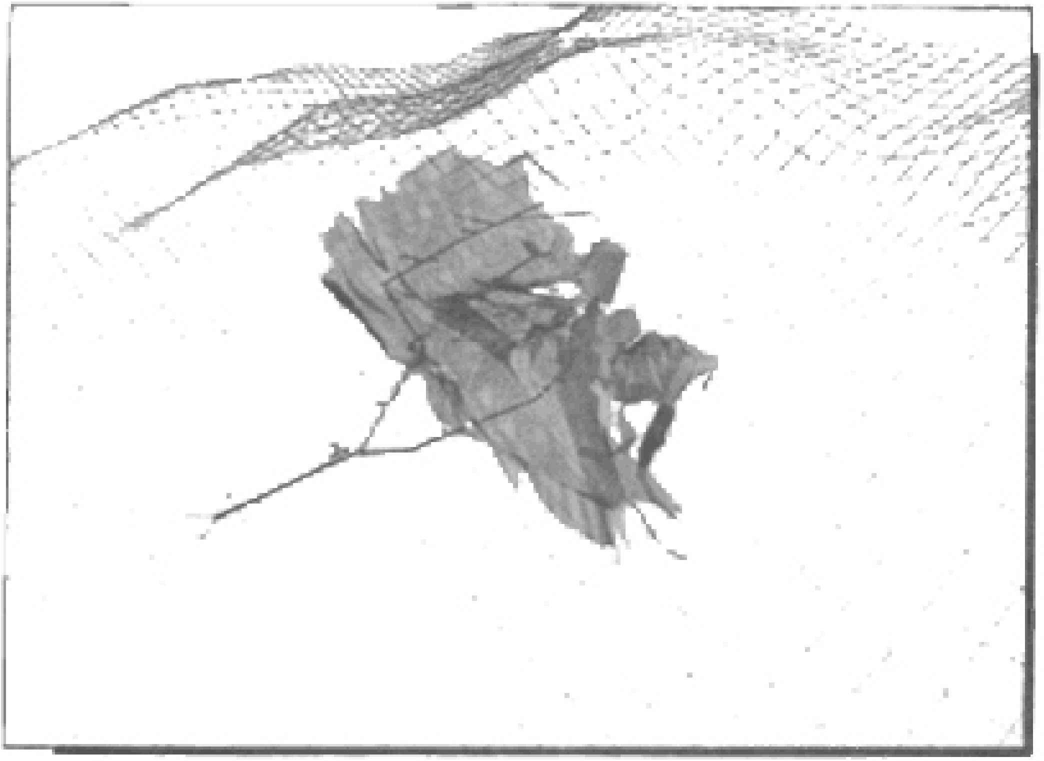
RI 9530

REPORT OF INVESTIGATIONS/1995

Computer Modeling and Analysis of the Greens Creek Mine, Admiralty Island, AK

By M. J. Beus and T. J. Orr



UNITED STATES DEPARTMENT OF THE INTERIOR

BUREAU OF MINES

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Cover: A detailed analysis of a mining block at the Greens Creek Mine requires that a mesh of the overlying rock mass be created to represent discrete segments, which are mathematically expressed. This mesh is assigned physical characteristics and forces that represent stress field and mechanical properties of the rock.

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UNITED STATES DEPARTMENT OF THE INTERIOR
Bruce Babbitt, Secretary

BUREAU OF MINES
Rhea L. Graham, Director

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

Metric Units

cm	centimeter	m	meter
GPa	gigapascal	MPa	megapascal
km	kilometer	pct	percent
km^3	cubic kilometer		

U.S. Customary Units

ft	foot	psi	pound per square inch
in	inch		

COMPUTER MODELING AND ANALYSIS OF THE GREENS CREEK MINE, ADMIRALTY ISLAND, AK

By M. J. Beus[1] and T. J. Orr[2]

ABSTRACT

The U.S. Bureau of Mines is conducting investigations to improve design methods for mining volcanogenic massive-sulfide (VMS) type deposits in environmentally sensitive regions. This study was conducted at the Greens Creek Mine, which is typical of many VMS-type deposits throughout southeast Alaska, and served as a case history for computer modeling and structural analysis. Results indicated that the finite-element design method provided reasonable comparisons with both the anticipated regional stress regime and the measured deformational response of the underground accessways. Investigators concluded that reasonable accuracy can be expected for stability analyses of proposed mine design scenarios at this mine using the results of this preliminary study.

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INTRODUCTION

One of the goals of the U.S. Bureau of Mines (USBM) is to help ensure that the United States has an adequate and dependable supply of minerals at an acceptable environmental cost. Recovery of mineral resources is contingent upon development of mining methods that can be used under strict environmental constraints. Although underground mining alleviates many environmental concerns prevalent with surface mining, the design and development of new underground mining methods and mining infrastructures that minimize environmental damage, such as subsidence, are of crucial importance.

Researchers at the USBM conducted a numerical simulation of an underground mine in southeast Alaska to assess the application of computer modeling techniques to stope and mining method design for volcanogenic massive-sulfide-type deposits. This initial effort provided baseline data for subsequent research to delineate problems common to the development of mineral resources where there are strict environmental constraints, such as in Alaska.

Mining methods that enhance ground control and ground conditioning operations are a primary consideration, because the method chosen affects mineral recovery as well as disturbance to an ecosystem. Procedures for ground conditioning and control of mine openings are therefore crucial aspects of overall mine design. Computer modeling and visualization of mine design concepts were used in this study to predict regional stress distribution, mining-induced displacements, and surface subsidence.

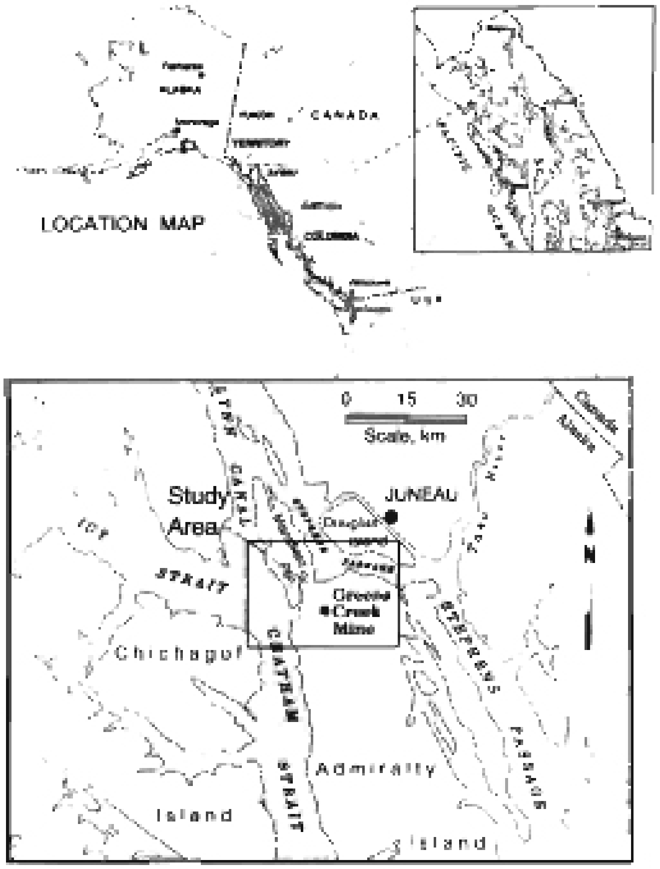
Underground mining involves drilling, blasting, and removing fragmented rock, thus creating a network of underground openings suitable for accessing and recovering mineral resources. This process results in a redistribution of preexisting overburden and tectonic forces, so that opening walls move inward as stress is concentrated. Displacement will continue until the forces within the rock surrounding the opening again come to equilibrium. The magnitude of displacements before instability or equilibrium is reached is dependent on many factors, including the quality of the rock, the design of the opening and support systems, and the use of backfill following mining.

The rock mass at the Greens Creek Mine is highly complex and involves many physical and geological unknowns. Mathematical modeling of structures in the rock mass requires extensive simplification of applied loads, material properties, mining geometry, and extraction sequences. Many mine design problems require three-dimensional analyses to account for nonsymmetrical loading and geometry. Some of the limitations and considerations for two- and three-dimensional analyses of mining and civil structures have been delineated (Ghaboussi, 1983; Pariseau and others, 1990). These are (1) defining and analyzing the scale of interest for the structure, (2) defining the loads acting on the structure, (3) determining the physical properties of the medium, (4) defining the geometry of mine openings, and (5) simulating removal of the rock mass and installation of support and backfill. Computer simulation and analyses are being applied to the present study at Greens Creek.

SITE DESCRIPTION

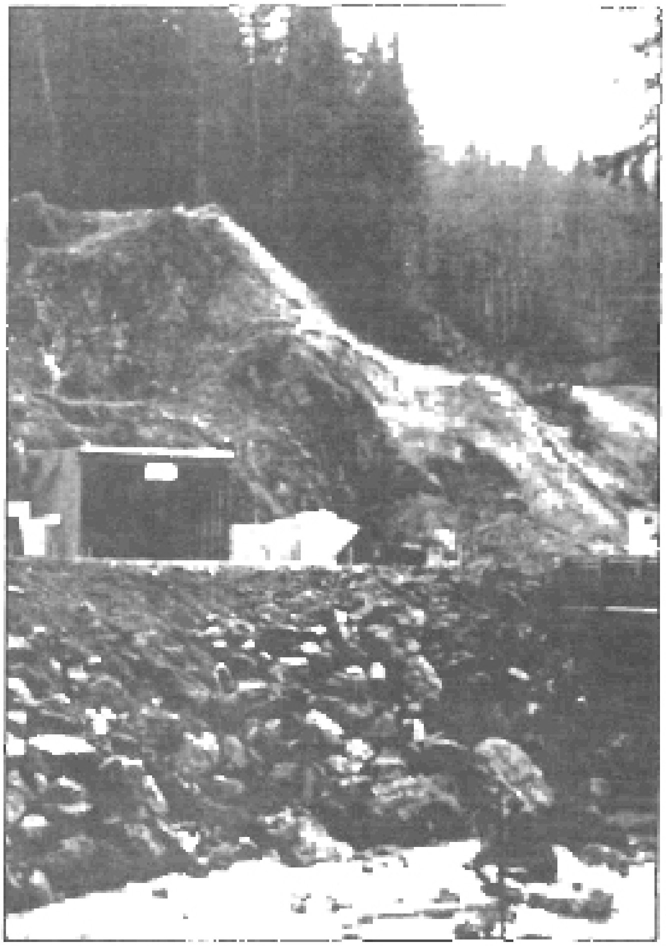
The Greens Creek project is located approximately 29 km (18 miles) southwest of Juneau, AK, on Admiralty Island (figure 1). The ore body is a high-grade sulfide deposit containing significant amounts of silver, gold, lead, and zinc and minor amounts of copper. The vein is very complex and has experienced two major folding events. The hanging wall is composed mainly of phyllite and massive and slatey argillite. The ore is generally very competent and stronger than the host rock. Approximately 50 pct of the ore body is less than 10 m (33 ft) thick. The host rock tends to have more stability problems than the ore body because of foliation created during folding. Argillite beds in the hanging wall range from 5 to 45 cm (2 to 18 in) thick and are far more competent than rock in the footwall, which contains graphite layers that create slip planes. Some areas of the hanging wall contain very weak and greasy chloritic serpentine. The ore body dips from vertical to horizontal, with most of it dipping less than 50°.

Figure 1



Location of Greens Creek Mine in southeast Alaska.

Figure 2



Topography around 920 portal at Greens Creek Mine.

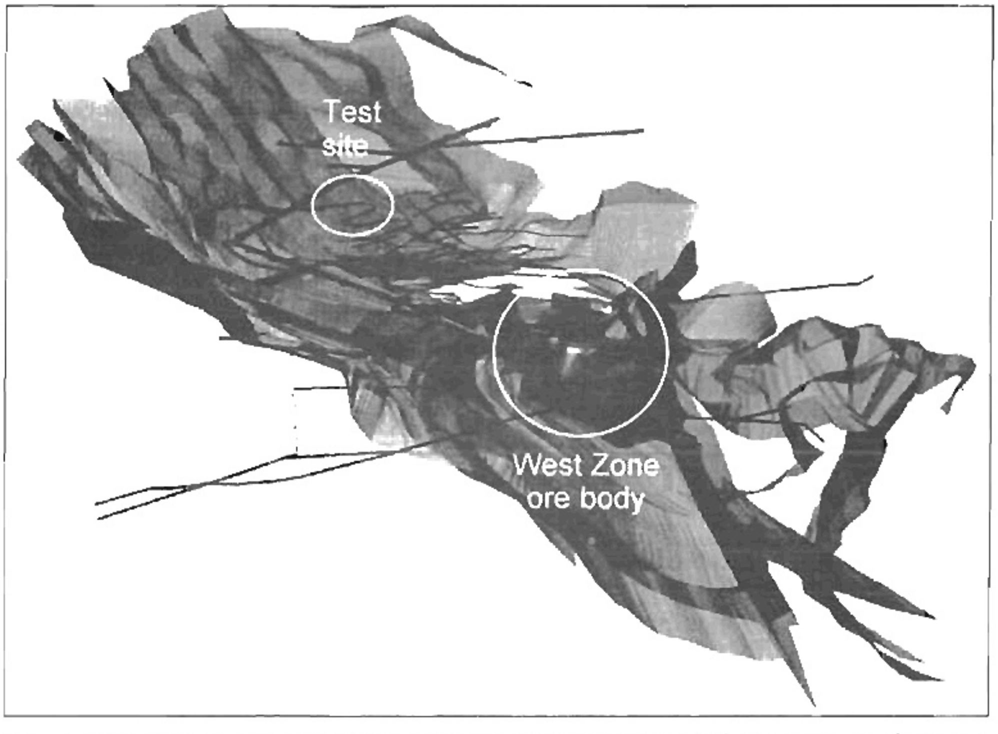
The main access to the mine is through an adit driven into the hillside to a maximum depth of about 762 m (2,500 ft). Presently the mine is developed on two levels, the main haulage level at 280 m (920 ft) above sea level and another access level at 411 m (1,350 ft) above sea level. Current mining methods, depending primarily on thickness and dip, are cut-and-fill, drift-and-fill, or room-and-pillar in large, flat-lying sections. Figure 2 shows the portal of the mine with Greens Creek in the foreground. The figure also shows the surrounding topography and the variability of the terrain.

Topographic data were formatted for input into the computer drafting program AutoCAD for further visualization and for compatibility with existing mine sections and layouts. Surface and subsurface models were generated using digitized vein cross sections and AutoCAD drawings supplied by the mine, as shown in figure 3. The digitized cross sections and plan view mine maps formed the basis for the three-dimensional, finite-element models. These cross sections were linked to develop ore body surface and solid representations to provide a better visualization of the deposit. Figure 4 shows the footwall contact of the ore body at the same orientation as shown in figure 3. The newly discovered West Zone ore body is shown in the foreground.

Figure 3

AutoCAD-software-generated surface and subsurface model showing linked cross sections and geometry of Greens Creek Mine, looking south.

Figure 4



Computer-generated three-dimensional map showing contact of ore body in footwall with test section 28 and West Zone ore body (circled).

BACKGROUND STABILITY ASSESSMENT

Initial rock mechanics investigations were conducted by Kennecott Mining Co., Salt Lake City, UT, and its consultants. Exploration diamond drill holes were logged for the preliminary design and mining method analysis. Core recovery was very good and averaged 98 pct in H, N, and B drill hole sizes, except for fault zones. The classification system used, the Mining Rock Mass Rating (MRMR), was developed specifically for an underground mining environment.

The mine is located along a very active crustal plate zone, i.e., the Queen Charlotte lateral strike-slip fault, and historically, extensive tectonic activity has affected the regional metasediments and volcanics. Extensive evidence of faulting and bedding slip, which would tend to relieve residual forces, indicates that minimal tectonic stress exists at the Greens Creek Mine. However, gravity-induced rock mass loading and a lateral stress component from Poisson's effect might be significant. Kennecott's consultant concluded that there appear to be no significant stress anomalies locked in from thermal, tectonic, or other factors because of the presence of extensive faulting and shearing.

Mountains in the area surrounding the mine approach 1,524 m (5,000 ft), so depth of overburden varies extensively, which causes variations in the stress field. The surface has considerable relief and a loose material cover, and there is high precipitation in the area. Movement resulting from subsidence could result in small cones of depression. Other factors that contribute to instability are (1) relatively complex geology and resultant variations in rock mass deformational (stiffness) properties, (2) complexity and variation in mine development and stope geometry (shape, size, orientation), resulting in significant stress concentrations in certain areas, (3) low strength of the rock mass, which causes many areas of the mine to exceed minimum safety factors, and (4) the discontinuous nature of the rock mass, which contributes to localized falls of ground.

The Greens Creek Mine has experienced localized ground falls at intersections and in large chambers or wide drifts. One failure occurred in an area that had been stable for many years. These failures appear to be the result of the highly sheared and foliated nature of the rock mass coupled with unfavorable orientations of the openings with respect to geology. Stability problems were encountered in the serpentine, and the Split-Set bolts and landing mats normally used throughout the mine did not provide adequate support. Air slacking and/or creep is suspected in some areas.

APPROACH

General research considerations for the Greens Creek Mine include (1) backfill design with engineered physical properties and analysis of installation procedures and support potential, (2) stope design, and (3) accessway design, including lateral haulage-exploration drifts, ramps, and raises.

Several questions were raised during preliminary design considerations.

1. How close to the back does the fill need to be to provide adequate support during pillar extraction in drift and fill zones, and does it even provide support?
2. What backfill strengths are needed for the wide variety of mining conditions?
3. What fill placement techniques can meet the needs of the mine?
4. What would be the most desirable sequence for pillar extraction?
5. How can design guidelines be obtained about optimum pillar sizes and spacing and maximum room span?

A comprehensive research program involving mine structure modeling, mine monitoring, and ore body visualization was undertaken by the USBM to resolve instability questions and develop guidelines for accessway, stope, and backfill design. The present work included an initial field instrumentation program, described in a companion Report of Investigations (RI),[3] and preliminary structural analyses of regional stress fields, subsidence, and effects of mining on stopes and accessways in a selected area of the mine.

Results from numerical modeling must be validated to assess the technique's usefulness in practice for future design scenarios. The most direct approach is to compare analytical results with actual measurements of the structure during construction or while it is in service. A high level of confidence can be attributed to rock mass displacement

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[3] Real-Time Monitoring of Field Measurements for Mine Design: Greens Creek Mine, Admiralty Island, AK, by T. J. Orr and M. J. Beus. Expected publication in 1995.

data and loads on support members. Information from borehole extensometers installed in rock abutments and pillars, when combined with structural analysis, can be used to identify stress concentrations caused by mining. If instruments are installed in both the backfill and the rock, the effect of mining can be verified by the complementary responses of each medium. The validated model for an area of the mine is used to predict stresses caused by mining in other, similar sections of the mine, to develop alternate sequencing patterns, or to evaluate the effects of various pillar widths. Considering these results, structural performance of accessways and stopes may be determined on a preliminary basis.

Rapid advances in computer modeling have allowed considerable progress to be made in the application of computer technology to design at a mine scale. Mining problems involve excavations of a finite size in an infinite medium (the rock mass), and many problems are obviously too complex to solve with a single model. In this report, a modeling approach is described in which only the large-scale features, such as surface topography and the intact rock mass, are analyzed prior to excavations of the openings. This "supermodel" can be used to define the input boundary conditions for more detailed "submodels" until the desired level of result is obtained for the target features. The analysis starts with a large feature, such as the rock mass surrounding the ore body, and progressively analyzes more detail in specific areas of interest. The procedure is repeated as many times as desired to obtain the level of refinement required to study the target feature.

REGIONAL STRESS FIELD

Topography can have a major effect on the magnitude and direction of in situ stresses. Research has shown (Pan and Amadei, 1993) that the magnitude and distribution of gravitational stresses in ridges and valleys depend on several factors, such as ridge and valley geometry, orientation of anisotropy with respect to ridge and valley axes, and the degree of rock anisotropy defined by the ratios of elastic constants.

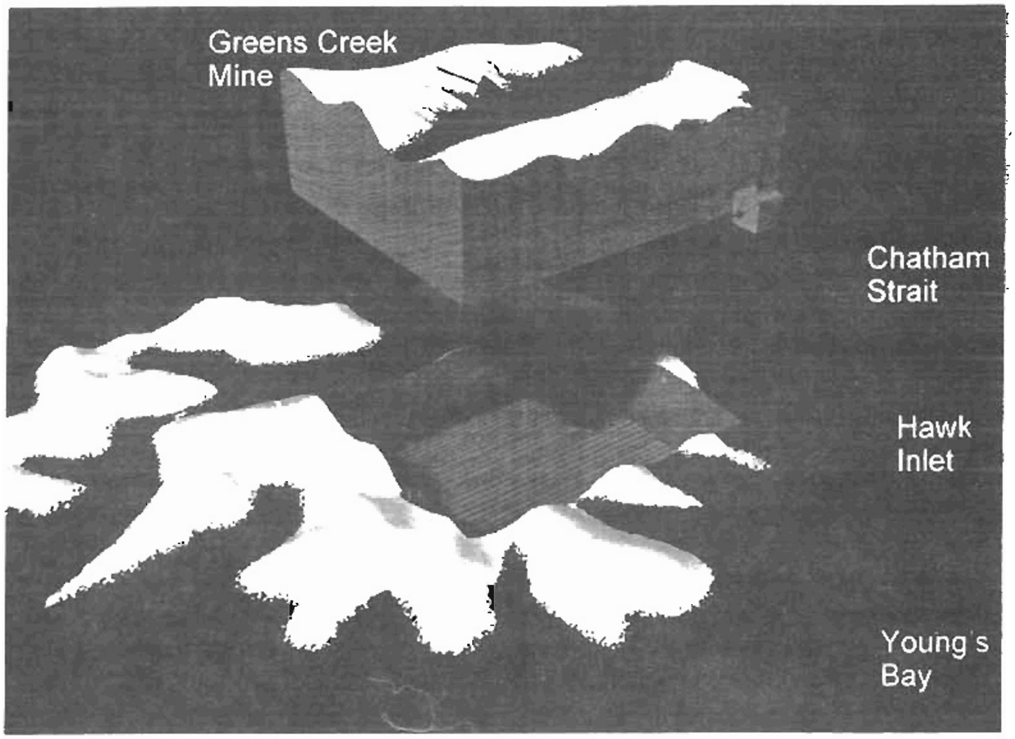
Of particular significance for analysis of mining methods in mountainous topography, such as that at the Greens Creek Mine, is an assessment of the regional stress field. Stress and displacement distributions are needed to conduct mine-scale analyses to evaluate subsidence, mining methods, development stability, and backfill efficiency. The presumption is that principal stresses are no longer lithostatic (i.e., vertical and horizontal) when the ground surface is not level. At or near ground surface, the principal stresses are normal and parallel with the topography.

An initial assessment of the stress and displacement field underlying the Greens Creek valley was conducted. A topographic model was used to determine in situ stresses and generate boundary conditions for detailed submodels of various parts of the Greens Creek Mine. The analytical procedure for the topographic stress model involved first selecting elevation points from a U.S. Geological Survey topographic map to define geographical information, such as mountain peaks and streams. To benefit from the symmetry of the region, boundaries were selected along ridge lines at higher elevations and across valley floors with gentle slopes. This information was then input into a database, and a three-dimensional surface mapping program was used to generate the composite topographic visualization model shown in figure 5. This figure illustrates the relationship between vertical and horizontal stresses. The portal of the 920 haulage level is located near the tip of the arrow on the surface of the "extracted" block and extends nearly 1,524 m (5,000 ft) into the mountainside to the south-southeast.

The lateral extent of the initial three-dimensional model is about 6 km (4 miles) east-west and 5.6 km (3.5 miles) north-south, extending from about 330 m (1,000 ft) below sea level to nearly 1,524 m (5,000 ft) above sea level at the northeast corner of the block. The topographic model fills a uniform grid of approximately 1,000 elevation data points with evenly spaced x, y, and z coordinates. A spreadsheet program was used to manipulate these coordinate data and convert x, y, z data into commands for structural analysis. A three-dimensional topographic supermodel represented a rock volume of approximately 63 km^3 (15 cubic miles). Material property input was based on the rock quality assessment conducted by Kennecott's consultant, according to the relationship $E_{mean} \cong 25 \log \sigma$, where E is the average deformation modulus and σ is the rock mass quality (Barton and others, 1980).

The mesh for the topographic model shown in figure 6*A* contains 5,000 elements. The three-dimensional stress distribution extends over a 6.2- by 7-km (3.5- by 4-mile) area. The northwest corner is removed to show lateral stress distribution in the north-south direction at approximately sea level. Surface stress appears to increase in areas of rapid elevation change, probably because of element averaging errors. A finer mesh would correct these minor deficiencies, but the overall distribution is considered accurate. Figure 6*B* shows a vertical north-south section through the mine along strike of the vein. Current mining is taking place on section 28, which is shown by the arrow. The three-dimensional stress distribution from this "intact rock" model shows the vertical stress ranging from near 0 at the 920 portal to over

Figure 5



Elevated composite view of topographic model, looking south-southwest, with three-dimensional stress cube.

12 MPa (1,700 psi) near the end of the level. Vertical stress increases linearly as depth of overburden increases, as expected. If the mine were to extend further into the mountainside, it would be subject to significant vertical stress from the effects of the nearby peaks.

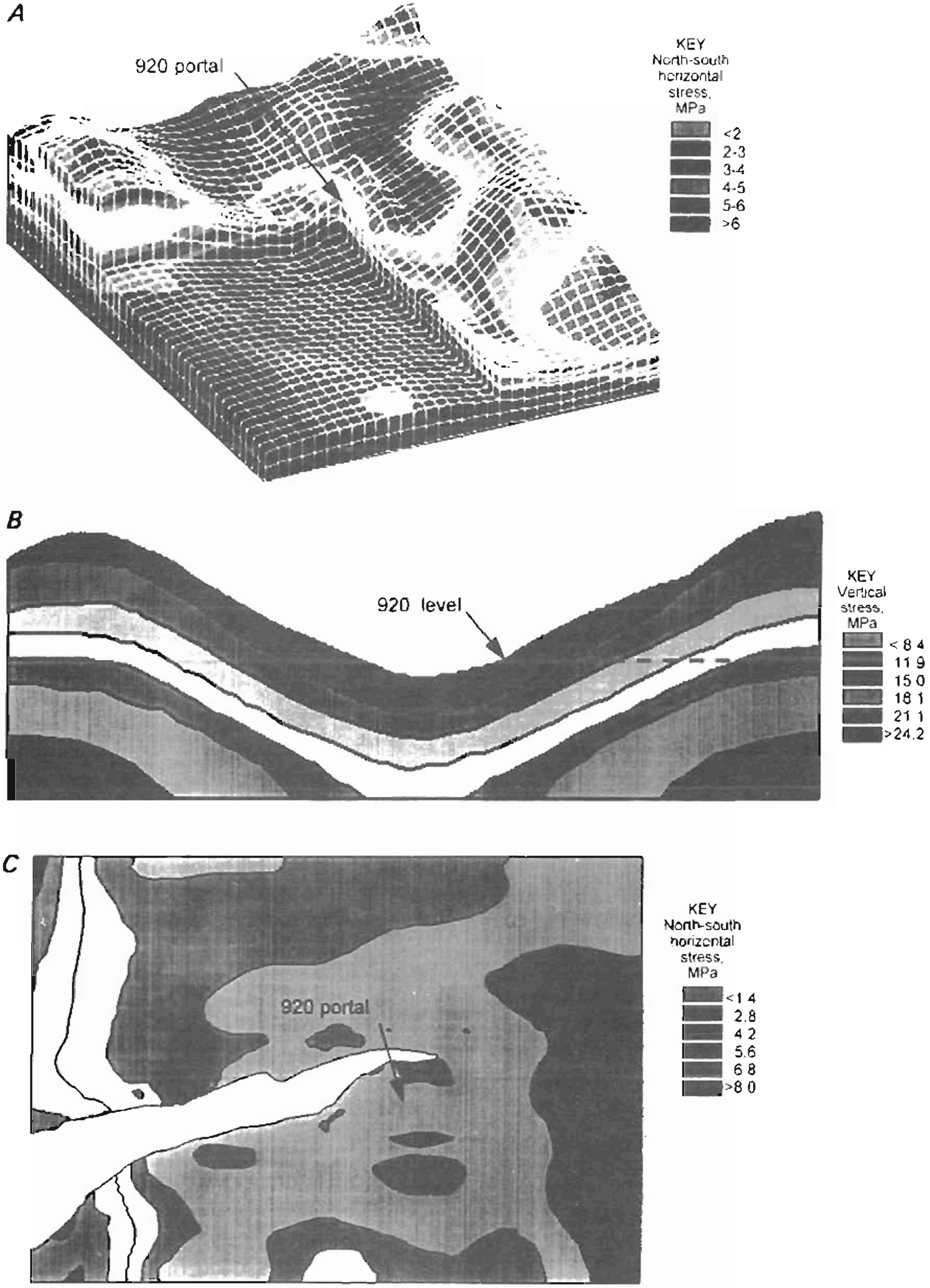
The horizontal stress is perhaps more significant for design purposes because the orientation of the development and mining openings can be optimized. Figure 6C shows the north-south horizontal stress distribution extending over the 6.2- by 7-km (3.5- by 4-mile) area. At the 920 elevation, the horizontal distribution is generally two times as large in the north-south direction as it is in the east-west direction. This is because of the rapid change in elevation north-south as compared with east-west.

MINING-INDUCED DISPLACEMENTS

The large scale of the topographic regional stress model prohibited direct analysis of the haulage levels or the effects of mining. A two-dimensional section along approximately the 28-00N mining section was modeled to determine the effects of mining and backfilling on critical openings, such as the 920 haulage level, to evaluate mine design variables, such as pillar size and mine sequencing, and to verify extensometer measurements at the diamond drill station on the 29 incline. It was assumed that, in this section, the vein structure persisted along strike, with no deviation in dip or geometry. In addition, the upper and lower limbs of the vein were eliminated to simplify the problem. Hanging wall phyllites were assigned an average modulus of deformation E equaling 14 GPa (2×10^6 psi), footwall argillite equaling 7 GPa (1×10^6 psi), and backfill equaling 1,400 MPa (0.2×10^6 psi). A gravity load of nonuniform horizontal stresses was assumed, based on results from the regional stress analysis.

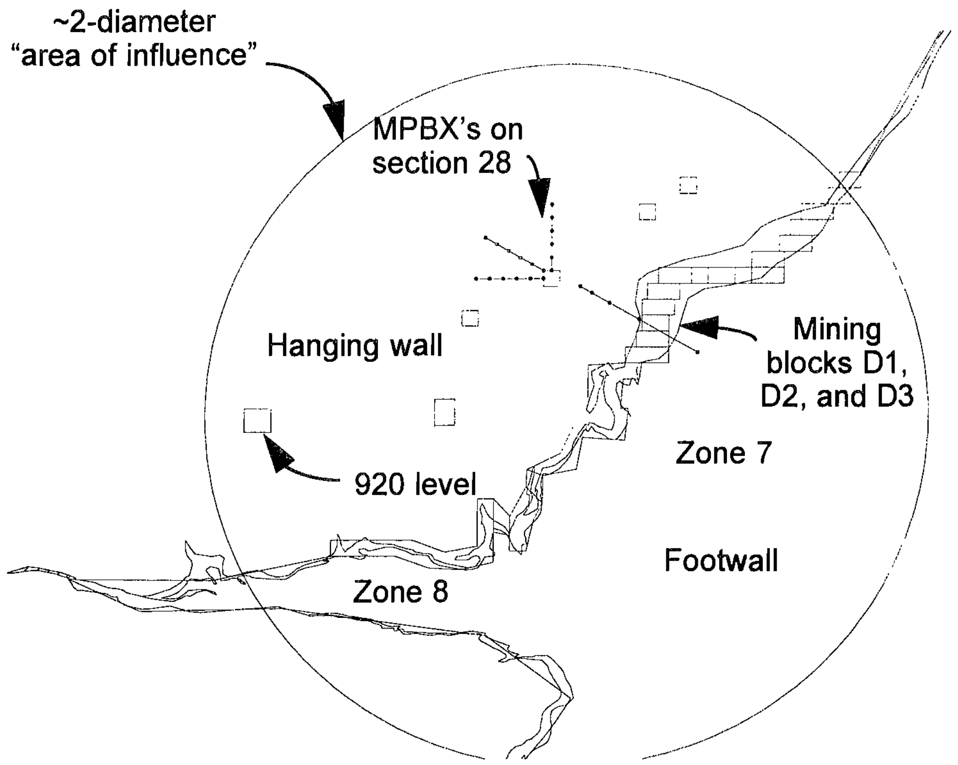
Figure 7 shows the mining zones on section 28 with mining and backfilling sequences approaching and passing the instrumented section. The model simulated the approximate boundaries of the vein structure, the hanging wall phyllites, and the footwall argillites, all of which required different material properties. The model was bounded 183 m (600 ft) from the centroid of the vein on either side (figure 7). The lower boundary lay about 457 m (1,500 ft) below the surface and extended 165 m

Figure 6



Computer model results showing stress distribution. A. Three-dimensional view of horizontal stress, north-south direction, looking southeast; B, elevated view looking east on north-south section along strike of vein; C, plan view of north-south stress distribution with north to top.

Figure 7



Mining blocks and locations of multipoint extensometers (MPBX's) in section 28, looking north.

(500 ft) below the 920 main level. Figure 8 is a closeup view of the resultant mesh for the vein and 920 level.

The model required multiple load steps to simulate mining and backfilling. Table 1 shows the relationship between computed load steps, plotted load steps, and actual mining and backfilling sequences. Twenty-one load steps were taken and computed up through mining block F3.

Three-meter (ten-foot) mining cuts were simulated and backfill properties were assigned on the basis of cemented fill moduli. Mining load steps were initialized to the cumulative effects of the intact rock mass, the development of premining accessways, and previous mining in zone 8 (load steps 1 through 4). The first load step established body strains caused by the boundary conditions and initial geometry. Additional load steps, including excavation and backfilling sequences, established the displacement and stress history for the stopes and development levels completed prior to excavation of block D1. Elements simulating backfill were coupled to rock elements only after displacements caused by excavation were determined. Thus, the backfill was affected only by that increment of displacement occurring after it was placed and was initially stress free.

Figure 9*A* shows safety factors based on the average nodal stress and uniaxial compressive strength around the 29 incline and stopes on section 28 after the accessways had been excavated and prior to mining (load step 2). The tensile component in the floor and back, indicated by a safety factor <1 (lightest color on scale), is significant relative to rock tensile strength. Figure 9*B* shows the same view after block E4 (load step 17) was mined. Note the high safety factors in the hanging wall and the relatively low safety factor in the footwall. In addition, there was a translation of the maximum stress direction aligned normal to the plane of the hanging wall. The displacement vectors in figure 9*C* show direction and velocities of displacement change for this load step. The 29 incline flexes in response to mining and filling blocks F1, E1, and G1 and mining blocks D3 through G2. Overall results show that mining-induced displacements in the 29 incline accessway were very small, on the order of a few micrometers.

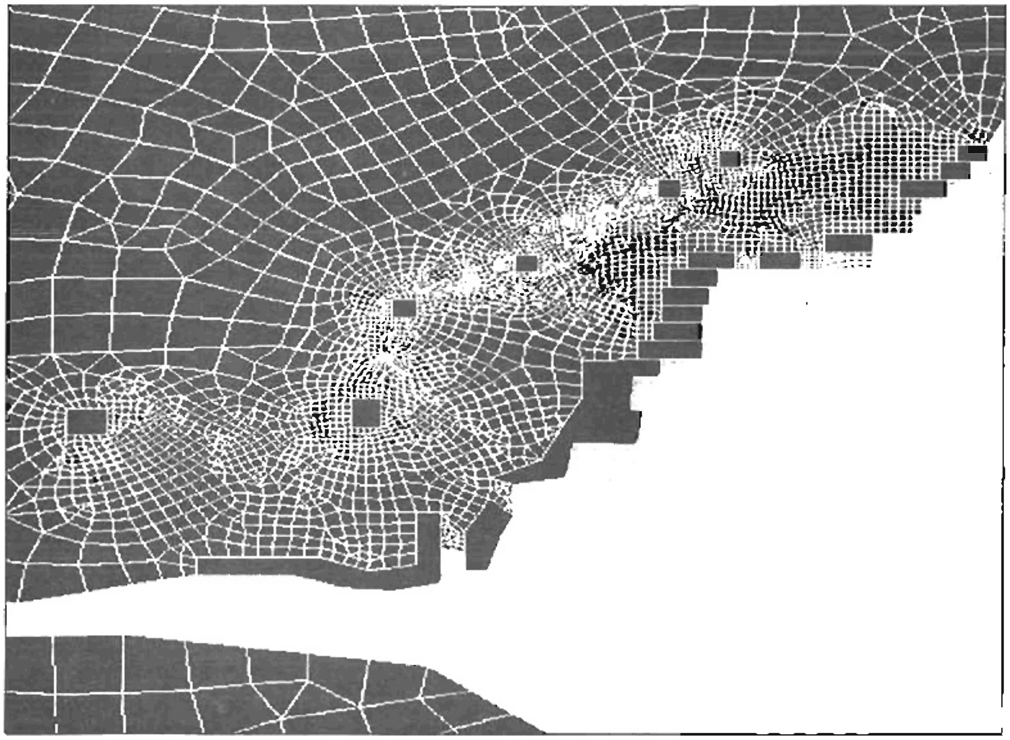
These magnitudes were verified by multipoint extensometers in the drill station in the 29 incline. Figure 10 compares the measured and computed results for hole 2, oriented normal to the vein through nine load steps, which includes six mining cuts after installation of the instruments prior to excavation of block D2. All extensometers

Table 1.—Computed and plotted load steps in relation to mining and backfilling

Computed load step	Plotted load step	Extraction sequence	Backfill sequence
1		Intact rock.	
2		Accessways.	
3		Previous mining.	
4			Previous backfill.
5	1	D1.	
6			D1.
7	2	D2, F1.	
8			D2, F1.
9	3	E1, G1.	
10			E1, G1.
11	4	D3.	
12			D3.
13	5	E2, G2.	
14			E2, G2.
15	6	H1, E3, G3.	
16			H1, E3, G3.
17	7	F2, H2, E4.	
18			F2, H2, E4.
19	8	E5, I1.	
20			E5, I1.
21	9	F3.	

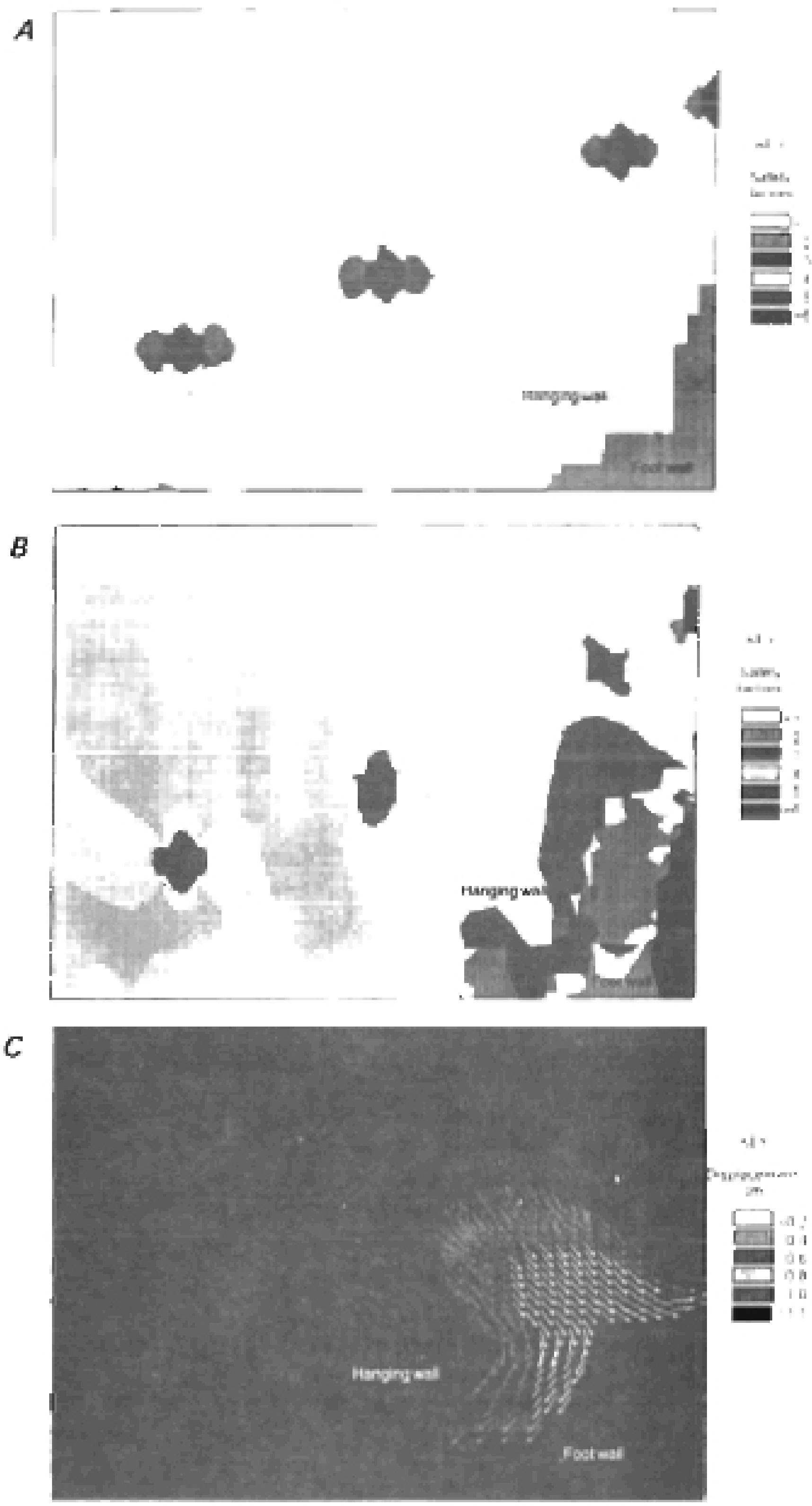
Note.—Alphanumeric designations indicate mining blocks.

Figure 8



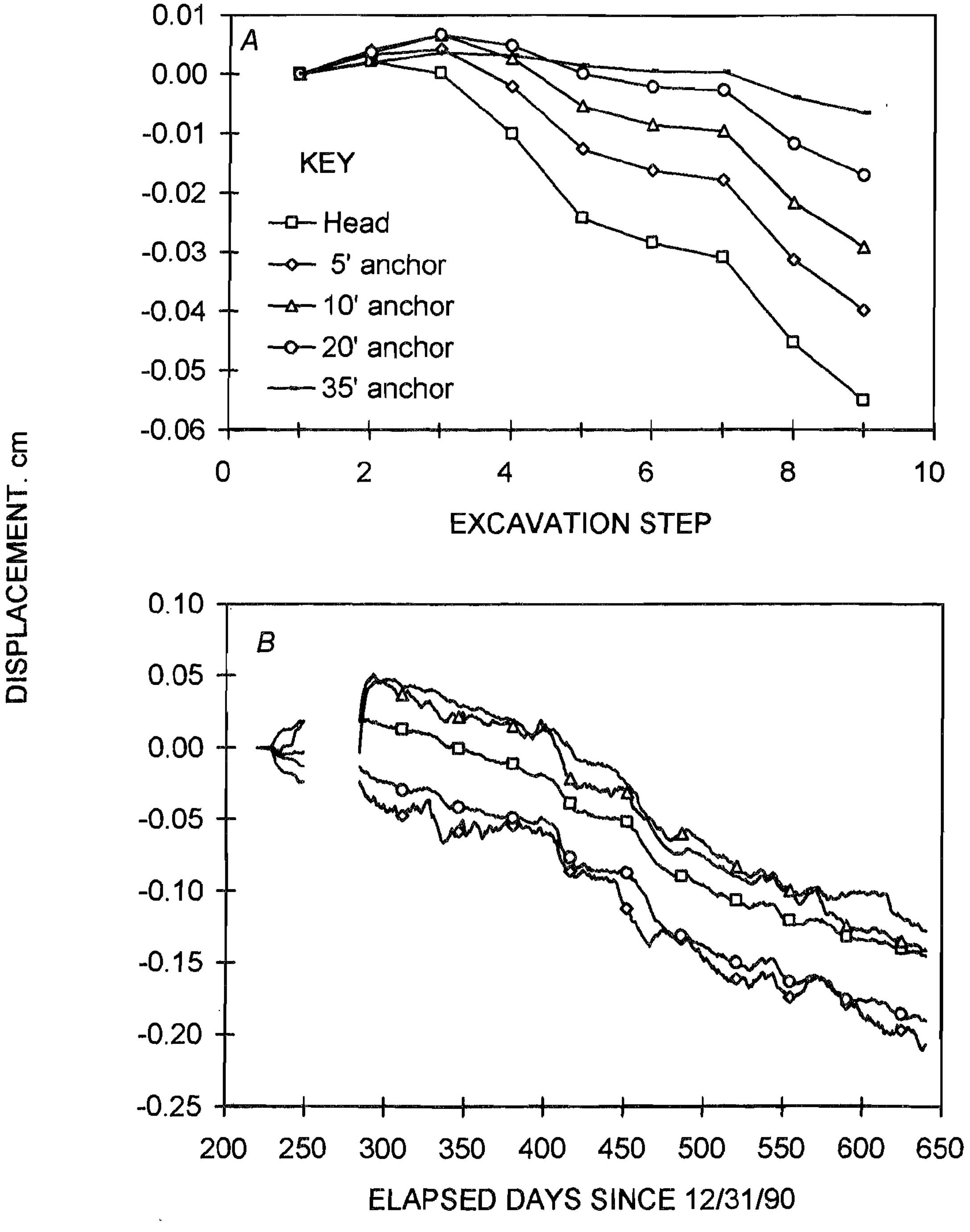
Closeup of mesh for vein and 920 level, section 28. Black rectangular shapes indicate excavation of accessways and stopes shown in figure 7.

Figure 9



Safety factors around 29 incline (black) and mining blocks, ***looking*** *north:* ***A,*** *Prior to mining; B, after mining block E4; C, displacement* ***vectors af-ter*** *mining block E4.*

Figure 10



Comparison of calculated (A) and measured (B) response to mining, hole 2, oriented normal to vein in hanging wall through nine load steps.

showed a direct response to excavation with no apparent time effects. Both the computed and measured response showed the abutment load approaching the extensometers. Computed magnitudes were about three times lower than measured magnitudes. As mining continued laterally from the instrumented section and new mining blocks were developed upward, the rock mass trended toward a compressive flexural mode of displacement. As mining stopped, the rock mass stabilized, confirming that very little creep or plasticity occurred.

SUBSIDENCE

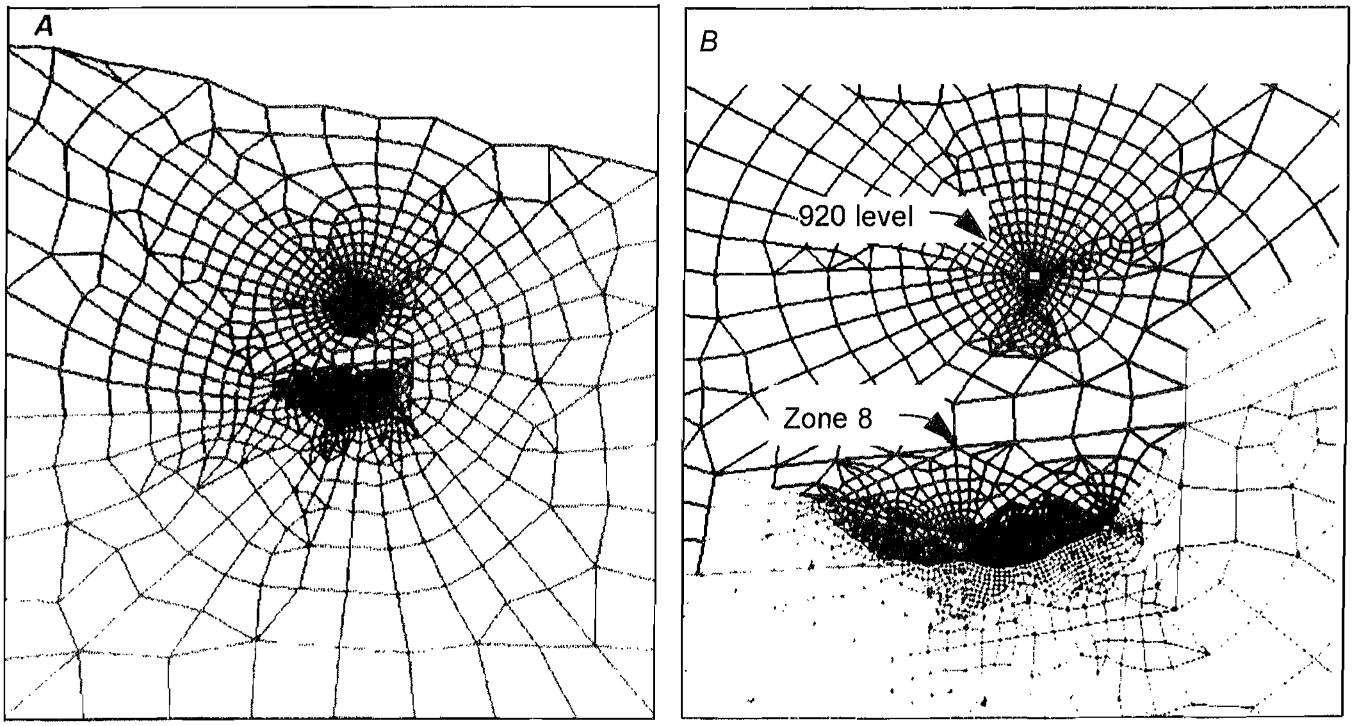
Surface subsidence caused by undermining can have severe consequences for mine production as well as environmental impacts. Possibly no other stability problem has such an immediate visual impact. Once subsidence has been initiated, it is difficult to control and nearly impossible to remediate. However, subsidence can be minimized initially and eliminated by proper mine design and practices. A recent study in the South African Witwatersrand District (Stacey and others, 1990) showed that "surface subsidence can be up to 40 percent of the total stoped-out width, although 0 to 10 percent is more likely."

Subsidence resulting from undermining depends on the physical properties of the rock mass, use of backfill and pillars, proximity of mining to the surface, geologic discontinuities, and mining sequences. A preliminary two-dimensional model of section 28 was generated on the basis of boundary conditions determined from the stress field supermodel. Three separate scenarios were considered: total removal of the vein without backfilling, pillar removal and subsequent backfilling, and alternating 3-m (10-ft) pillars. The model mesh contains over 8,000 elements (figure 11*A*). Near the center of the model, a single void represents the gross structure of the major vein areas. The ore body is represented as a single tabular feature and the 920 haulage level as a rectangular tube in the blown-up mesh in figure 11*B*. This simplification requires that the vein be analyzed as having a constant dip over some distance, a constant thickness with no undulations in the plane of the vein, and no variation in material properties.

Physical properties and stress conditions were the same as used in the mining model, with zone 8 and zone 7, blocks D1 and D2, being 100 pct mined and filled. For this analysis, the material was removed in a single mining step without backfill or support. This is a very conservative approach and does not include the fact that backfill and support pillars are part of the mining method as well as primary support.

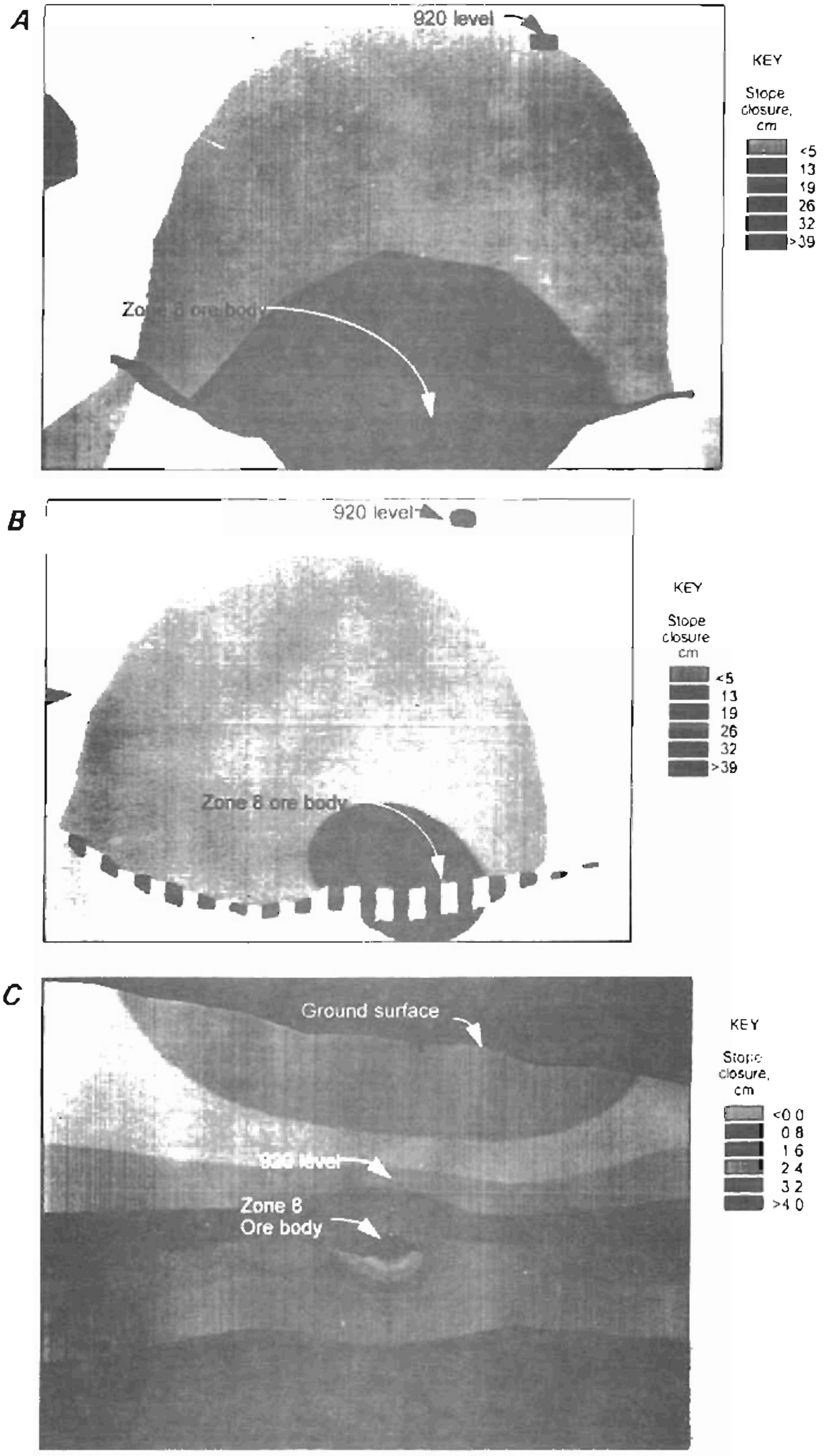
Removing the total ore body without backfilling or leaving remnant pillars caused total stope closure exceeding 38 cm (15 in) and resulting surface displacement exceeding 10 cm (4 in) (figure 12*A*). Most of the displacement was aligned normal to the centerline, and the

Figure 11



Subsidence model of section 28. A, Model mesh of entire section; B, ore body and 920 level.

Figure 12



Displacement contours on section 28, looking north. A, Stope closure without stope filling or remnant pillars; B, alternating 3-m (10-ft) mine cuts with pillars intact; C, recovery of remnant pillars and introduction of backfill.

footwall came up more than the hanging wall deflected downward. A cone of depression could be expected to develop on the surface directly over the stope. In contrast, stope closure and subsidence were significantly reduced in the pillar and backfill models. Removing alternating 3-m (10-ft) slices but leaving the pillars intact yielded a decrease in total closure by approximately an order of magnitude (figure 12*B*). Removing remnant pillars and introducing backfill allowed 30 pct more closure than leaving remnant pillars but not adding backfill (figure 12*C*). The vertical displacement field at the surface 470 m (1,400 ft) away deflected down about 2.5 cm (1 in) and extended about five times the width of the stope [approximately 200 m (660 ft)]. The maximum closure was limited to areas between the fill where the remnant pillars had been mined, leaving a void. This model assumed that the fill was placed tight to the hanging wall and developed a no-slip interface.

DISCUSSION

Underground mine design in environmentally sensitive regions such as Alaska must consider local mining-induced stress and displacement instabilities at stope scale as well as regional in situ effects of mountainous topography. Computer modeling and simulation provide a useful alternative to trial-and-error approaches to mine design and can be used to evaluate many of the factors affecting mine stability and surface subsidence. This case study showed the effects from overlying mountainous topography and mining geometry and sequence.

Preliminary results of two- and three-dimensional modeling indicated considerable amounts of stress deviation from what would be expected from simple depth-of-overburden calculations. Even though the mine is not under a significant amount of overburden, the nearby mountains exert considerable influence. The vertical stress in the vicinity of the mine could approach 28 MPa (4,000 psi) in the deepest areas in the southwest quadrant. Although the magnitude of stress is small, particularly in lateral extent, it is significant in the area of the mine because of the low strength of the rock mass, particularly the footwall argillites. The large ratio between horizontal stresses and vertical stresses could cause significant stress concentrations and instability to develop. Vertical stress generally follows the overlying topography, but horizontal components vary by a 2:1 ratio. In addition, there are surprising variations in horizontal stress throughout the mine as determined from the three-dimensional topographic model. Mine development openings and stopes may be more unstable because of these stress variations, particularly within the weak argillitic rocks found along the vein-footwall contact. This instability is important because it affects mining and backfill practices and potential surface subsidence.

In the subsidence model, total vein removal resulted in vertical surface displacements exceeding 10 cm (4 in), as well as nonuniform displacements around the opening at the 920 haulage level. Closure exceeded 38 cm (15 in) over a wide portion of the stope. The addition of pillars to the model resulted in a significant reduction in displacement magnitude and extent, reducing the total closure to less than 2.5 cm (1 in), limited to just the wide part of the vein near the footwall side and between pillars. The addition of fill and removal of the remnant pillars increased vertical displacement, but still considerably less than did total removal without backfill. The footwall was displaced upward considerably more than the hanging wall deflected because of the effects of weaker argillites in the footwall.

It must be emphasized that this initial assessment of the stress and subsidence field at Greens Creek is highly simplified. In particular, the effects of geology, both on a large scale (such as the tectonic influence of the Queen Charlotte fault zone) and local effects (such as strike-slip planes and joints) have not been fully considered in the analysis. Also, ultimate stability should be assessed in terms of an elastic-plastic rock mass behavioral model rather than an elastic one, such as was used here.

Use of the advanced analysis and simulation technology used in this study can have considerable benefits. The technology is applicable to many similar deposits where surface disturbance cannot be tolerated. Recent developments in this research have shown that generic computer design and simulation software can adequately model mining, geologic, hydrologic, and geochemical parameters. This finding makes it possible to visualize and assess initial mine design approaches for environmentally sensitive regions on a personal computer without the added cost and complexity of expensive hardware and specialized software.

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