondary support in the draw lines, as shown in Figure 7. A 15-cm-thick shotcrete liner (46-cm-thick poured floor) was proposed for the Haulage drifts, as illustrated in Figure 8. Lastly, a 6.4-mm-thick Grade 60 steel liner was proposed for the transfer raises between the Grizzly and Haulage levels.

Detailed FLAC$^{3D}$ modeling was conducted to assess the performance of the preliminary designs. The primary design criterion was the prevention of crushing or squeezing of the liners during abutment loading. A local-scale model was constructed of the complete transfer raise system, illustrated in Figure 9. Support elements were attached to the excavations to represent the concrete and steel liners. Minor support components, including bolts and mesh used for support during development, were not included in the model.

Non-linear Mohr-Coulomb rock mass behavior was prescribed in the model per the properties presented in Table 1. Peak abutment stresses were specified for different rock types according to the stress tensors derived from the large-scale abutment stress model. In the transfer raise model, entries were excavated and allowed to reach initial equilibrium before liners were installed. After installing the liners, abutment stresses were applied. Liner pressures developed in response to both elastic and plastic deformation in the surrounding rock mass.

Support performance was gauged by the amount of entry convergence and yielding in the liner elements. For example, local crushing of the concrete liner is indicated in Figure 9 by the yield zone around the left draw window.

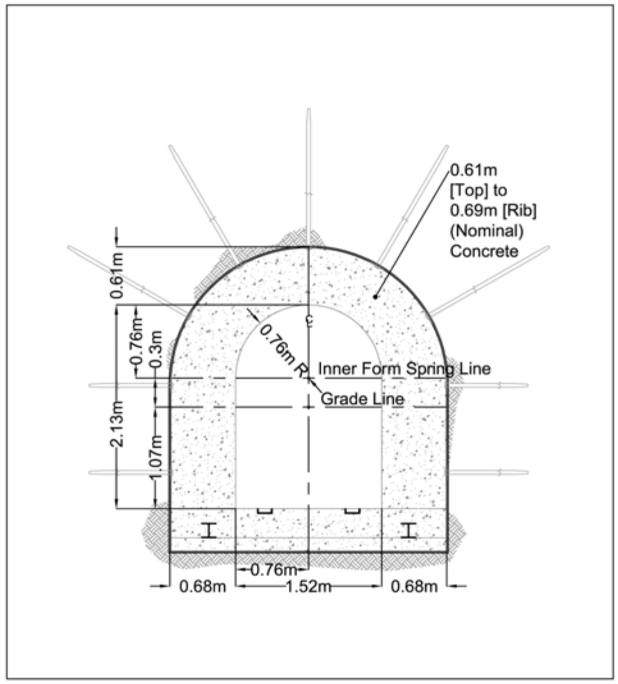


Figure 7: Proposed Support Design for the Grizzly Level Draw Lines

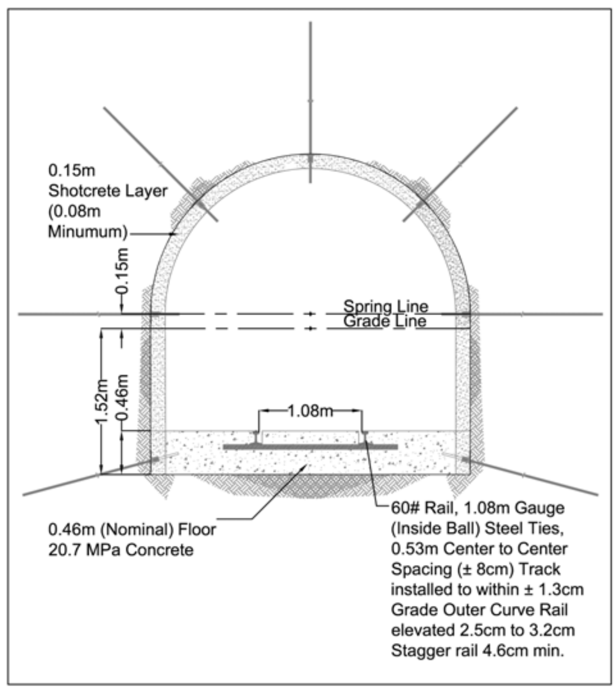


Figure 8: Proposed Support Design for the Haulage Level Drifts

Figure 9 indicates limited liner yielding when the proposed draw line design was tested in the strongest aplite rock mass. Damage significantly increased when the same liner was tested in weakest andesite. Figure 10 shows extensive concrete yielding, indicative of major crushing in the liner, in the weak ground.

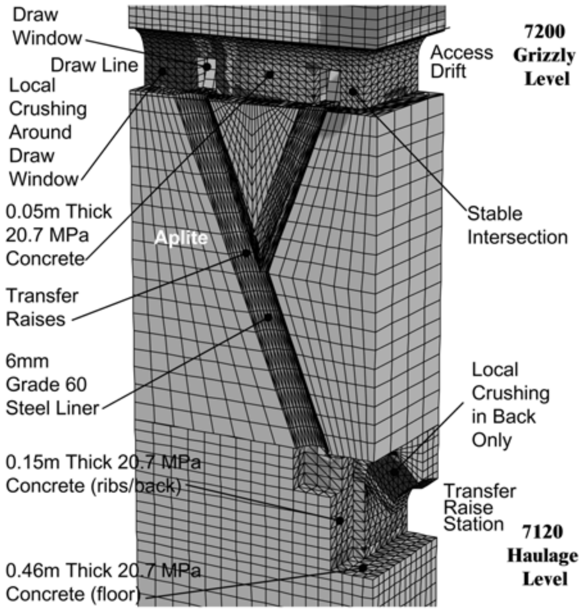


Figure 9: Transfer Raise System Model and Liner Yielding during Abutment Loading in Aplite

Less damage occurred in the stronger andesite and breccia rock masses.

Even in the strongest rock, the preliminary designs were determined to be vulnerable to excessive crushing under transient abutment loads. The benefits of a thicker liner and higher strength concrete were tested by modeling. Results showed that concrete as thick as 91 cm on the Grizzly Level and 30 cm on the Haulage Level increased liner stiffness, but attracted more load and gained little in terms of net stability.

Greater benefit was achieved by increasing the strength of the concrete. Crushing was shown to decrease moderately by increasing concrete strength from 21 to 41 MPa, and almost no risk of damage was determined for very high-strength concrete (83 MPa), as indicated by Figure 10. Although steel reinforcement was not considered effective for preventing crushing, light reinforcement was recommended for augmenting tensile strength and retaining unstable blocks in the event of cracking.

Results indicated that a steel liner was necessary to prevent adverse closure of the transfer raises in the weak andesite and breccia. The 6.4-mm-thick steel liner proposed in the preliminary design was determined to be adequate to control squeezing under most conditions.

From the analysis, and based on experience at Questa, the proposed designs were concluded to

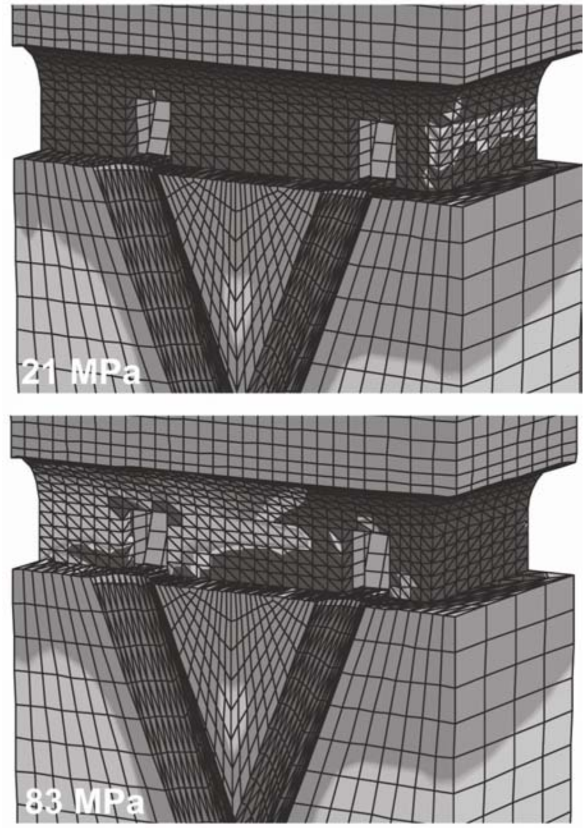


Figure 10: Comparison of Liner Damage in the Draw Lines using Normal (21 MPa) and very High (83 MPa) Strength Concrete in Weak Andesite

be reliable in the stronger aplite and breccia rock masses, except for localized areas of geological weakness (e.g., shear zones and faults) which would require additional support. In the weakest andesite, the same design posed significant risk of concrete crushing over large areas on the Grizzly Level, unless higher strength concrete was used or supplemental steel arches were added. Upon consideration of the findings, Molycorp adopted the preliminary designs, but elected to use high-strength concrete (41 MPa) on the Grizzly Level to limit risk.

## 6 PERFORMANCE

A total of ten draw lines (Lines 6–15) have been developed in Block 1 of the D Orebody since the cave was initiated in October 2000. The southernmost line (Line 15) was abandoned for geologic reasons in 2003. Lines 4 and 5 were mined, but never completed because of declining grades to the north. Approximately 3.3 million tonnes have been produced from Block 1 through May 2004.

By June 2002, Block 1 was entirely undercut. During this phase, transient abutment stresses passed over the draw lines, reaching maturity some time in 2003, coincident with the onset of subsidence at the surface. Measurements since July 2003 have shown steady subsidence at a rate of 0.4 m per month and maximum subsidence at the surface of 3.0 m in April 2004. Approximately 70 m of the 200-m Block 1 ore column has been drawn as of March 2004.

Generally, very good ground control has been achieved in Block 1 with the recommended support. The photographs in Figures 11 and 12, respectively, show a typical Grizzly Level draw line just prior to and soon after pouring the nominally 61-cm-thick concrete liner. Figure 13 shows the typical condition of the liner after passage of the stress abutment. No liner damage is evident except for a horizontal 12-mm open separation along a concrete cold joint near the spring line. This pattern of separation occurred consistently in almost every draw line as a result of stress relief after passage of the undercut. Operations personnel, concerned with the fractures, initially installed steel sets (Figure 13) and straps at some locations as a precautionary measure. This practice was later relaxed after it became apparent that the liners were stable.

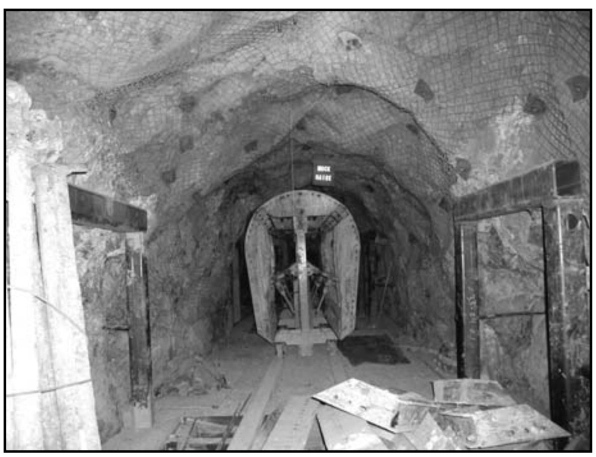

Figure 11: Draw Line Development Showing Original Excavation and Concrete Forms

Early pours attempted to use nylon fibers for tensile reinforcement. However, their use was soon abandoned because the fibers proved difficult to pump and clogged concrete lines. The fibers showed no significant improvement in controlling tensile fracturing.

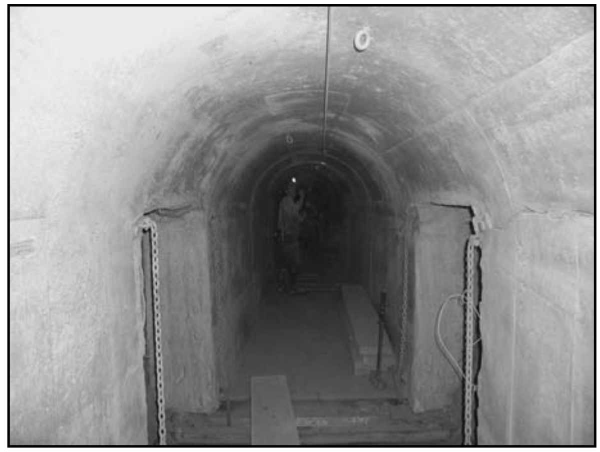

Figure 12: Typical Draw Line after Liner Construction

Figure 13: Horizontal Tensile Fracture at a Concrete Cold Joint and Precautionary Steel Sets in a Draw Line

Compressive abutment stresses caused only occasional cracking in the draw lines. Any damage was generally superficial and transient with passage of the undercut, and did not impede production. Figure 14 shows a compressive fracture along the crown of a draw line. No significant damage occurred on the Haulage Level.

Compressive fractures, where they did occur, often initiated at construction defects in the liner, including thin spots and voids in the concrete, pipe embedded in the liner, and burlap and other debris included in the pour. Figure 15 shows a small hole near the crown of the liner caused by an incomplete pour. Steel sets were sometimes required at these locations. Defect-related damage was largely eliminated in later lines with improved construction methods. Measures included excavating a higher back, using two concrete pour lines, and shortening pour lengths.

Figure 14: Compression Cracking and Straps along the Crown of a Draw Line

Figure 15: Void in the Concrete Liner near the Crown Caused by an Incomplete Pour

## 7 CONCLUSIONS

Experience mining in the Goathill Orebody provided a reliable starting point for the design of ground support in the D Orebody. However, considerable risk lay in the geotechnical uncertainty posed by mining at almost twice the depth of the Goathill Orebody. From inception, reliable ground support was recognized to be key to successful mining. In spite of recent experience with LHD draw at Goathill, a more labor-intensive gravity-draw system was selected, in part, to limit geotechnical risk.

Detailed numerical modeling proved valuable for reducing geotechnical uncertainty by accurately predicting abutment stress effects and allowing different ground support options to be tested before mining. Designs implemented on the basis of modeling have performed reliably during 43 months of mining in Block 1.

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