STRUCTURAL STRESS AND CONCENTRATION OF MINING-INDUCED SEISMICITY

By J. K. Whyatt,[1] B. G. White,[2] and W. Blake[3]

ABSTRACT

In situ stress on the scale of a tunnel or mine may be distorted by geologic structures. The resulting variations of in situ stress have a direct bearing on the potential for mining-induced seismicity. New evidence from the Lucky Friday Mine collected by U.S. Bureau of Mines researchers, as well as a review of case studies, demonstrates that in situ stress variations affect the spatial distribution of mining-induced seismicity. Although overcore stress measurements have been useful in these studies, they are too expensive and, depending on conditions, may be too difficult to use routinely in mapping stress variations. However, information from borehole and raisebore breakouts; deformation of mine openings; and patterns of seismicity, ground-control problems, and rock-burst damage can be used to build a stress database. This database can then be used in conjunction with maps of mine structure and geology and models of rock mass behavior to build a map of in situ stress variations. Such a map provides a means to anticipate patterns of mining-induced seismicity that are likely to be encountered and, hence, provide a means for planning appropriate measures to ameliorate rock-burst hazards.

INTRODUCTION

Rock bursts constitute a serious ground-control problem in many mines, particularly the deep mines of the Coeur d'Alene Mining District of northern Idaho. The research described here was undertaken by the U.S. Bureau of Mines (USBM) as part of its effort to protect miners from ground control hazards. Protecting miners while preserving the economic viability of seismically active mines requires efficient employment of rock-burst countermeasures, including enhanced ground-control systems, preconditioning, and use of alternative mining methods.

It is well known that mining-induced seismicity is affected by stress magnitude. The pattern of induced stress developed in the vicinity of mine openings has been studied extensively and has provided the basis for improvements in mining methods and sequences. However, mine seismicity often clusters in ways that cannot be explained by mining-induced stress alone.

Because stress is a key factor in determining the intensity of mining-induced seismicity, it appeared likely that some of this clustering was related to natural variations in stress associated with geologic structures. Structural redistribution of stress creates concentrations of stored elastic energy that may drive seismic rock mass failure. As mine excavations approach a structure where stress is concentrated, mining-induced magnification of stress levels hastens loading of intact rock, pillars, and faults to the point of failure.

In situ stress is generally considered to be a primary factor in determining rock mass response to mining and is normally thought of as a uniform rock mass condition. However, solid mechanisms require that, as William Pariseau noted (1994), "loading of a heterogeneous material leads to a heterogeneous stress field." For

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instance, Brady and others (1986) argue that the episodes of tectonic and gravitational loading, fracturing, unloading, heating, cooling, water infusion, drainage, and drying that have occurred in most rock masses preclude a homogeneous stress field. Each of these physicochemical processes is capable of generating a highly heterogeneous stress state in a rock mass. Brady and others also infer that stresses associated with current tectonic processes will dominate the current stress state.

Fairhurst (1986, p. 5) emphasizes the role of rock mass failure in the following argument for presuming variability in natural in situ stress:

> The existence throughout the earth's crust of faults, folds, and fractures in geological structures that have not totally disintegrated clearly indicates that stable redistribution of loads and stresses, and hence heterogeneity of stress distribution, is a pervasive feature in rock masses. Given the usual inhomogeneities, such as folded and faulted rock formations of differing compressibility, and discontinuities, such as faults, joints, bedding planes, it is clear that the in situ gradational and tectonic forces will be distributed more or less nonuniformly through the rock mass.

The critical element of Fairhurst's argument is the stiff or "nonfollowing" nature of the forces that drive disintegration or slip (in the case of rock masses, with joints or discontinuities) within rock masses at depth. That is, unlike many artificial structures, the "essentially infinite" outer boundary of a rock mass ensures the opportunity for the forces to be redistributed from disintegrating or slipping regions into other regions that can sustain these forces. In this case, the disintegrating or slipping rock unloads as it deforms and hence will not disintegrate fully but will stabilize with some residual strength.

Empirical evidence of stress variations associated with geologic structures has been widely reported. Regional, continental, and world-wide patterns of stress have been the subject of considerable study (e.g., world stress - Zoback, 1992; stress in North America - Zoback and Zoback, 1989; stress in Europe - Muller and others, 1992; stress in China - Zhorghuai and others, 1992). Moreover, a number of case studies have documented mine-scale and smaller structural stress variations, some of which have been associated with rock bursts. A selection of these case studies is reviewed in this paper.

Recent advances in rock mechanics and computing power have greatly increased the precision with which the evolution of mining-induced stress fields can be followed over the life of a mine. The ability of numerical models to track a rock mass through significant periods of geologic time, however, is primitive. The controlling variables, especially load history and long-term (geologic) rock mass properties, are difficult to estimate. This factor led Budavari (1983) to conclude that—

> Neither tectonic nor residual stresses lend themselves to analytical treatment. Consequently, their magnitudes are impossible to predict even to a fair degree of certainty without the measurement of in situ stress. In order to obtain a reasonable knowledge of the state of the virgin stress in a region, one must be familiar with its geology, collect and analyze the results of previous stress measurements, and observe the effects of natural stresses on existing structures in rock.

However, some insight into patterns of stress variation can be gained by studying the numerous instances of natural stress variation that have been reported in the literature. This USBM paper describes an investigation of natural stress variations associated with geological structures and the resulting spatial distribution of mining-induced seismicity. A case is made for using geologic information, mine observations, and simple mechanical models to recognize stress variations in operating mines and to apply this knowledge to the design of mine geometry, mining method, mining sequence, and ground-control systems.

INVESTIGATION OF STRUCTURAL STRESS

The greatest obstacle to mapping structural stress distributions in a mine is obtaining sufficient baseline information. As a practical matter, the expense of obtaining in situ stress measurements precludes building stress maps from measurements alone. In this study, direct measurements of in situ stress are supplemented with observations of rock mass conditions and structures indicative of the pattern of in situ stress variation. Various sources of in situ stress information are described in this section. Interpretation of stress patterns with simple mechanical models is described in the following section.

An investigation of in situ stress at the Lucky Friday Mine (Coeur d'Alene Mining District, Idaho) is used to illustrate this procedure. This investigation began with a simple goal: improve in situ stress estimates to support a numerical model of an experimental stope. However, an overcore measurement collected to provide this improvement was at odds with all previous work involving stress field characteristics in this mine. Additional information was needed to confirm and bound this anomalous stress measurement and support investigations of the underlying structural stress mechanisms.

REGIONAL TECTONIC SETTING

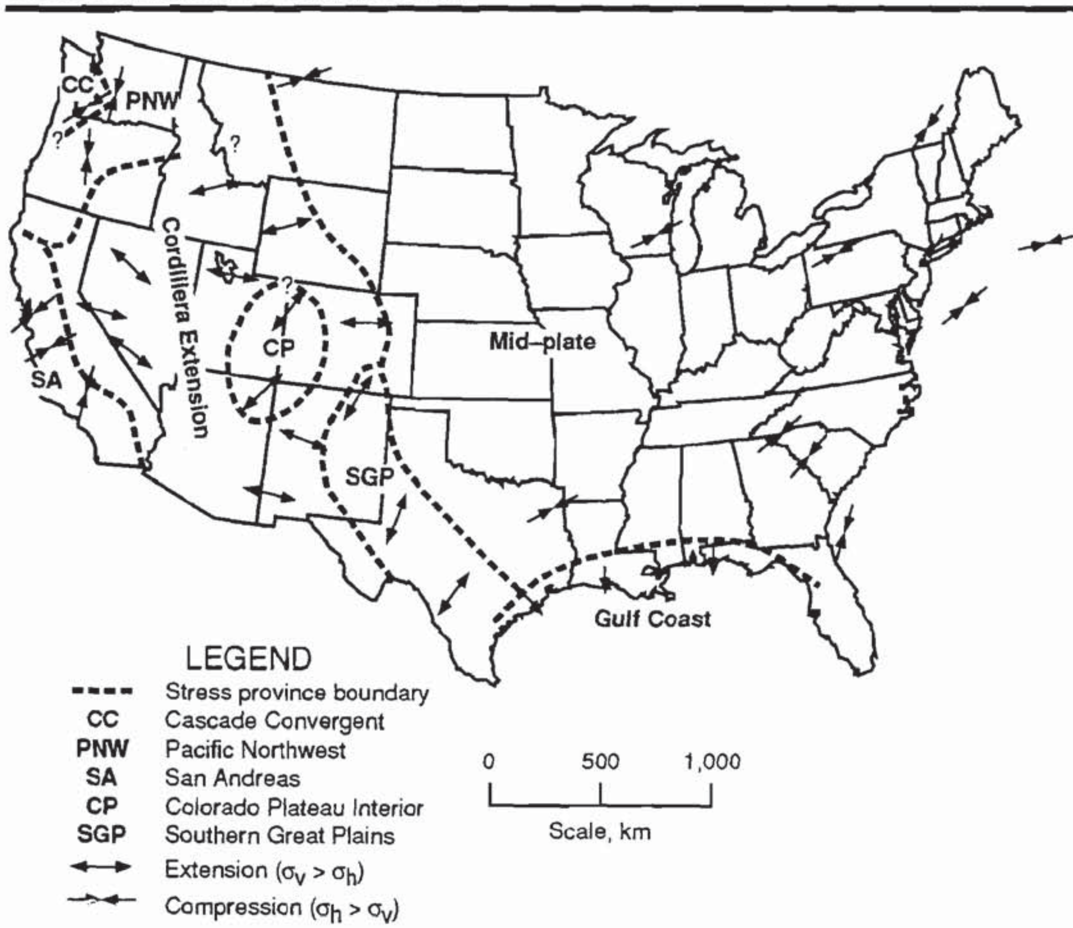
Knowledge of regional geology and tectonic loading provides a foundation for studying local stress fields. Tectonic stresses extend over large areas (hundreds of square kilometers) and have been well mapped for the continental United States (figure 1). However, Cuisiat and Haimson (1993) note that local stresses can differ from regional stresses as a result of topographic relief, rock structure (faults, folds, or joints), or changes in rock properties. They estimate the extent of these stress perturbations to be as large as several square kilometers. Thus, while a region may be characterized by a well-documented state of stress, stress on the scale of a mine, or a part of a mine, may be quite different.

The Coeur d'Alene district lies within the Lewis and Clark line (figure 2), a major tectonic lineament that has undergone right-lateral slip, indicating a northwest orientation of maximum principal stress. This orientation has been generally confirmed by other indications of stress direction (Hobbs and others, 1965; Skinner and others, 1974). [On the other hand, Zoback and Zoback (1989) place a question mark in this area on their tectonic map of North America (figure 1).]

GEOLOGIC MAPPING AND ANALYSIS

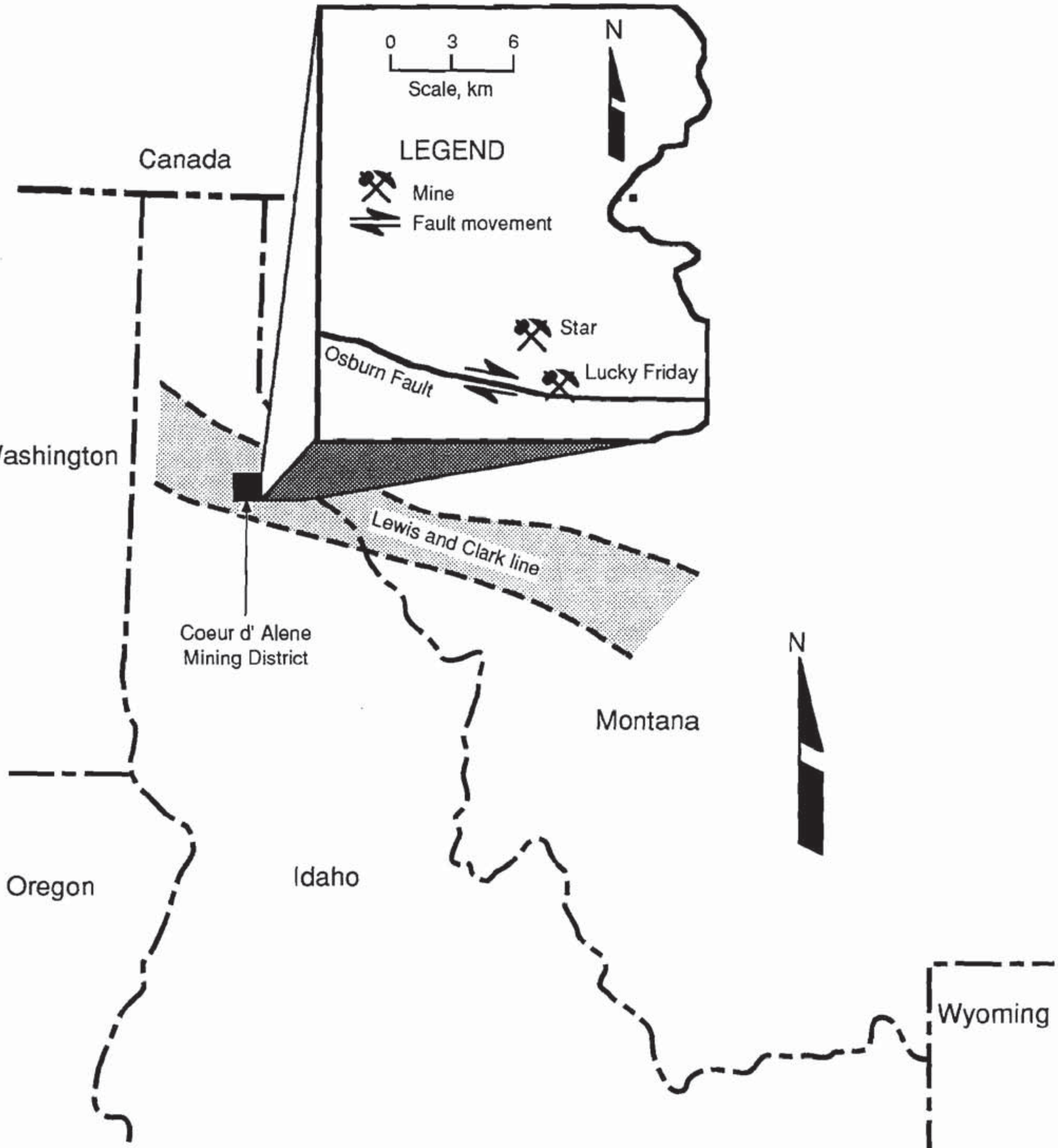
A good understanding of rock structure and the relative mechanical properties of rock mass elements is essential to any study of structural stresses. Some geologic features relevant to rock bursts are only observable on a

Figure 1
Stress Provinces of United States.



σ_v = **Vertical stress.** σ_h = **Horizontal stress. (After Zoback and Zoback, 1989.)**

Figure 2
Lucky Friday Mine and Regional Geology.



microscopic scale. Examination of these small-scale features often aids understanding of rock mass behavior. However, most geologic information can be acquired through careful mine mapping at standard mapping scales. Proper interpretation and clear presentation of these features are keys to recognizing significant structural stress patterns and mechanisms.

Geologic mapping was a significant part of the Lucky Friday Mine investigation, and a number of features were mapped, including faults, folds, and stratigraphy. Rocks are predominately composed of quartz and fine-grained white mica, generally known as sericite in this region, and are classified into three major rock types according to relative sericite content. From sericite-rich to sericite-poor, these types are defined as siltite-argillite, sericitic quartzite, and vitreous quartzite. The strength, stiffness, and brittleness of the rock increases greatly as sericite content is reduced. The argillite-siltite beds are very weak, have a soapy feel, and occur in laminations ranging from millimeters to several centimeters thick. Sericitic quartzite beds are considerably more competent. Vitreous quartzite beds are extremely strong, stiff, and brittle.

Direct mapping of these beds, few of which are greater than a meter in thickness, produced complex geologic maps that were difficult to relate to large-scale rock mass behavior (figure 3). However, soft sericitic quartzite beds occur in clusters and are associated with thin, very soft, argillite-siltite beds. Hard vitreous quartzite beds also occur in clusters and are often joined by a relatively strong, fused interface. These natural groups of relatively hard and soft beds were used to define subunits 20 to 50 m thick. The result (figure 4) provided a much clearer picture of mine-scale variations in lithology.

OVERCORE MEASUREMENTS

Overcore measurements provide a full three-dimensional measure of principal stress magnitudes and directions at a specific location. Hydraulic fracturing can also be used to measure some stress components. These techniques are covered in most rock mechanics texts (e.g., Goodman, 1989; Jaeger and Cook, 1979), and standard test procedures have been published by the International Society for Rock Mechanics (1987). While useful, these measurements are generally too expensive for routine use in mapping of structural stress patterns. Rock mass conditions, including core discing, may also preclude use of some overcore cells altogether. However, conducting one or two measurements provides a valuable anchor for establishing stress magnitudes.

The Lucky Friday Mine investigation benefitted from three overcore measurements,[4] two of which were conducted during early development of this method. While the original analyses of the early measurements were largely valid, a detailed reanalysis improved the solutions and provided a look at small-scale stress variability. One site, on the 4250 level of the mine, straddled vitreous and sericitic subunits and provided a direct view of structural stress differences between hard and soft subunits (figure 5). A similar measurement on the 5300 level, located in a hard subunit near a fault, presented a puzzling stress rotation that became the motivating factor for much of this work. An adequate explanation of this anomalous rotation required much more information than the single overcore measurement could provide. In order to avoid the costs associated with additional overcore measurements, other sources of information were sought.

BREAKOUT MAPPING

In many cases, stress characteristics can be observed in the deformation of mine openings. Breakouts in boreholes, bored raises, and relatively equidimensional drifts can provide essential information on stress direction (figure 6). The use of breakouts to deduce stress orientation has been widely reported (e.g., Zoback and others, 1985) and is used in well bores. Similar routinely observations of rock deformation and failure have also been used to deduce the orientation of stresses in coal mines (Mucho and Mark, 1994). Any evidence of spatial variations in the existence or severity of ground control problems can also be instructive.

At the Lucky Friday Mine, several vertical bored raises and ore passes experienced breakouts that indicated the orientation of horizontal secondary principal stresses (figure 7). Stress directions in sericitic and vitreous subunits (figures 8 and 9, respectively) were generally in agreement. A breakout in a vitreous quartzite subunit near the 5300-level site confirmed the overcore stress rotation and bounded it to vitreous subunits near the 38/Offset Fault, considerably clarifying the problem.

SEISMICITY

The distribution of mining-induced seismicity is also a good indicator of structural stress conditions because

[4]This research by Whyatt and others will be published in a forthcoming series of USBM Reports of Investigations, of which the first (Whyatt and Beus, 1995) is now available.

Figure 3
Geologic Map Showing Closely Spaced Features at Lucky Friday Mine.

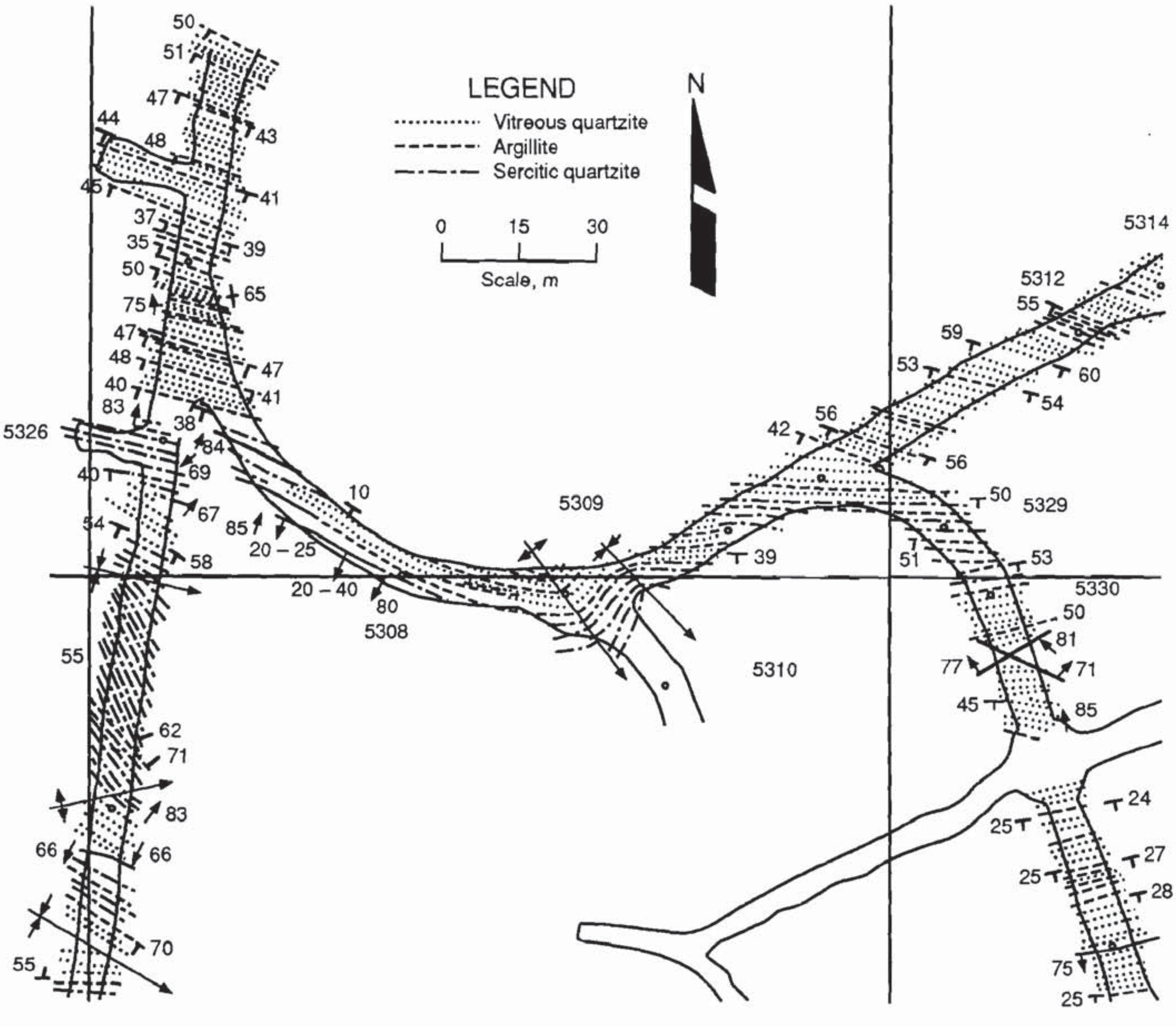
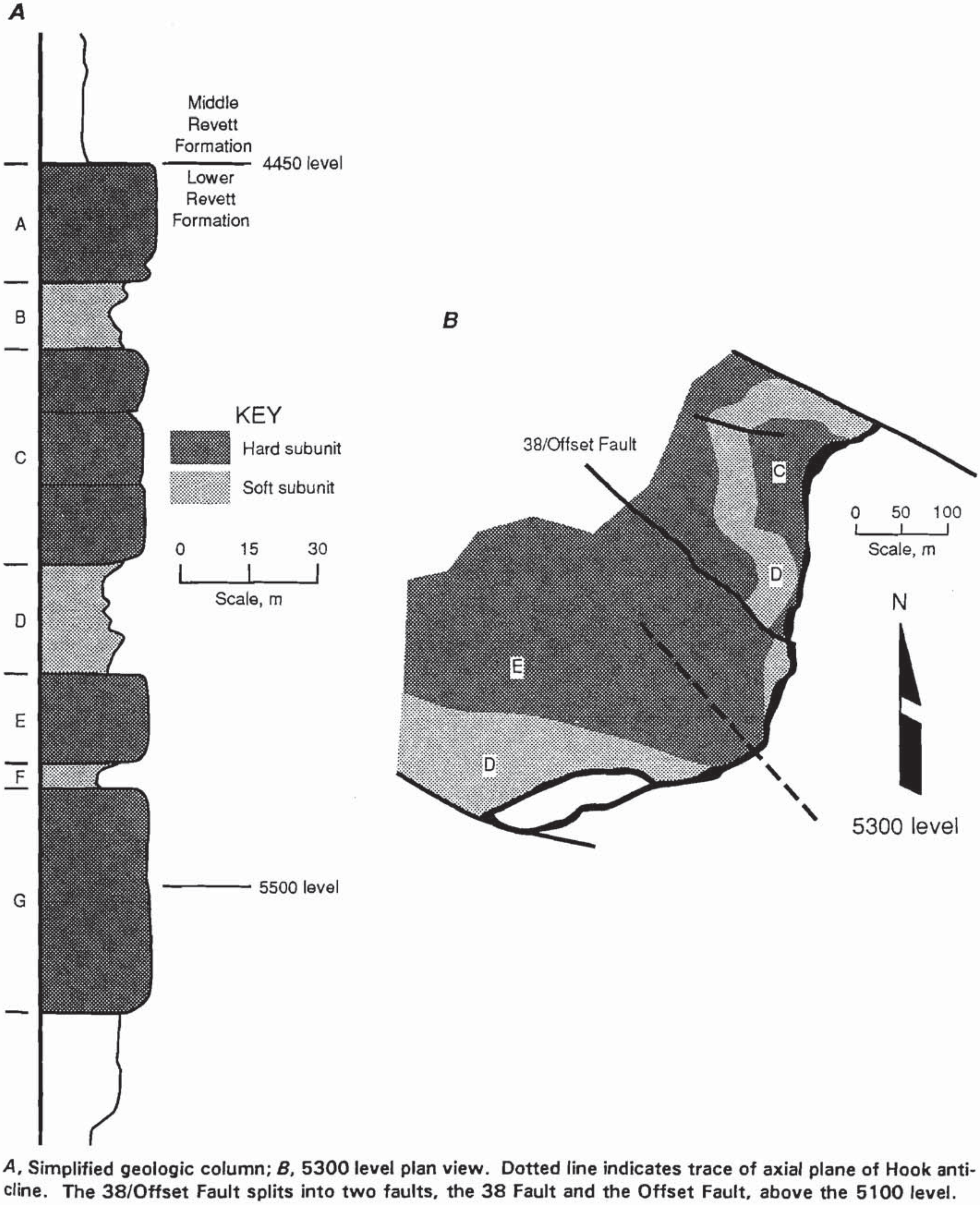
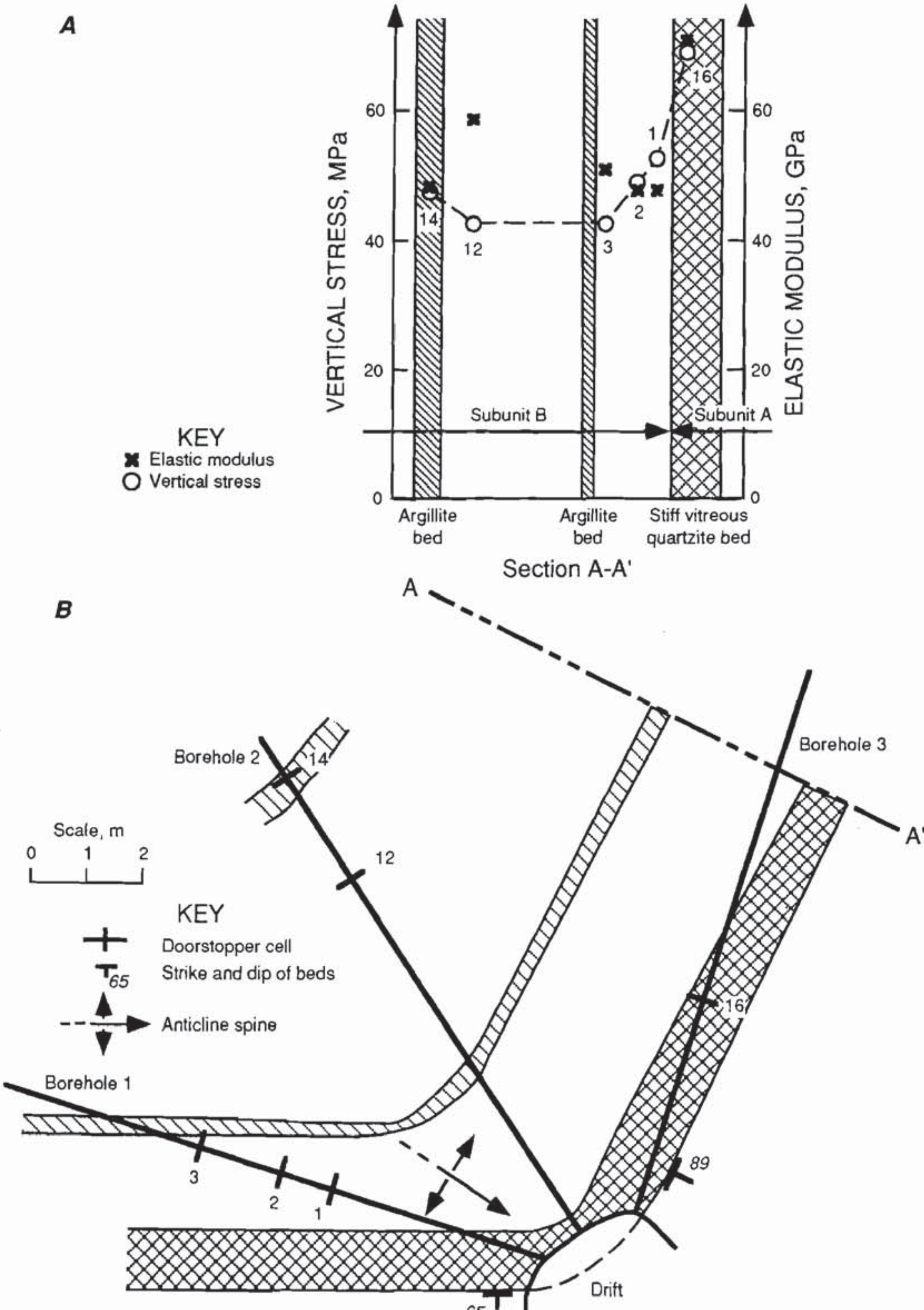


Figure 4
Geology of Lucky Friday Mine.



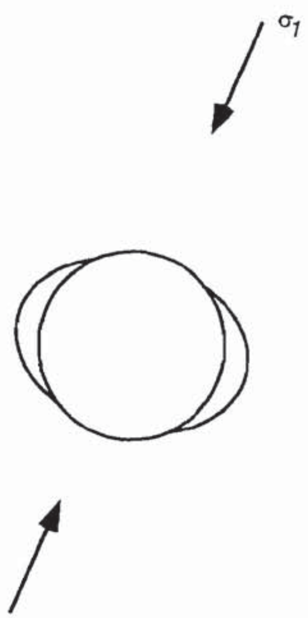
***A*, Simplified geologic column; *B*, 5300 level plan view. Dotted line indicates trace of axial plane of Hook anticline. The 38/Offset Fault splits into two faults, the 38 Fault and the Offset Fault, above the 5100 level.**

Figure 5
Stress Change Across Subunit Boundary Measured at 4250-Level Site, Lucky Friday Mine.



***A*, Vitreous quartzite is part of hard subunit A, while argillite and unmarked sericitic quartzite are part of soft subunit B. *B*, Vertical stress and elastic modulus plotted by stratigraphic location in an anticline at test site.**

Figure 6
Typical Breakout Pattern and Orientation of Maximum Stress (σ_1) in Plane Perpendicular to Opening.



seismicity generally results when a geologic structure is stressed to its limits. Seismicity is generally preferred to rock-burst damage for tracing structural stresses because rock-burst damage depends on many other factors, including ground support measures and local geologic structures. In mines with digital seismic monitoring systems, first-motion patterns of seismic events can also be measured. For slip events, a double-couple, first-motion pattern shows directions of lengthening and shortening consistent with local stress conditions.

Geologic factors clearly influence the occurrence of bursting in development openings at the Lucky Friday Mine and the adjacent Star Mine. Beds of massive vitreous quartzite have proven, in general, to be more burst-prone than the thin-bedded sericitic quartzite (e.g., Blake, 1987). However, not all massive quartzites have proven to be burst-prone, and damaging rock bursts in thin-bedded sericitic quartzite do occur.

At the Lucky Friday Mine, clusters of large seismic events and damaging rock bursts are routinely reported. Some of these clusters are clearly controlled by mining-induced stress (in pillars, etc.). However, other clusters occur in development openings far enough away from mining that natural stress concentrations are suspect. One such cluster was noted by mine staff in development openings and immediately east of the axial plane of the Hook anticline (figure 10), from the 5150 to the 5400 levels.

One of these rock bursts, documented by Williams and others (1992), indicated a direction of strike-slip movement that was clearly impossible in the regionally predominant in situ stress field. Evidence of the direction of strike-slip movement, including direct observations of slip offset in a ramp and a first-motion analysis of digitally recorded waveforms, indicated a local rotation of the maximum principal stress from a north-west to a west-southwest direction.

STRESS PATTERN INTERPRETATION

Developing descriptions of stress patterns likely to exist in common geologic structures is the next step in this mapping procedure. These patterns are used to extrapolate stress conditions in unmeasured portions of the rock mass from the stress database. In this section, structural stresses resulting from simple models including (1) regions of different elastic properties and (2) discontinuities are examined. Model conditions have been selected to provide a sample of simple structural stress mechanisms, but are not meant to be all-inclusive. These simple models are compared to a number of published case studies and Lucky Friday Mine stress information.

CONTRASTING ROCK PROPERTIES

One of the simplest and most common set of assumptions in developing numerical models is that the rock mass is initially unstressed, elastic, homogeneous, and subject to simple displacement or stress boundary conditions. This set of assumptions disregards the complex load and deformation history of the rock and considers only the elastic response of the rock to present tectonic loading. The ideal, unfractured rock mass responds to changes in load as if it were a continuum, and the resulting stresses and strains can be calculated with the tools of continuum

Figure 7
Bored Raises and Ore Passes, Lucky Friday Mine.

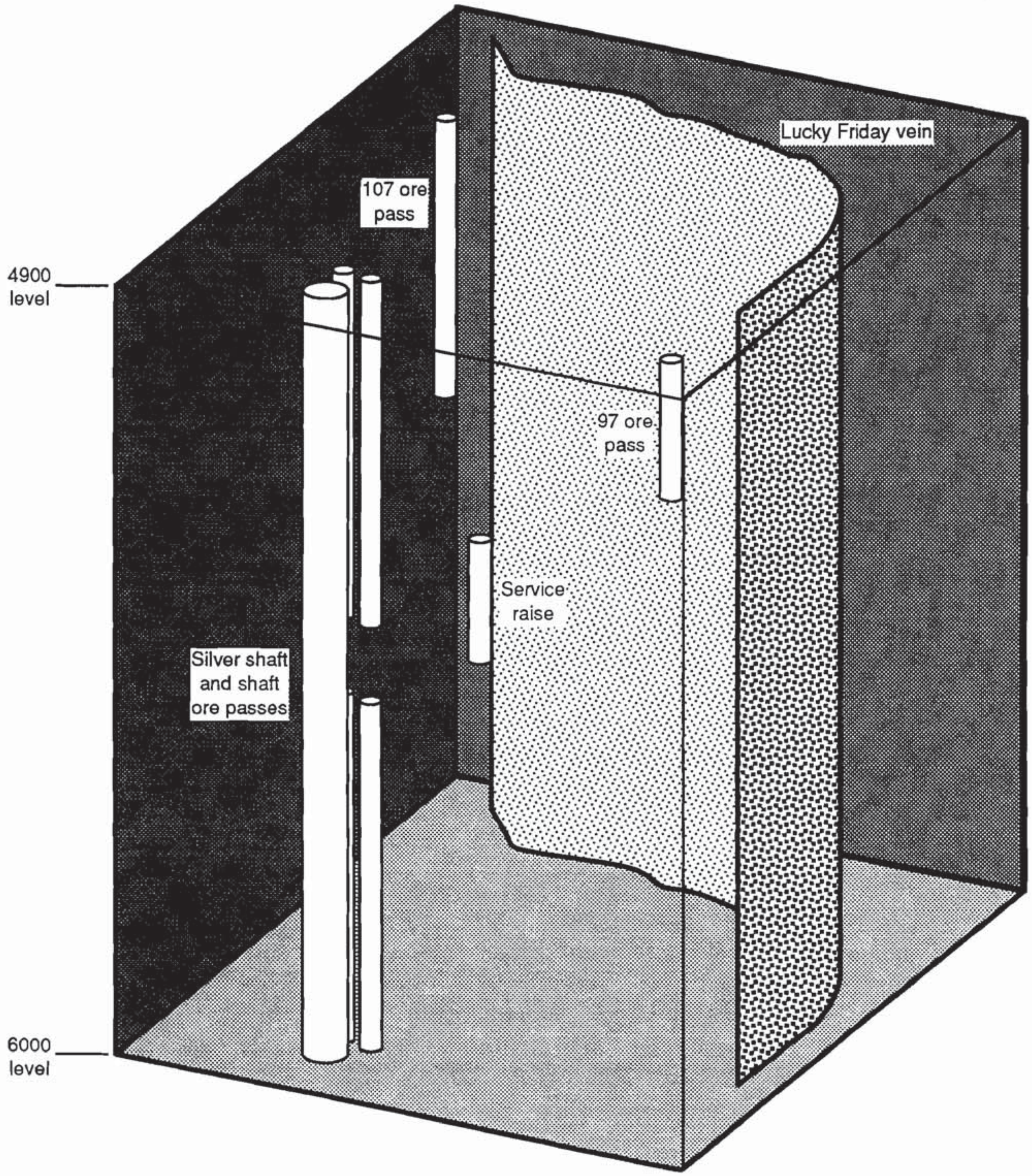


Figure 8
Horizontal Stress Orientation in Sericitic Quartzite Subunits On and Around 5300 Level, Lucky Friday Mine.

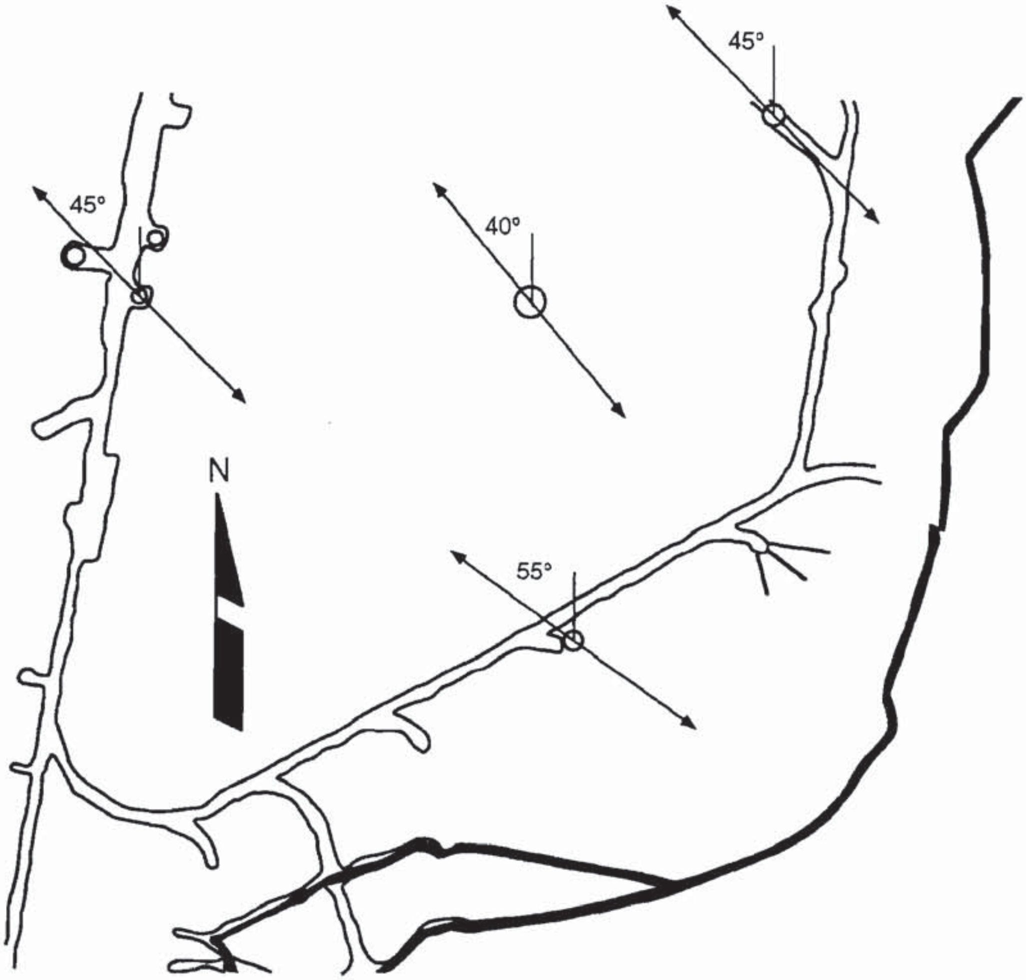


Figure 9
Horizontal Stress Orientation in Vitreous Quartzite Subunits On and Around 5300 Level, Lucky Friday Mine.

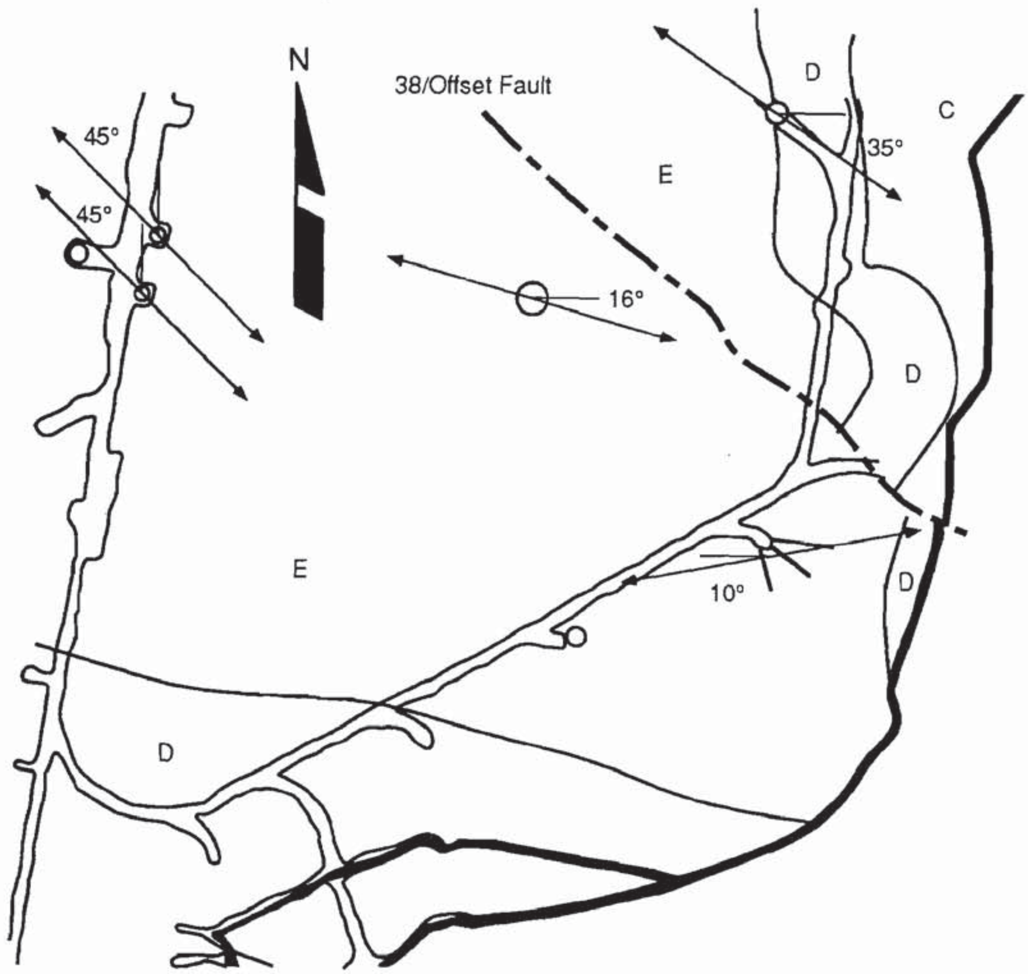
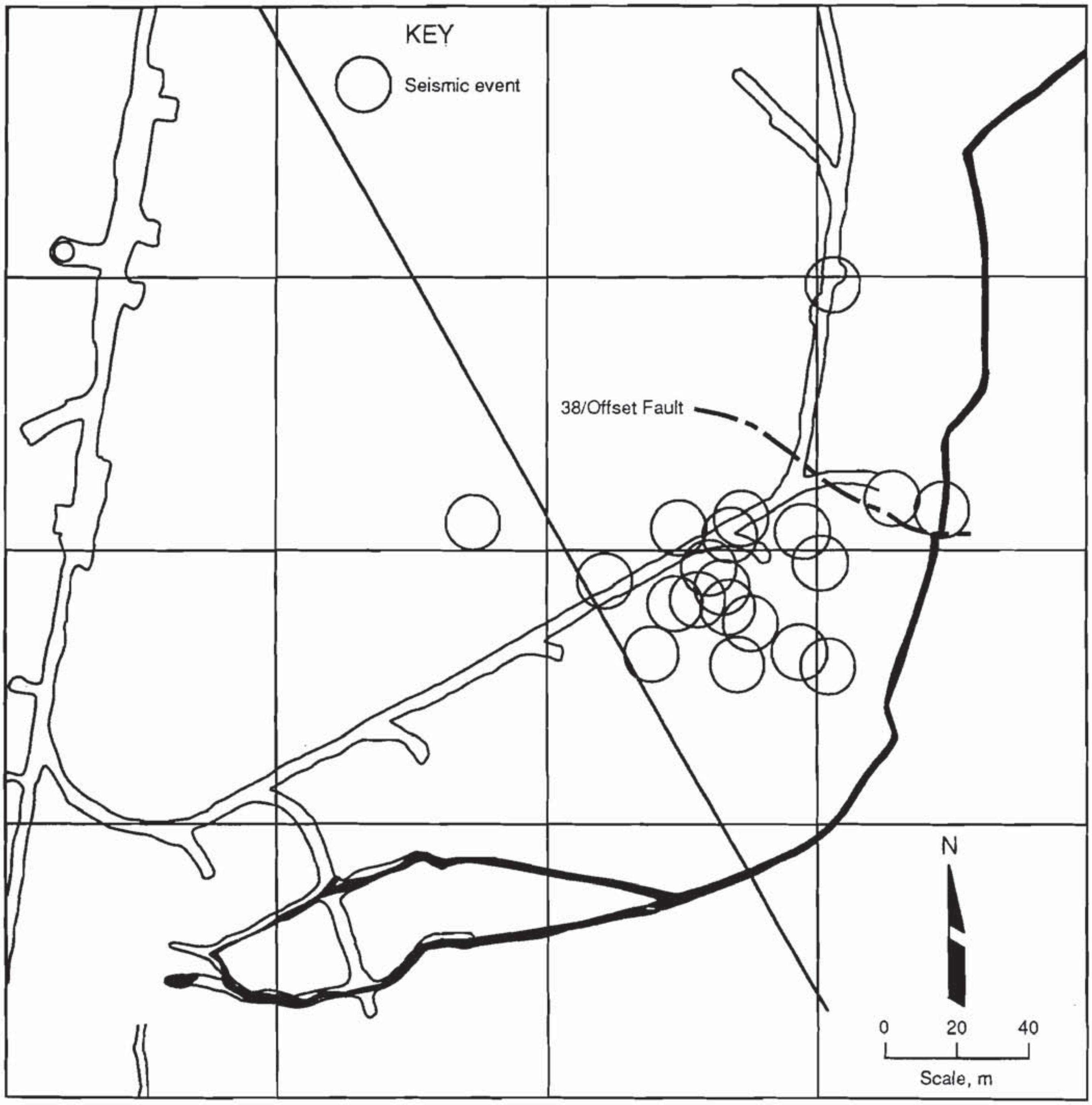


Figure 10
Concentration of Seismicity and Rock Bursts Near Axial Plane of Hook Anticline During Development.



mechanics. This approach has proven to be both appropriate and valuable for studying stresses and deformations induced by mining.

Rock masses often contain a number of rock types with different elastic properties. The introduction of regions with different elastic properties is a simple extension of this approach that can generate significant structural stresses. For purposes of analysis, the shapes of these regions can be classified generally into inclusions and strata, depending on whether the region is locally bounded or extends indefinitely. Stresses and displacements induced in these complex geologic structures by mining can be readily estimated with any of a number of computer programs. The types of structural stress associated with each of these geometries can be explored through simple models and case studies.

Inclusions

The primary effect of hard and soft inclusions is that hard inclusions attract soft inclusions and shed stresses from the surrounding rock mass. One of the simplest cases to solve involves a cylindrical inclusion of rock that has either a stiffer or a softer elastic modulus than the surrounding rock mass. This problem has been solved exactly (see Jaeger and Cook, 1979, pp. 261-264). The stress pattern induced around a soft inclusion resembles the pattern that develops around a similarly shaped void (a void is obviously a very soft inclusion).

Irregular inclusions can be readily analyzed with most stress analysis programs. As an example, a rectangular soft inclusion with one-fourth the stiffness of the surrounding rock was analyzed using a ratio of principal stresses in a horizontal plane of 2:1. The greatest principal stress was oriented perpendicular to the long axis of the soft inclusion. The results show both concentration and reduction of stress (figure 11).

A soft inclusion encountered at Minnovà, Inc.'s, Ansil deposit 500 km northwest of Montreal, PQ, in the Canadian shield has a similar rectangular geometry in plan section. Germain and Bawden (1989) measured highly unusual in situ stress tensors at depths between 1,200 and 1,500 m. The stresses were seemingly unrelated to normal regional field stresses. They concluded that the mine's massive sulfide ore body behaved as a soft inclusion relative to the host formations. Consequently, the natural concentration of stress around the soft inclusion resulted in zones of rock bursting and heavy ground in some development openings (figure 12). Zones of reduced stress, which resulted in sections of loose blocks in the stope wall, were also encountered.

Strata

The ability of parallel plates to develop in-plane stress in proportion to elastic modulus under constant strain conditions is well known. In geologic settings, stiffer strata tend to concentrate in-plane stress as well. Goodman (1989) provides a simple example of a tunnel encountering varying stresses as it passed through a fold (figure 13). This model is a simple, two-dimensional version of the saddle-shaped folding of vitreous quartzite strata in the vicinity of the Lucky Friday Mine (figure 14). Vertical stress jumps in hard strata can be seen in the generic example of figure 13 and stresses measured at the 4,250 level overcore site (figure 5). Similar results have been reported in coal mines (Maleki and others, 1992).

McGarr and others (1975) studied seismicity in East Rand Proprietary Mines and found activity concentrated in a stiff set of beds in the reef hanging wall. These beds were unusually thick and consisted of quartzite with a glassy texture. In contrast, the rocks in the footwall were thinly bedded and more argillaceous. McGarr and others also noted increased activity in an aplite sill (actually a dike cutting the strata at a low angle). They found that both stress and seismicity were concentrated in the quartz strata and aplite sill.

FAULTS, JOINTS, AND FRACTURES

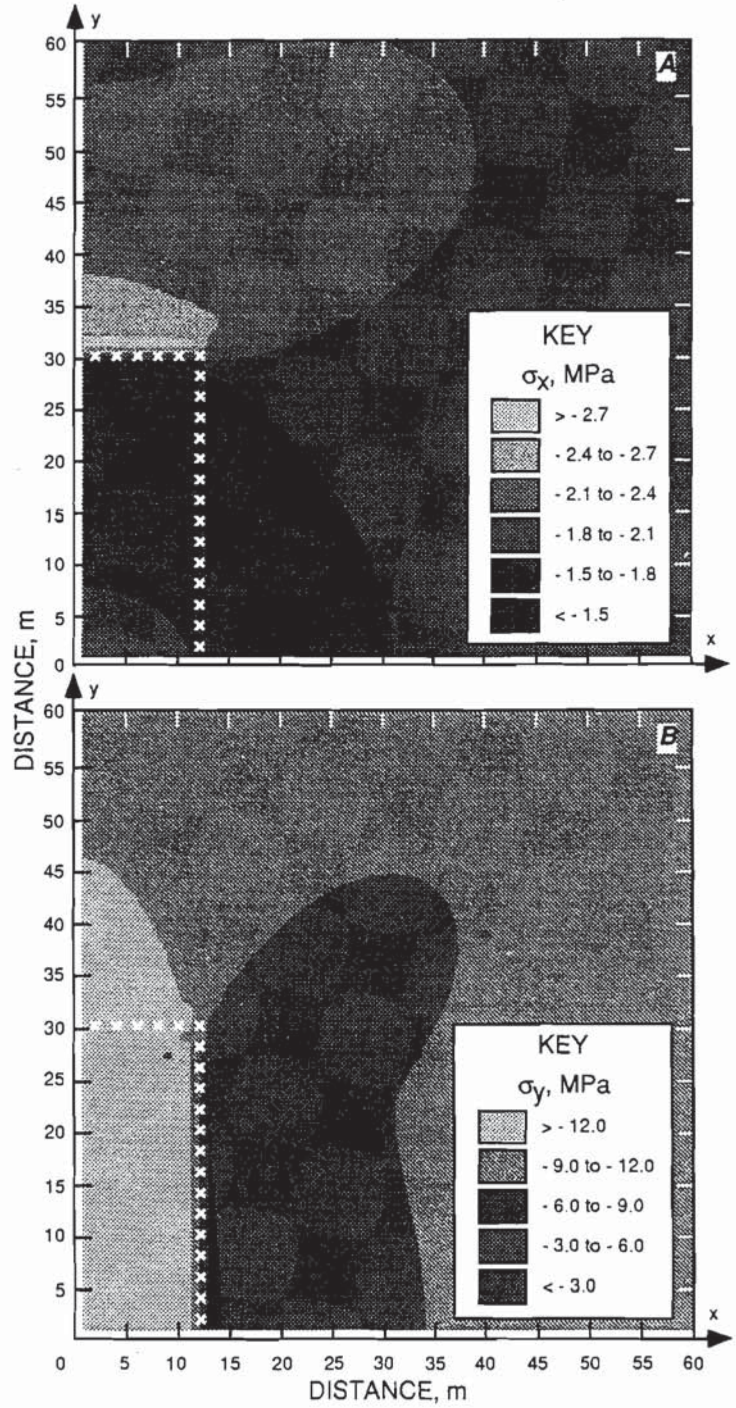
An alternative set of simple models can be built from the same initial ideal rock mass by introducing discontinuities representing faults, fractures, and/or joints instead of regions containing different rock types. For this analysis, the discontinuities are treated as simple frictional interfaces with no cohesion, although the friction angle is allowed to vary. This model is available in most stress analysis programs for rock mechanics.

Slip

Slip on discontinuities disrupts the continuous variation of stress and concentrates shear strain, redistributes shear stress, and causes jumps in the stress component parallel to the discontinuity. The effects of discontinuity slip are illustrated in the case of steeply inclined faults near the surface (Crouch and Starfield, 1983). In this case, the faults are considered to be frictionless. Fault slip causes a rotation of principal stresses towards orientations either parallel or perpendicular to the fault (figure 15).

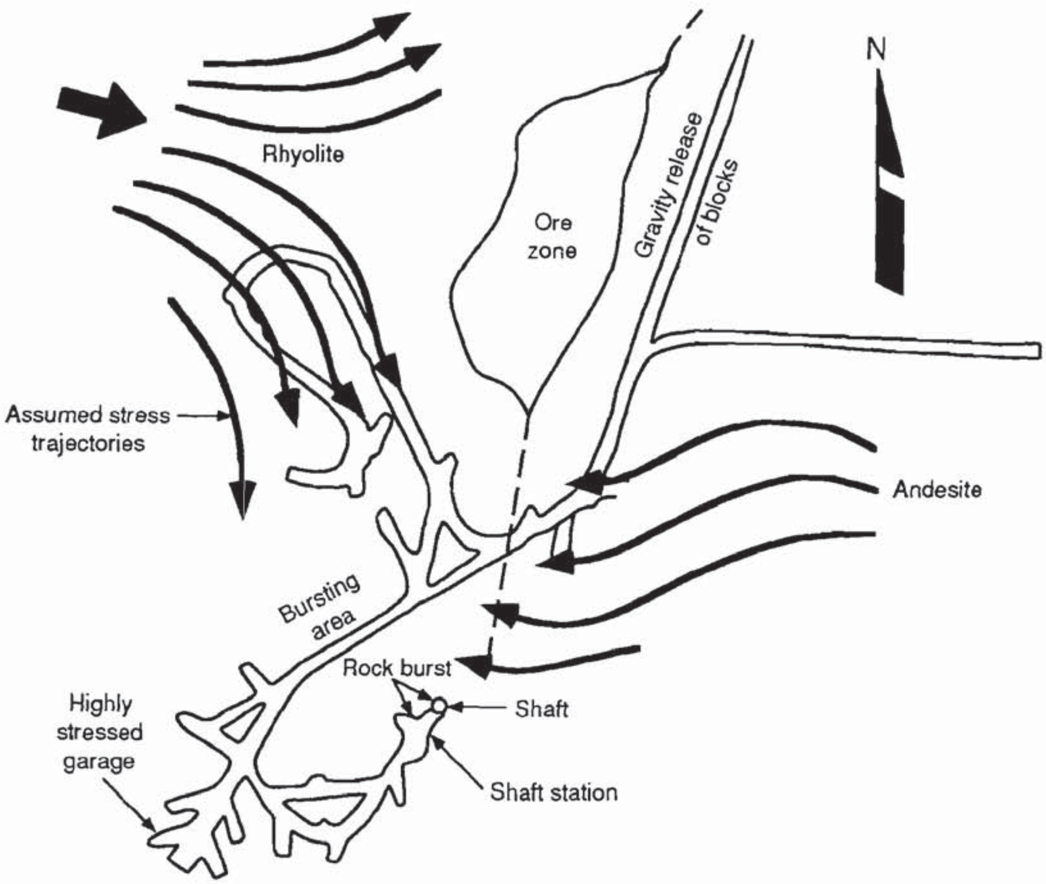
An example of the ability of discontinuities to create spatial variability in both stress and rock bursting was reported by Martna and Hansen (1986). They describe

Figure 11
Structural Stresses Developed by Rectangular (2.5:1) Soft Inclusion in Biaxial Stress Field (σ_x:σ_y = 2:1).



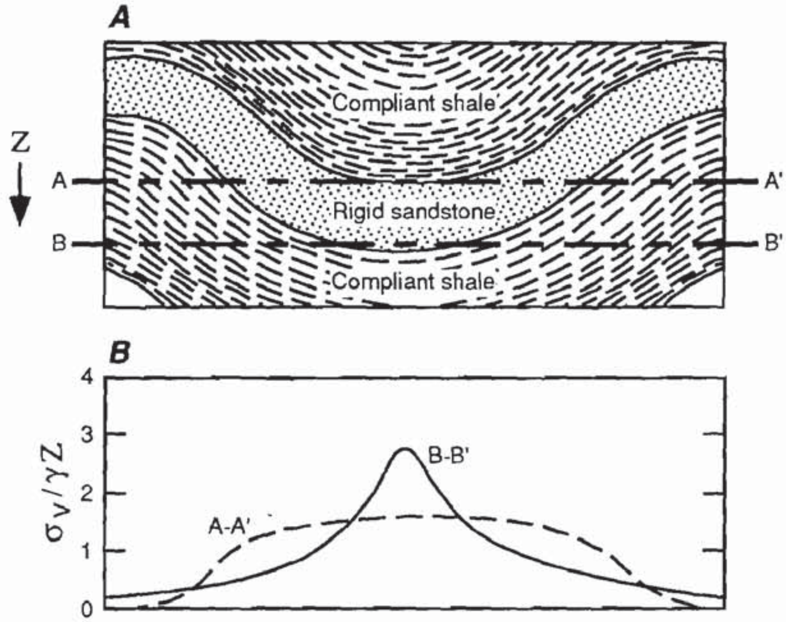
The soft inclusion has one-fourth the elastic modulus of the surrounding rock. Tangential stress in the surrounding rock on the boundary of the soft inclusion is (*A*) increased on the boundary parallel to the greatest principal stress (σ_x) and (*B*) reduced parallel to the least principal stress (σ_y). The stress analysis was conducted with the finite-difference program FLAC, version 3.22 (Itasca, 1993).

Figure 12
Ground Conditions and Assumed Stress Behavior.



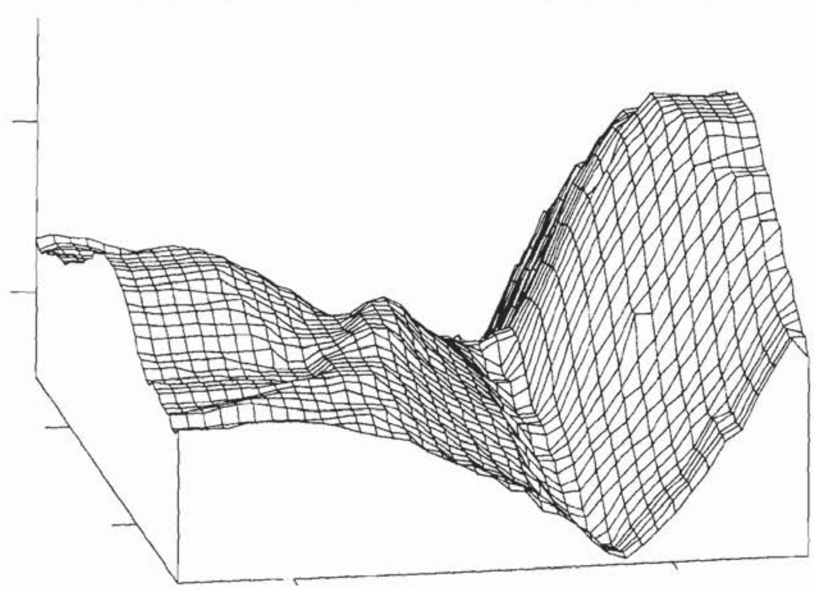
Plan view of 9th level, Ansil deposit (after Germain and Bawden, 1989).

Figure 13
Influence of Fold in Heterogeneous, Layered Rock on Vertical Stresses.



A, **Vertical section cutting across typical fold;** ***B*****, vertical stress sections A-A′ and B-B′ (after Goodman, 1989). Z = Depth. σ_v = Vertical stress. γ = Density.**

Figure 14
Folds in Vicinity of Lucky Friday Mine.



Intersecting west-northwest- and north-northeast-striking sets of folds create complex saddle-shaped geometry. Limbs of saddle concentrate stress as indicated by 4250 overcore measurement (see figure 5) and Goodman's model (see figure 13).

a set of 134 rock stress measurements and rock burst experiences during excavation of Vietas headrace tunnels No. 2 and 3 in Sweden. Very high stresses were measured in sections of the tunnel where rock bursts occurred, with the maximum stress four to five times overburden pressure. Other sections were relatively unstressed except for overburden pressure. The high-stress rock-burst zones appeared to be controlled by a series of faults that formed a graben. Stress measurements provided a clear picture of a significant stress discontinuity across a fault boundary of the graben (figure 16).

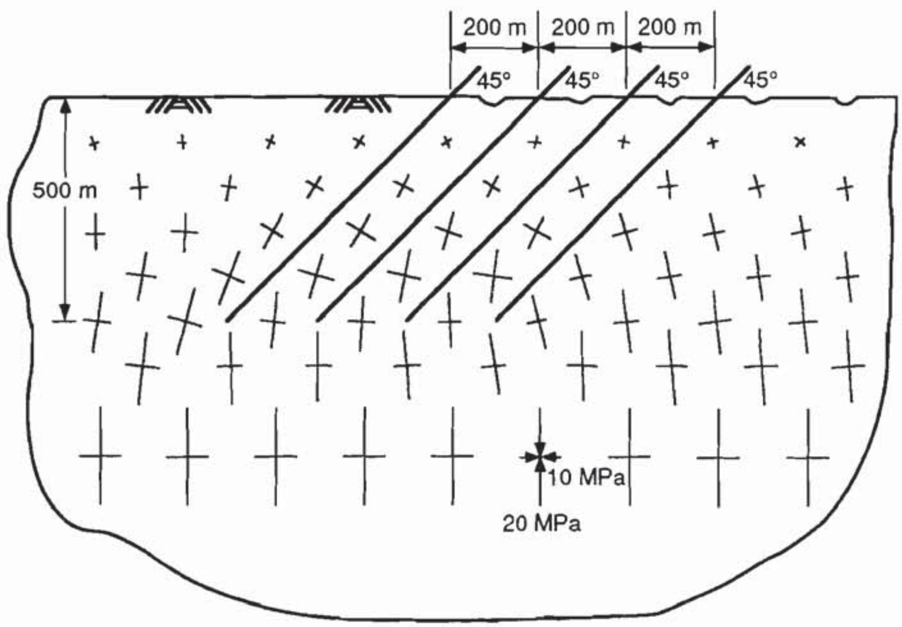
Asperities

The resistance to slip on a discontinuity depends on a number of factors, many of which vary along the discontinuity. For instance, surface roughness and material properties are important factors in determining the friction angle of sliding surfaces. Discontinuities that have experienced significant offset through geologic deformation are often slickensided in the direction of slip, although they often are corrugated in other directions.

Corrugations and variations in friction angle introduce spatial variations in the resistance to slip and result in structural redistribution of stress. Strong sections, commonly referred to as asperities, concentrate shear stress when weaker sections slip. The resulting stress field (figure 17) can be calculated with off-the-shelf software. In this case, the model shows local elevation of shear stress magnitudes and rotation of principal stress orientation. Slip at such an asperity has an increased potential for releasing a significant amount of seismic energy and damaging mine openings.

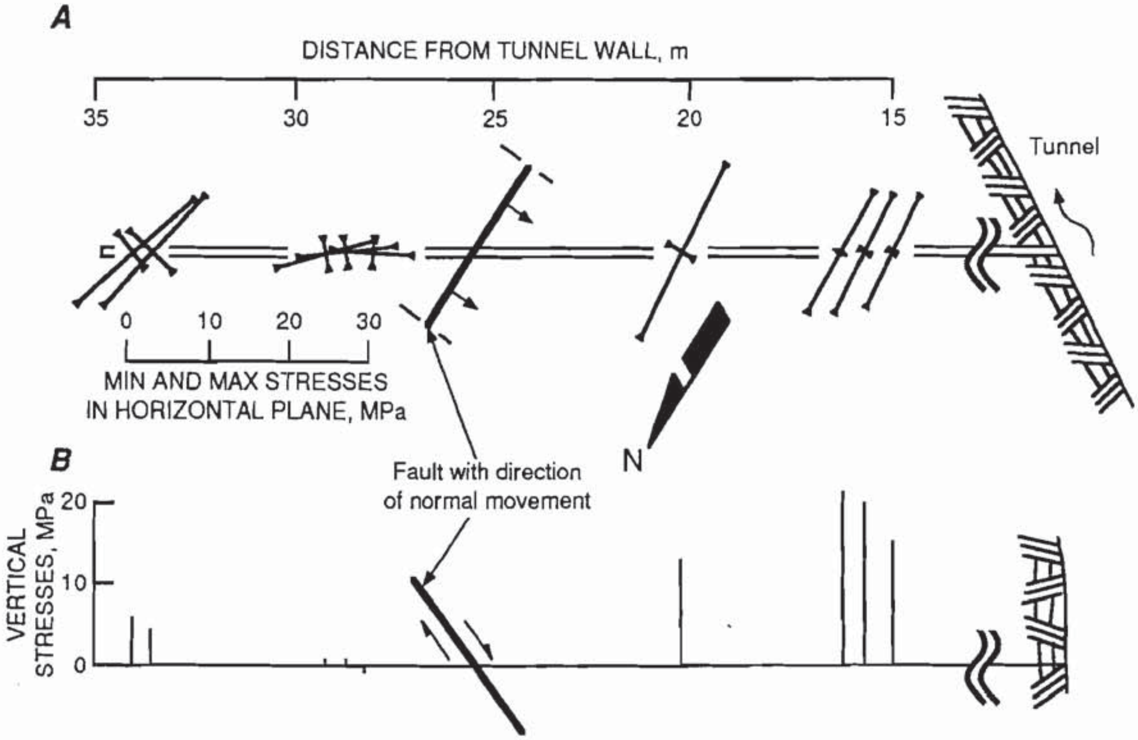
The localized stress rotation and rock bursting observed along the Offset/38 Fault at the Lucky Friday Mine (recall figures 9 and 10) correspond to the characteristics observed in the fault asperity model. The asperity appears to be located in a small area where vitreous quartzite is contained in both walls of the fault (figure 4). Adjacent regions of the fault have weaker sericitic quartzite in one or the other wall.

Figure 15
Stress Field Computed for Inclined Faults With Boundary-Element Method.



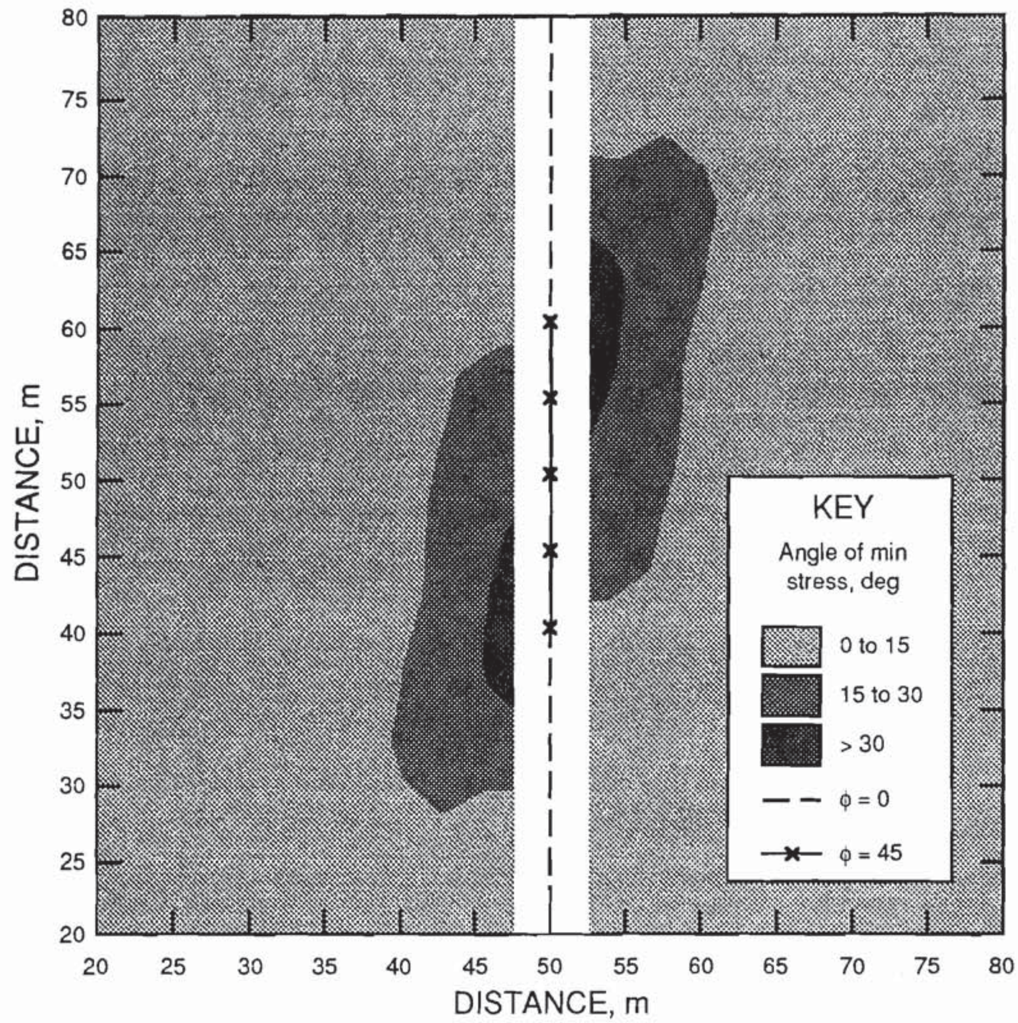
(After Crouch and Starfield, 1983.)

Figure 16
Rock Stresses Around Fault at Section 5 + 320 (Tunnel 3), Vietas Headrace, Sweden.



A, **Horizontal principal stress;** ***B*****, vertical stresses measured in borehole crossing normal fault. Note differences in stress direction and level between hanging wall and footwall on fault (after Martna and Hansen, 1986).**

Figure 17
Idealized Model of Structural Stresses.



This model shows pattern of structural stresses resulting from strong asperity on weak fault. Weak sections of fault are modeled as having no strength, and asperity is modeled with friction angle (ϕ) of 45°. Stress analysis was conducted with finite-difference program FLAC, version 3.22 (Itasca, 1993).

DISCUSSION AND CONCLUSIONS

An understanding of the structural stress variations present in a seismically active mine can be used to optimize design criteria for support elements, preconditioning, and pillars. In the absence of any knowledge of stress field variation, a design must be sufficiently conservative so that localized stress variations, whatever they may be, will not exceed design strength, a potentially expensive provision. With adequate knowledge, barrier pillars can be positioned in zones of natural concentrations of stress while extraction ratios can be increased in other, naturally destressed, areas, providing a sufficient safety factor while freeing ore reserves.

The formation of rock occurs during a complex load and deformation history spanning geologic epochs, creating an intractable mechanical problem. However, the mechanical response of rock to short-term loading is well understood, and models constructed on this basis can produce stress patterns that are qualitatively comparable to those encountered in a number of case studies. Quantitative stress estimates can be developed by fitting the stress pattern to stress measurements and observations.

This process has been used successfully to develop an understanding of a number of structural stress mechanisms at the Lucky Friday Mine, including increased in-plane stresses in hard subunits and rotation of principal stress directions near a fault asperity, that have localized mining-induced seismicity. Ongoing work is aimed at identifying additional zones of localized seismic activity, analyzing stress patterns in three dimensions, and projecting structural stress patterns to anticipate future patterns of mining-induced seismicity.

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