A Summary of the Thesis
"Numerical Examination
of Mining-Induced Seismicity"

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1.0 Introduction

In the future, ever-greater reliance will be made on the extraction of deep ore reserves. Already, mining in South African gold mines exceeds 3500 m, and is approaching 3000 m in many mining districts around the world. One of the great technical challenges and one of the primary safety and production problems associated with deep mining is rockbursting. Rockbursting is the violent failure of a rock mass in close proximity to an underground excavation, often resulting in the expulsion of rock fragments into the opening at high velocities. The primary modes of rockbursting generally recognized in the literature are instabilities of small volumes of rock associated with localized stress concentrations at the mining face (termed crush or volume bursts) as well as shear-failure within the rock mass, either on pre-existing geologic discontinuities or through formation of new shearing fractures. The two approaches which are commonly used in the mining industry in dealing with rockbursting include: (1) attempts at real-time prediction using the data produced by in-mine seismic monitoring systems; and (2) mine planning through practical experience, or through the use of numerical representations of seismic source mechanisms. This thesis addresses the latter approach and presents a methodology for employing numerical methods for representation of seismicity related to the predominant shear-failure mode.

The problem of mine seismicity is, in general, stochastic in nature due to the variability in distribution (e.g., fracture lengths and orientation) of geologic structure in the rock mass. In some cases, the controlling geologic structures are well known, as in the case of slip on large-scale faults. In other cases, the seismicity is related to families of through-going joint or bedding structures, shear zones or faults whose geometry can be described statistically, but is not known with great certainty. A methodology for assessing the seismic potential of a rock mass is presented which recognizes both the stochastic nature of mine seismicity as well as the deterministic nature associated with faults whose seismic behavior is well-known to the mine staff.

In order to represent seismicity associated with shear failure on existing discontinuities, the problem of representation of the stochastic nature of rock mass fracturing in a numerical method must first be addressed. Using work from the literature, a scheme is presented for random generation of a "representative" rock mass using probability density functions of the rock mass fracture geometry as derived from underground detailed line mapping. In this case, the number of possible fractures to be represented is manageable since we are concerned only with those whose continuous length is great enough to generate seismic events.

It is impossible to **explicitly** examine the slip potential of all possible fractures, so an approximate method for *estimation* of seismic potential is developed, based on work by Salamon (1993). The mining-induced stress state, determined using a separate numerical analysis, is mapped onto the location and orientation of each of the statistically-defined structural features. The slip potential for each fracture is determined using the standard Mohr-Coulomb slip condition, and an estimate of the resulting slip area, ride and approximate seismic moment determined using the Excess Shear Stress (ESS) technique of Ryder (1987). Using modern personal computers, it is possible to examine the slip potential and approximate seismic output of a very large number of fractures, thus obtaining a statistical representation of the seismic potential of a complex rock mass. More importantly, the effect of the geometric and strength properties of fractures on their seismic potential can be examined efficiently, thereby allowing the engineer to define possible seismic source mechanisms.

For such a model to be useful, the results must be verified against field data. Fortunately, most mines which experience a rockbursting problem have developed an extensive seismological data base which often includes estimates of source parameters as well as the source locations. Since the numerical model is capable of producing the equivalent source information, it is often possible to determine the correspondence between the predicted and actual seismic behavior. This, in turn, leads to a better understanding of the geological and mining factors which control the seismicity. It is suggested that the model can then be used for *relative* assessments of the seismic potential of varying mining methods or sequences, as opposed to attempts at precise predictions of seismic response. In this way, mining methods which minimize the dominant source mechanism can be specified.

A demonstration of the method is given for a parameter study of the seismicity associated with advance of a thin, horizontal longwall stope at great depth. The impact of the variability of the geometric properties and frictional strength of the geologic structures as well as the *in situ* stress state on seismic response are examined through the use of standard Gutenburg-Richter plots of event frequency and magnitude. An application of the model to analysis of the seismicity at the Lucky Friday Mine in Idaho is given. The model is used to elucidate the mechanisms for the rockbursting, and practical conclusions regarding mining methods which will reduce seismicity are presented.

2.0 Mechanisms of Rockbursting

2.1 Evidence for Predominance of Shear-Failure as a Rockburst Mechanism

There appears to be general agreement that the mechanisms for most rockbursting fall into two classes (Ryder, 1987): one associated with the crushing of highly stressed volumes of rock, and one associated with unstable slip or rupture along weakness planes in the rock mass. The first class is often referred to as "strain," "crush," or "volume" bursting, and the second as "fault-slip" rockbursting.

Gibowicz (1990) relates the strain- or volume-failure events directly to the geometry of mining operations. Volume events tend to occur where the mine geometry results in stress concentrations, such as in pillars or at an advancing mining face. The fault-slip mode of rockbursting may occur in close proximity to the excavations (Hedley et al., 1985) or may occur hundreds of meters within the rock mass. In either case, as pointed out by Gibowicz (1990, p. 4):

> Mine seismicity is strongly affected by local geology and tectonics, i.e., by rock mass inhomogeneities and discontinuities, and interactions among mining, lithostatic, and residual tectonic stresses on local and regional scales.

Therefore, even though rockbursts are often grouped into the two convenient classes given above, geologic discontinuities and their interaction with the in situ and mining-induced stresses are of primary importance in control of the failure response of the rock mass and, as described below, are generally attributable to the same shear failure mechanism.

The advent of waveform-recording seismic systems in the late 1970s has allowed detailed studies of the source mechanisms of seismic tremors (e.g., Gibowicz, 1990). A significant body of data has now been published which identifies a primary shear failure mechanism for mine seismicity, in which the failure is associated with pre-existing planes of geologic structure. Typical of the field studies is the work of Spottiswoode (1984), who analyzed source mechanisms from 11 seismic events at a South African gold mine. His interpretation was that the mechanisms of the events were best-fit assuming a pure shear source with no volume change. Fault-plane solutions showed that the events were attributed to shear failure on planes striking parallel to the face direction or to dykes intersecting the face. These conclusions are consistent with underground observations of fractures observed in the stope hangingwall.

2.2 Mechanical Model for Representation of Shear Failure on Geologic Discontinuities

Mining engineers often regard fault planes as planar features with smooth surfaces; in fact, Scholz (1990) shows that faults have roughness at all length scales. This roughness may take the form of topographical variations on the surface such as striations, and both microscopic and macroscopic waviness and splaying of the fault from a main branch into multiple features. These and other forms of macroscopic asperities, including intersections of faults with dykes or offsets by other structures, can create regions of high cohesive strength on the fault surface. Ryder (1987) examined the problem of an excavation in a high vertical to horizontal stress field in a fractured rock mass (Figure 1).

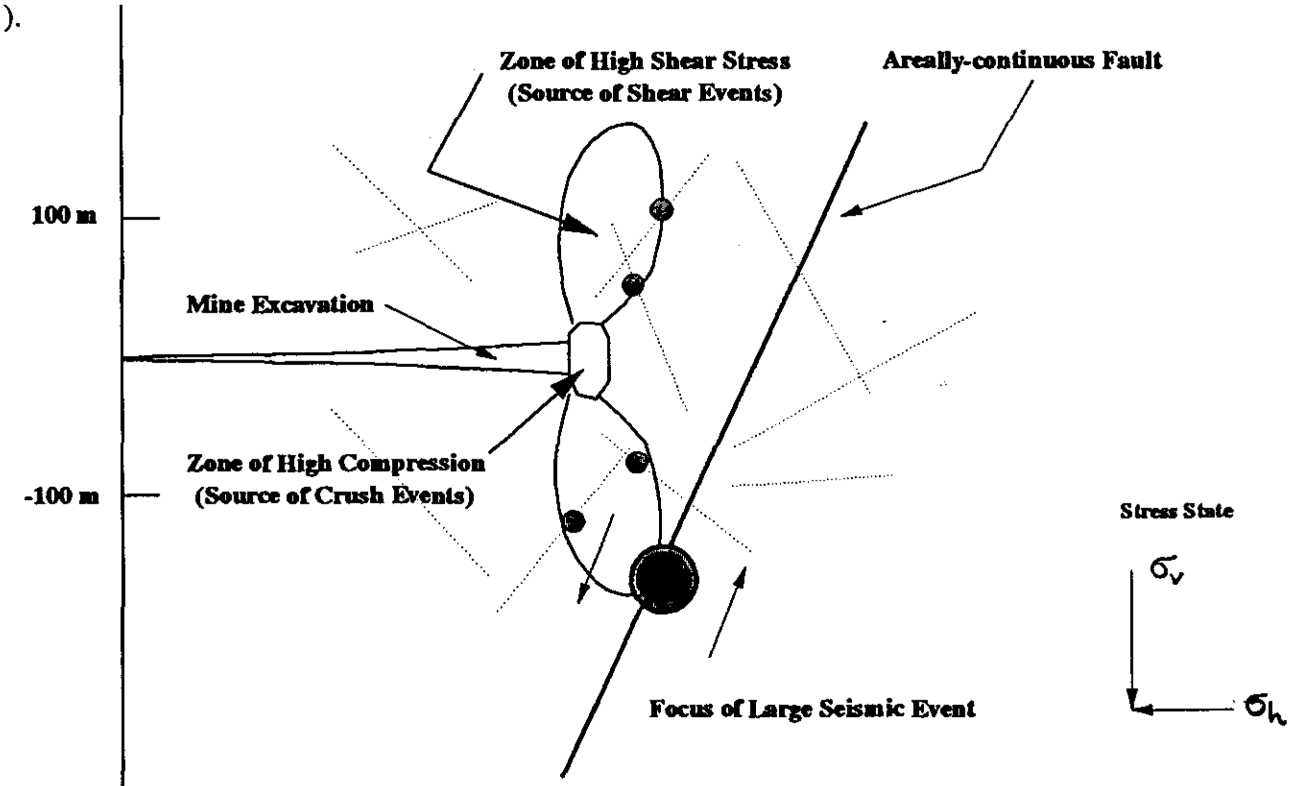


Figure 1. ***Cross-section taken through an advancing stope face illustrating the zones of high shear and compressive stresses around the face in a high vertical to horizontal stress ratio stress field.***

As the regions of increased shearing stress above and below the face "sweep" through the rock mass with the progress of mining, slip may occur on structures influenced by the increased shears. Occasionally, a long continuous structure such as a fault may be affected. Slip on the fault is possible if the stress state satisfies the Mohr-Coulomb slip condition:

$$\tau_s = c + \mu_s \sigma_n$$

where τ_s = static shear strength,
μ_s = static friction coefficient,
σ_n = normal stress, and
c = cohesive strength.

The cohesion, c, along the discontinuity is governed by in-filling or perhaps the degree of "welding" or adhesion of asperities. Once the static strength is overcome and slip initiates, dynamic conditions prevail, and the friction coefficient will drop suddenly to μ_d. Fault plane motion will then be resisted by the dynamic shear resistance (τ_d), where:

$$\tau_d = \mu_d \, \sigma_n$$

Here, it is assumed that once dynamic conditions prevail, all cohesion has been eliminated along the slipping surface. The reduction in strength from a static to a dynamic state can be viewed on a standard Mohr diagram and in terms of the shear stress-shear displacement behavior as shown in Figures 2a and 2b. Under static conditions, the shear strength will be a function of the normal stress, cohesion and static friction. When peak strength is reached, the cohesion introduced by strength variations along the fault will be destroyed along the rupture, and strength will be reduced to a function of the normal stress and dynamic friction angle only. The peak stress-drop potential, termed $\hat{\tau}_e$ by Ryder (1987), is determined by the difference in shear strength of the two failure surfaces. This peak excess shear stress drop is equivalent to shear of the "most energetic asperity" (McGarr, 1981). Since the static friction angle and the cohesion of the fault surfaces may be highly variable, Ryder suggests that seismological evidence be used to estimate $\hat{\tau}_e$. A value of 5 to 10 MPa is suggested for unstable slip on planes of weakness, while 20 MPa (essentially the cohesive shear strength of the intact material) is suggested for unstable rupture of intact rock.

Figure 3 is a conceptual depiction of the variation of static strength on a fault. Significant local variability may result from asperities or strong regions, as seen in the previous figure. Superimposed on this plot is the variation in shear stress along the fault surface. This stress variation is a consequence of mining in the surrounding region. Figure 3 also includes a line to represent the dynamic shear strength of the fault, given by $\mu_d \, \sigma_n$. The stress field surrounding the excavation will be disrupted by the presence of the opening, resulting in stress concentration and reorientation ahead of the face. As the excavation approaches the fault, the shear stress on the fault surface may eventually reach the static shear strength ($c + \mu_s \, \sigma_n$) at some location, thereby initiating rupture. The stress drop accompanying shearing of this initiation point will have a maximum, $\hat{\tau}_e$, determined by the difference in the peak (static) and dynamic shear strengths at this point. To determine the ultimate region of slip which will occur after the initiation of rupture, one must examine the stress conditions on the surrounding fault surface. The **excess shear stress** (ESS) (τ_e) at any point along the fault is the magnitude of shearing stress in excess of the shear stress produced by dynamic friction:

$$\tau_e = |\,\tau\,| - \mu_d \, \sigma_n$$

where τ_e = excess shear stress (ESS),
τ = shear stress acting on the fault, and
$\mu_d \, \sigma_n$ = shear stress due to dynamic friction.

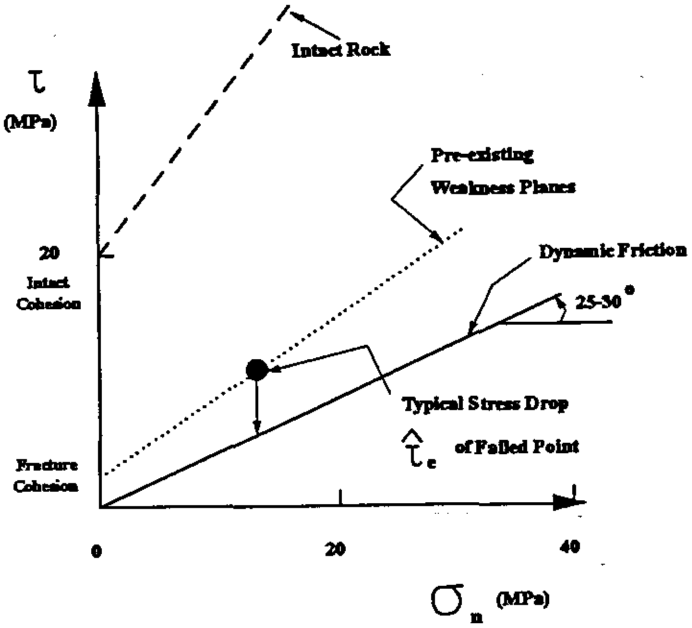


Figure 2a. *Softening response of discontinuity from static to dynamic strength during slip as shown on a Mohr-Coulomb diagram [Ryder, 1987]*

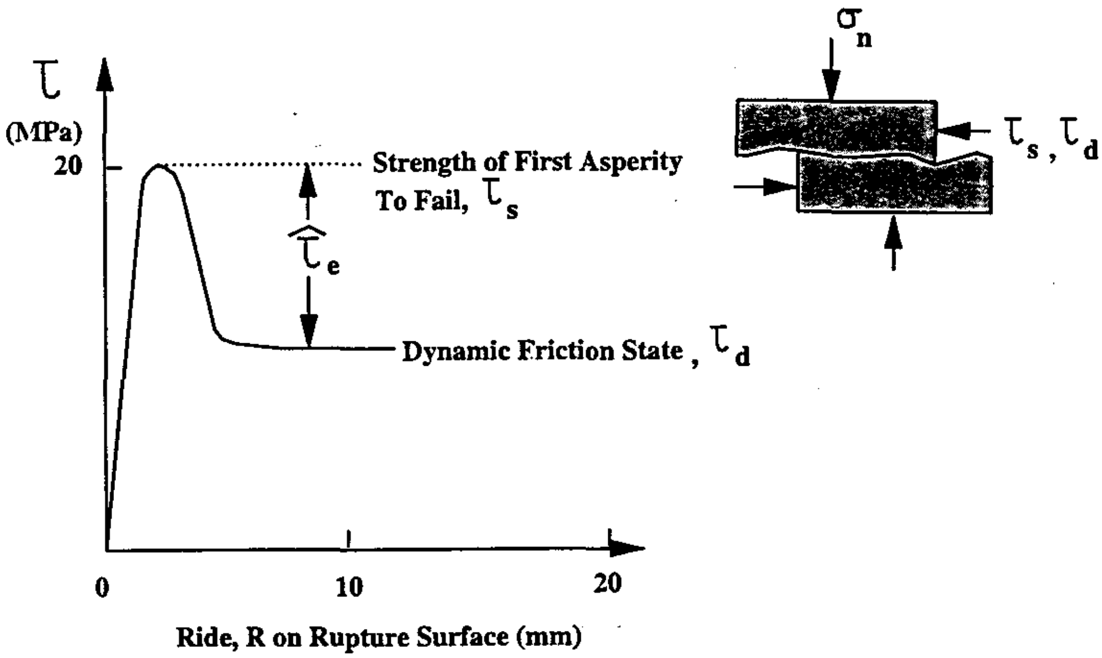


Figure 2b. *Shear stress-ride behavior for a discontinuity illustrating the "stress drop" occurring during slip [Ryder, 1987]*

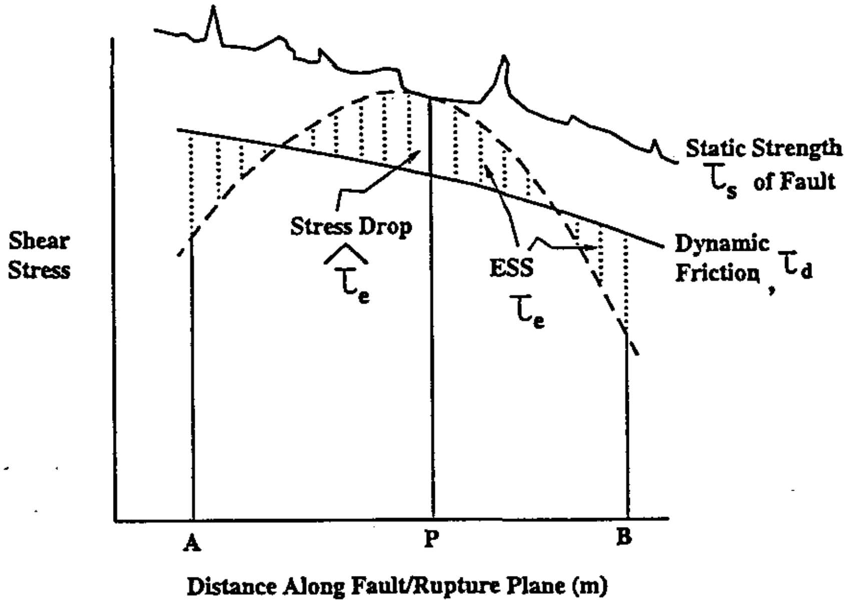


Figure 3. ***Conceptual depiction of the variation of shear strength and shear stress along a fault (The variation in shear strength may be a function of the topography of the fault or variations in in-filling materials.) [after Ryder, 1987]***

Positive values of the ESS indicate that slip is possible under dynamic conditions. Thus, once rupture begins, it will propagate from the initiation point, possibly through other asperities, eventually stopping when the ESS is sufficiently negative to inhibit further movement. Variations in static strength along the fault are largely irrelevant since, once rupture begins, it is assumed that the dynamic strength is operative and continuation of rupture depends on the ESS distribution. A consequence of the assumption that the dynamic frictional strength along the fault is uniform is that the ride and seismic event magnitude may be over-predicted. This reinforces the need for verification of this approach against field data.

The stress drop $\Delta\tau$, and the length (L_s) of the fault subjected to positive ESS, can be used to estimate the average relative shear displacement of the opposing surfaces of the fault, with the analytical expression for a circular displacement dislocation [Salamon (1964)] in the following equation:

$$u_{ave} = \frac{8\,(1 - \nu)\,\Delta\tau\,L_s}{3\pi\,(1 - \nu/2)\,G}$$

Once shear stress drop, radius (or area) of slip of the event, and relative shear displacements have been determined, it is possible to make estimates of the seismic source parameters of the ensuing event. The relevant parameter to most mining engineers is the event magnitude, expressed in a local magnitude scale. A robust measure of the magnitude of a shear event is the scalar magnitude of the seismic moment tensor, given by (Aki and Richards, 1980):

$$M_o = G\, u_{ave}\, A$$

where M_o = seismic moment,
G = shear modulus of the rock mass,
u_{ave} = mean ride or slip vector averaged over the fault surface,
A = area of the slipping fault surface,

Once the seismic moment is estimated, scaling laws for converting moment to local magnitude can be used. Spottiswoode and McGarr (1975) established the following relation for local Richter magnitude, M_L, in terms of M_o (units of MN - m):

$$\log M_o = 1.2\, M_L + 4.7$$

3.0 Implementation of the Excess Shear Stress Method in a Numerical Scheme

3.1 Introduction

The ESS approach has been applied successfully to back-analysis of numerous fault-slip seismic events in South African mines in particular, and has shown great promise as a tool for estimating the seismic potential of individual structures. General application of the ESS approach as a design tool faces a difficulty in that it is presumed that the engineer knows, in advance, the locations and orientations of critical failure planes. In this sense, the problem of estimation of fault- or discontinuity-related seismicity is, to some extent, **deterministic** in nature in that one often seeks to model the mechanical response of uniquely defined geologic structures. However, as pointed out by Morrison et al. (1993), the problem of discontinuity-related seismicity is often far more complicated due to the complex geologic structure of the typical rock mass. These authors discuss the need for

> ... development of some form of hybrid deterministic model, which incorporates aspects of weakly chaotic systems . . . . The object of this kind of simulation would be to generate the range of likely responses of the discontinuities rather than to calculate a unique solution to a particular set of pre-determined conditions (p. 236).

The main difficulty in modeling the seismic response of geologic discontinuities is the inherent uncertainty in the knowledge of rock mass structure. In this sense, the problem can be considered to be of the "data-limited" variety discussed by Starfield and Cundall (1988). Data-limited problems are defined as those for which little detailed information is available on either the structure or mechanical behavior of the material. This lack of data is typical of problems encountered in geotechnical and mining engineering. The approach suggested by these authors is exactly that expressed by Morrison et al. — that the model should be used as a tool to supplement the intuitive sense of the engineer — providing a means for checking hypotheses, or making parametric evaluations, rather than as a tool for making specific predictions or precise calculations.

In the thesis, a simple numerical approach to simulation of mine seismicity is suggested for analysis of the data-limited problem of the seismic response of a fractured rock mass. The technique employs a methodology similar to that suggested by Salamon (1993), which recognizes:

(1) the statistical nature of the distribution and geometry of the discontinuities which make up the "fabric" of the rock mass; and

(2) the fact that major faults, shears and dykes may occur sporadically and may not be particularly amenable to statistical description, although their geometries may be fairly well-established by the mine geologist.

A detailed knowledge of the mine geology is identified as a key parameter in the development of a seismic simulation method. The seismic source parameters for a given in situ stress state and mining geometry are estimated using the ESS method discussed previously. The unique aspect of the suggested approach is that an **exact** prediction of the timing and location of rockbursts is not attempted — this is felt to be a relatively fruitless approach in most circumstances. Instead, a methodology is developed for determining the most likely locations and magnitudes for seismicity based on the given degree of fracturing and mining-induced stress conditions. In this way, the modeling can be used to guide appropriate mine designs in rockburst-prone conditions.

3.2 A Seismic Source Simulation Approach

Figure 4 presents a methodology for simulation of shear-related seismic source mechanisms using the ESS approach. A "representative" rock mass fracture network is first developed statistically for a given mine, based on a combination of underground detailed line mapping as well as geologic-scale mapping of major, through-going structures. [A simple numerical fracture generation scheme based on those used in modeling of fluid flow in fracture systems (e.g., Kulatilake, et. al., 1990) has been developed]. Detailed line mapping is then used to develop probability density functions of the spacing, dip and dip direction of the fractures which have continuous length in excess of a few meters. The length variation is assumed to fit a general negative exponential distribution (Priest and Hudson, 1981) with exponential decay coefficients determined from the field mapping. The geometry of the fracture network is generated, with random locations conforming to the probability density functions. This network may be supplemented with the location, attitude and length of known fractures or structural features as desired.

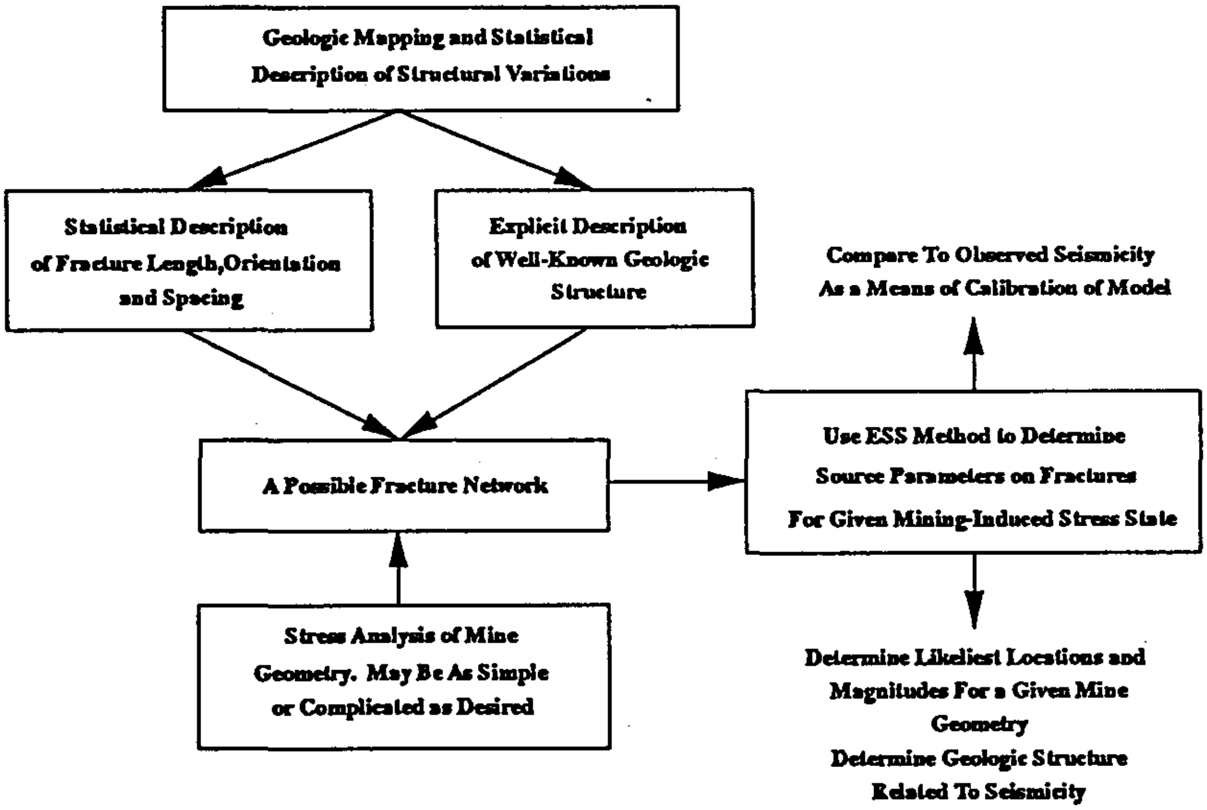


Figure 4. A flow diagram illustrating the primary concepts of the seismic simulation model

In a separate step, a two- or three-dimensional stress analysis of the mining geometry for all steps in a mining sequence is performed. In all of the analyses conducted in the thesis, it was assumed that the rock mass behaved elastically. The type of numerical method used is unimportant, except that the method must be capable of determining the mining-induced stresses in a dense array of points in the rock mass surrounding the excavations. In a post-processing step, the calculated stresses are projected onto the locations of the fractures at many points on their surfaces. The shear and normal stresses are determined at each point on each fracture, and the static Mohr-Coulomb slip condition examined. If this criterion is exceeded for the assumed values of static friction angle and cohesive strength, slip is assumed and the area of positive ESS is determined. The resulting values of shear stress drop, area of slip and average ride (relative shear displacement) are used to estimate a seismic moment, and, through the local scaling relationship, a magnitude. Cycling through each fracture is a fairly rapid procedure using a personal computer, since only stress rotations are involved. Two assumptions are made based on field observation (Salamon, 1993), thus:

(1) if a fracture slips at some location on its surface, that region is assumed to be in a residual strength condition and not allowed to fail again; and

(2) if a fracture is subjected to tension in the normal direction, non-violent failure is assumed and the fracture is, likewise, not examined further.

The effects of these two restrictions tends to build a "history" into the rock mass as the extraction ratio increases.

The result of this fairly simple procedure is to provide a picture of the potential seismic response of the fracture system without explicitly attempting to model slip on each individual feature. The critical locations and structural orientations for shear failure are determined, and the extent of this failure into the rock mass. The ability of this approach to determine seismic source parameter estimates (e.g., locations, magnitudes, source radii, stress drop, relative shear displacement, etc.) allows the model to be verified against field data from existing waveform digitizing seismic systems. In this way, the model provides a "linkage" between mining methods or sequences and an estimate of seismic potential.

3.3 Example Problem — Seismicity Associated With Advancement of a Deep Longwall Face

A simple problem is examined in order to demonstrate the approach (Figure 5). A horizontal, thin-reef longwall face at 2500 m depth is advanced in a rock mass subjected to a 2:1 horizontal to vertical stress field. A fracture network characterized by random dip, dip direction and location and by a normal distribution of spacings with a 5 m average is generated in a volume of rock approximately 400 m on a side. The continuous length of the fractures is defined by a negative exponential distribution of fracture radii, with average of 5 m. In this example, the fractures were all assumed to have the same properties, i.e., cohesionless with a static friction angle of 30° and a dynamic friction angle of 25°. A stope of 1.5 m height was advanced in this rock mass in seven increments from zero to a total stope length of 200 m. At each face advance increment, the stress state was determined from an elastic stress analysis and mapped onto each fracture at a number of locations along the fracture surface, using the technique described above.

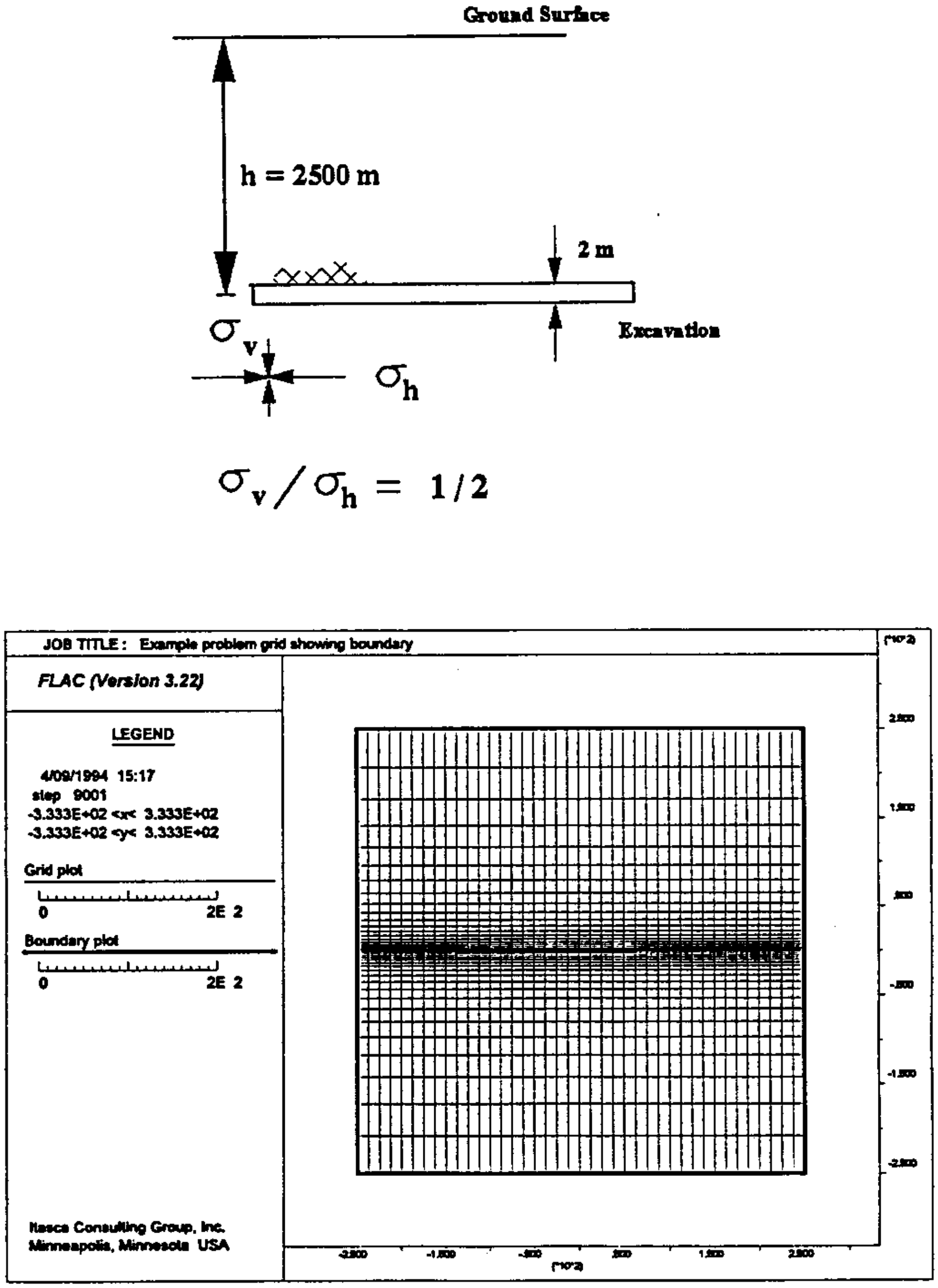


Figure 5. Geometry of example problem and model representation

A sectional view of the stope at an advanced state is shown in Figure 6. Here, the event source locations are shown as well as the slip length of those fractures which have failed. As seen, the source locations arch in a "bow-wave" fashion around the advancing stope face. This is expected, due to the high horizontal stress component. The region directly adjacent to the stope behind the face appears to be free of seismicity; this is the result of plotting only the seismicity resulting from the most recent face advance increment. A common method of representing the seismic response of mining a block of ground is to plot the log of the cumulative number of events with a magnitude exceeding a given value, versus the magnitude (the Gutenburg-Richter plot). This relationship for the example problem is given in Figure 7. As seen, the plot is roughly linear for large events [defined as those with a magnitude M greater than (approximately) zero], i.e., in agreement with the equation $\log(N) = a - b\ M_L$, where N is the cumulative number of events, and M_L is the local event magnitude. The intercept, a, is dependent primarily on the volume of excavation, but the slope, b, is a characteristic value for the rock mass and mining situation. Earthquake seismology records usually indicate b values around 1.0, with mining seismicity reporting values varying from around 0.6 to in excess of more than 1.0. Morrison, et. al., (1993) report a value for b of approximately 0.97 for large events at the Creighton Mine, whereas Spottiswoode and McGarr (1975) determine a "b" value of approximately 0.6 to 0.7 for the ERPM Mine in South Africa. As seen in this example, the slope is approximately 1, corresponding well to field observations. The distributions of stress drop and slip radii (Figure 8) also agree reasonably well with field observations (Gibowicz, 1990). Here, the greatest frequency of stress drops is in the range of 3 to 4 MPa, with values as high as 30 MPa. Field data indicate that values in the range of 0 to 10 MPa are most common. The corresponding slip radii range from less than 1 m for the smallest events to approximately 50 m for the largest events, with relative shear in the range of 1 to 15 mm. Spottiswoode and McGarr (1975) report slip values, estimated from seismological observations, ranging from less than 1 mm to approximately 13 mm at a South African Gold mine.

The effect of stress ratio on the location of seismicity for the same fracture network is given in Figure 9a for the case of a 1:2 horizontal to vertical stress field. As seen here, the seismic source locations are now contained within the regions of increased shearing stress in advance of the face. These locations compared favorably with source locations observed in South African mines in which a major vertical principal stress is found (see Figure 9b).

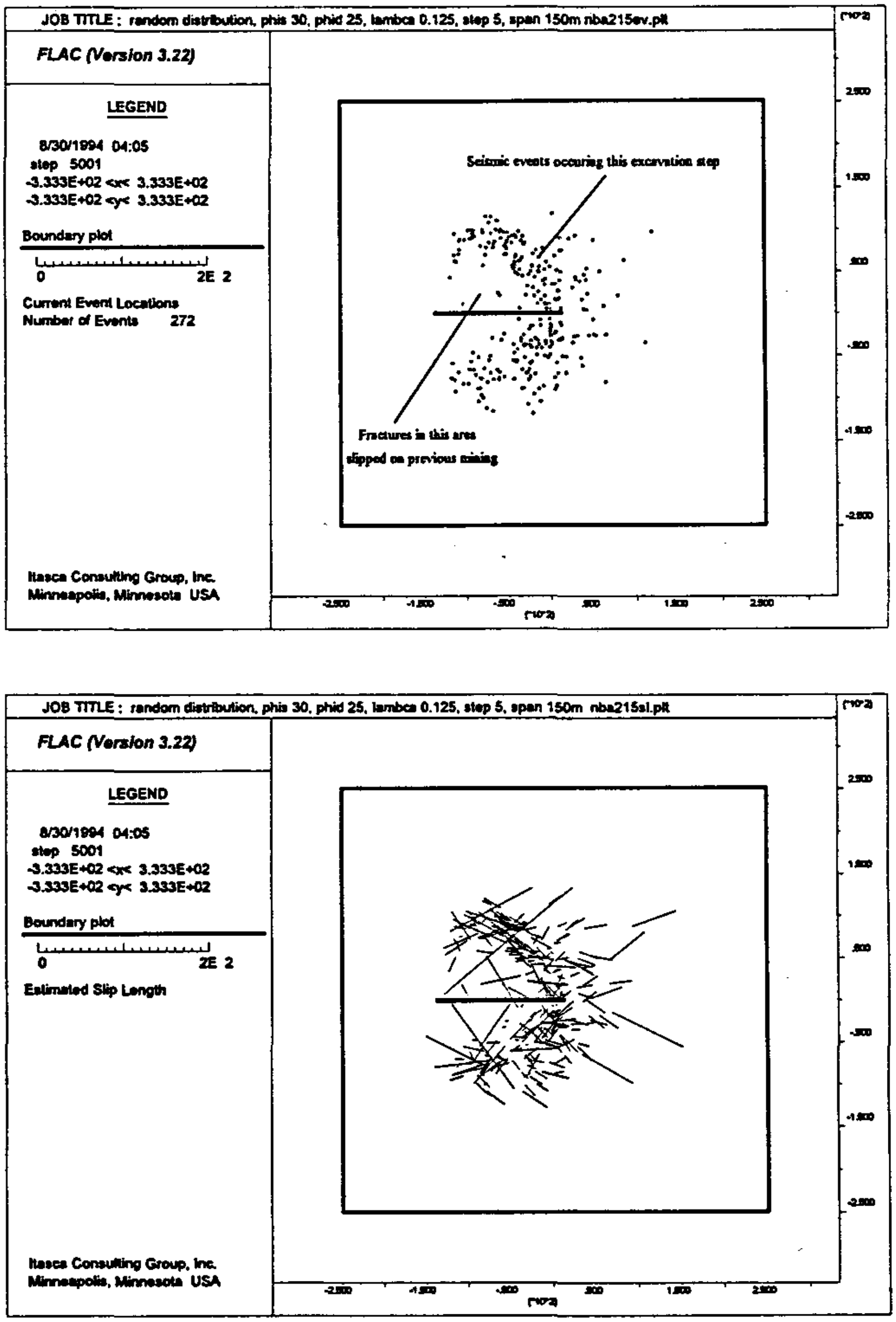


Figure 6. Plot of seismic event locations and slipping lengths for a stope span of 150 m

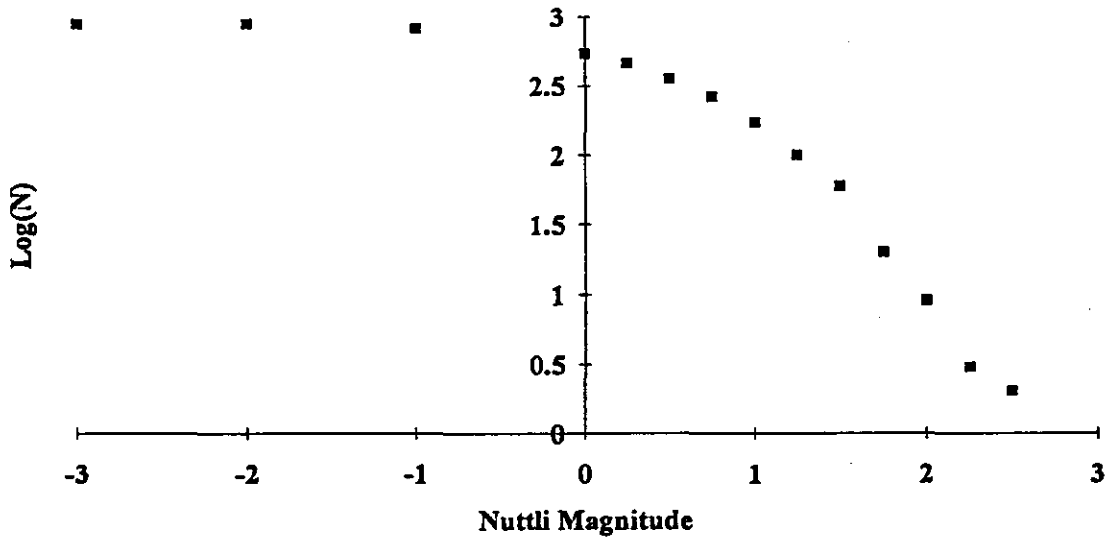
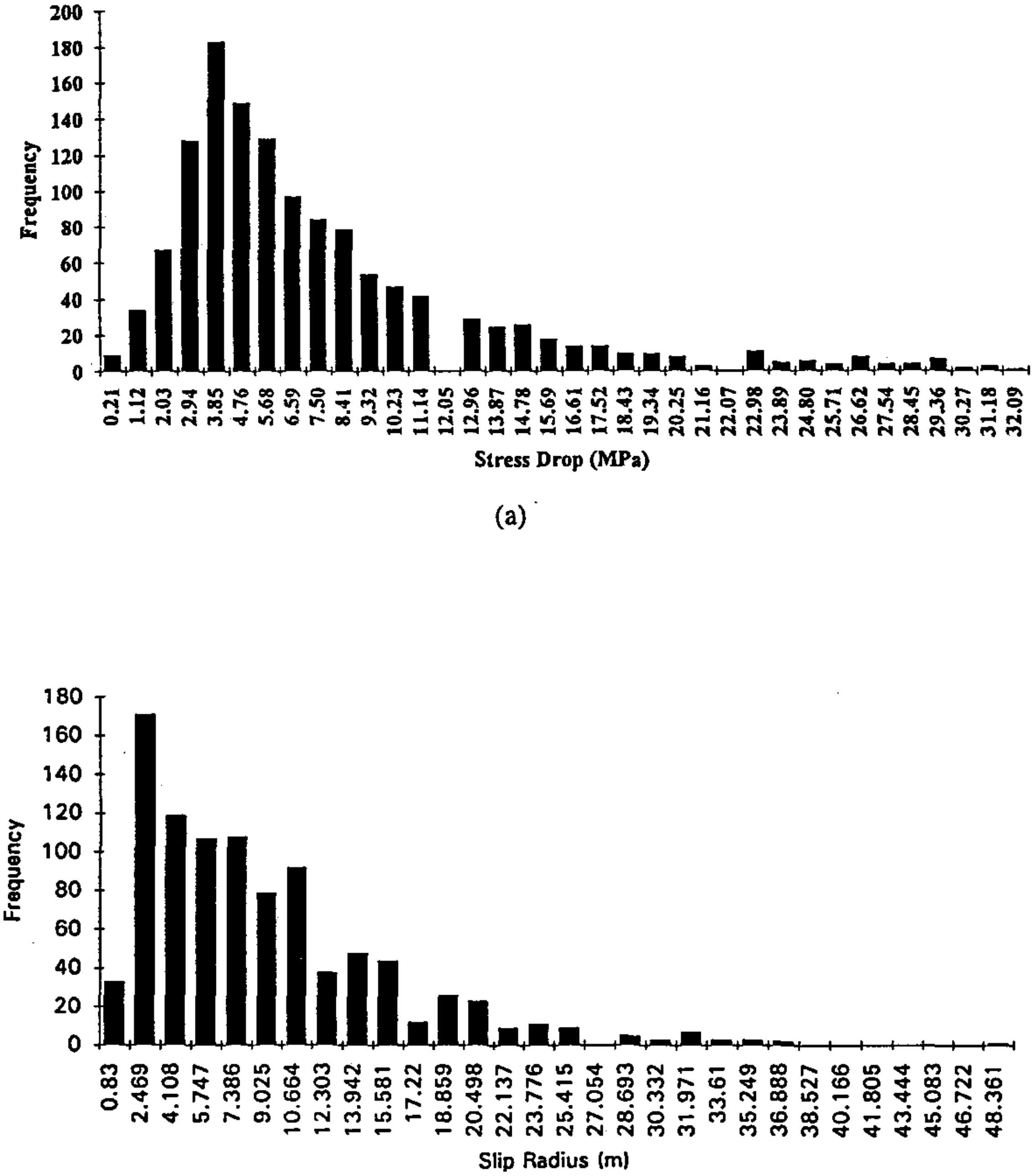


Figure 7. Frequency-magnitude distribution for the base case of $\phi_s = 30°$, $\phi_d = 25°$, $\lambda = 0.125$ (The b-value is approximately 1.)



(a)

(b)

Figure 8. Histograms of (a) predicted stress drop and (b) slip radius for the base case

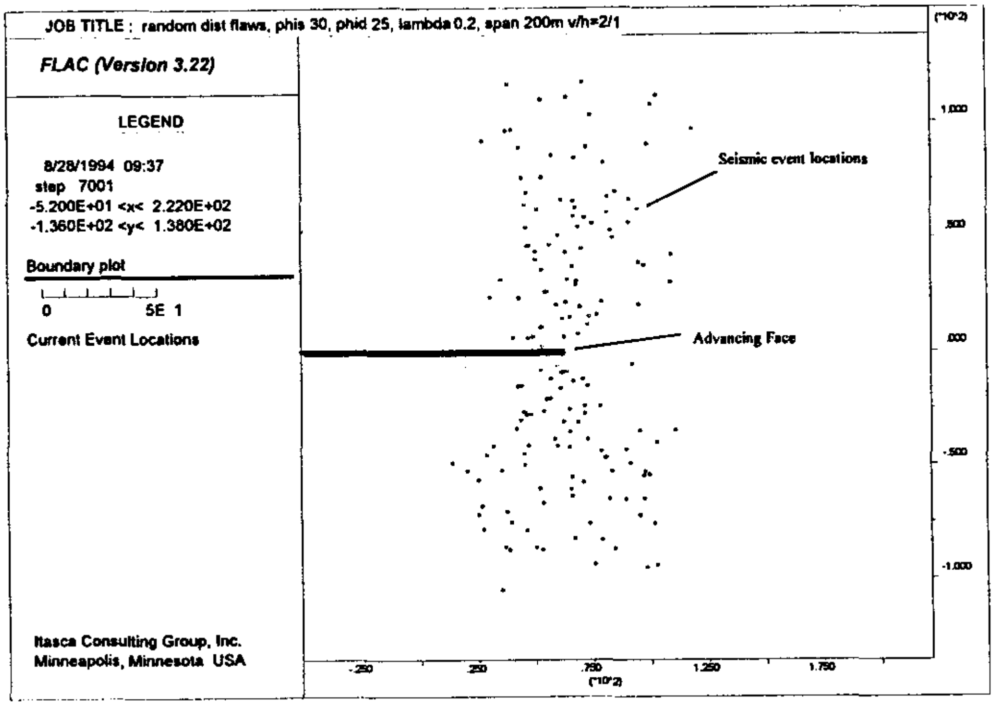


Figure 9a. Plot of the immediate face area showing predicted seismic events for a stress ratio of 2:1 vertical-to-horizontal stress

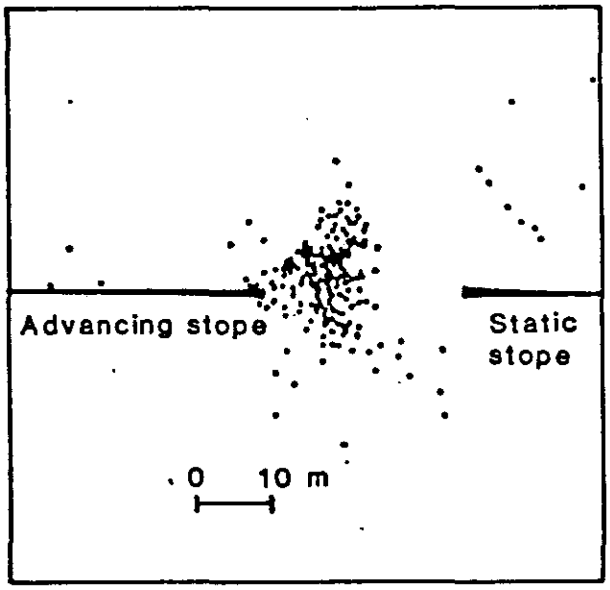


Figure 9b. Seismic event locations in advance of a longwall face for a deep South African gold mine [Legge and Spottiswoode, 1987]

A parametric study was completed in which the various fracture geometric and strength properties, in situ stress magnitude, and stress ratio were varied to determine their impact on the estimated seismicity. The factors of greatest influence were found to be the difference between the static and dynamic friction angle of the fracture surfaces; the continuous length of the fractures and the in situ stress magnitude. The results of these calculations indicate that, using reasonable assumptions of strength and fracture length variation, one can produce a seismic response, which compares well with the observed response. The real advantages of this approach are:

(1) it is verifiable by comparison to field seismological observations at any given mine; and

(2) it attempts to directly tie mine geometry and geology to seismic potential.

The statistical variation in geologic structure can be mapped and described to at least a reasonable level of detail. Assuming the in situ stress state is known, the primary unknown parameters which require calibration are the strength values for the fractures.

The thesis then describes a case example, the seismicity at the Lucky Friday Mine in Mullan, Idaho, USA to demonstrate the verification process. A short summary of this verification is given below.

4.0 Field Example: Verification of Seismic Source Mechanisms at the Lucky Friday Mine

4.1 Problem Statement

The Lucky Friday Mine of Hecla Mining Company is located in the Coeur d'Alene mining district of northern Idaho. It is a lead-silver mine which extracts narrow (3 m), near-vertical ore shoots at depths to greater than 1700 m. Currently, the mine uses a longwall undercut-and-fill mining method to extract the approximately 400 m of vein length. Mining progresses in an overall downward direction by breasting beneath the cemented backfill placed in the previous cut. Excavation continues to the next level downward by crosscutting from a number of footwall ramps. The orebody is a relatively hard, siliceous ore, located in the bedded, argillaceous quartzite of the Belt Series of Western Montana and Idaho (Figure 10). The beds range in character from hard, brittle quartzites to softer, impure quartzites and argillites which dip to the southeast at 60°, and are thus intersected by the near-vertical vein. Of particular significance in this problem is a series of argillitic interbeds (thin, pure argillite beds) which occur every ten meters or so in the bedding sequence. The vein and bedding are conformably folded by a steeply-plunging anticline which gives the orebody a "hooked" appearance. Finally, the vein is terminated on its north and south extremities by two major west-north-westerly striking faults — the North and South Control Faults.

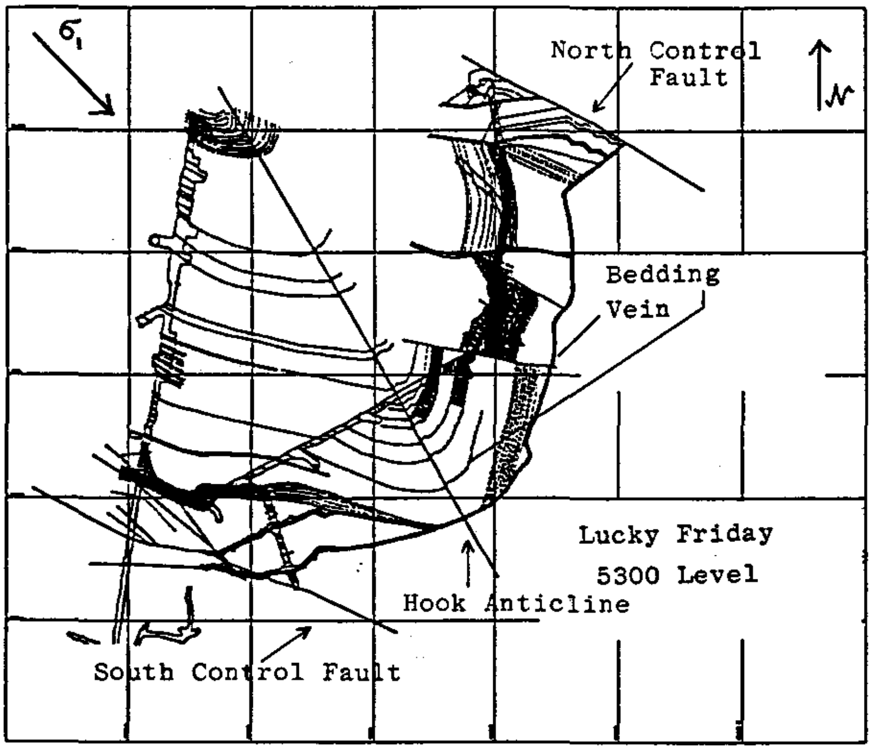


Figure 10. Plan view of the 5300 level (-1615 m) of the Lucky Friday Mine showing the general geology (This map is typical of the geologic mapping performed at the mine.)

Rockbursting at the mine has been a severe problem since the 1960s, with mining then at depths of less than 1000 m. Until the mid-1980s, overhand cut-and-fill mining was used, creating sill pillars between 65 m levels. Rockbursting would begin when these pillars were reduced to less than about 15 m in height. This prompted the changeover to a longwall system, which eliminated the vertical pillars. In recent years, the mechanics of the rockbursting has been related to unstable slip on the argillite interbeds as well as on the North and South Control Faults (Blake and Cuvelier, 1990). However, to this date, no study has clearly identified the relationship between these structures and the location and frequency of the seismic events.

4.2 Seismic Studies

Since the early 1970s, the Lucky Friday Mine has used a first arrival-only seismic system for locating seismic events in the mine. In the 1990s, this system was supplemented with a digitizing seismic system which has been used to determine source parameters (Lourence, et. al., 1993). Thus, the available seismic data base consists primarily of source locations, and some recent values of magnitude for large (>0 M_L) events. This database indicates that most large seismic events occur in the footwall of the orebody, either in the hook region or along the locations of the terminating fault structures. Figures 11a and 11b show the source locations and magnitudes of events in longitudinal and plan view from a several month period of study in 1992, during which the digitizing seismic system was being tested. In general, events at the Lucky Friday Mine range up to M_L magnitude 4, with magnitude 2 events occurring every one to two months.

4.3 Numerical Analysis of the Seismicity

The seismicity simulation approach discussed above was used to examine the seismicity associated with possible slip on the ubiquitous argillite interbeds as the longwall face was advanced. Slip potential on the terminating fault structures was examined by explicit modeling of the slip using a three-dimensional discontinuum method (*3DEC*).

Detailed line mapping of the bedding structures was performed to define their statistical variation in dip, dip direction and spacing; the structures have continuous lengths, varying from 10's to 1000's of meters. As will be shown, in the case of the Lucky Friday Mine, the length of the structures was found not to be the controlling factor in seismic response. A series of two and three-dimensional analyses were conducted in which the longwall advance was simulated over a four year period in one-year increments. The bedding surfaces are generally slickensided and quite planar, and were thus assumed to have zero cohesion.

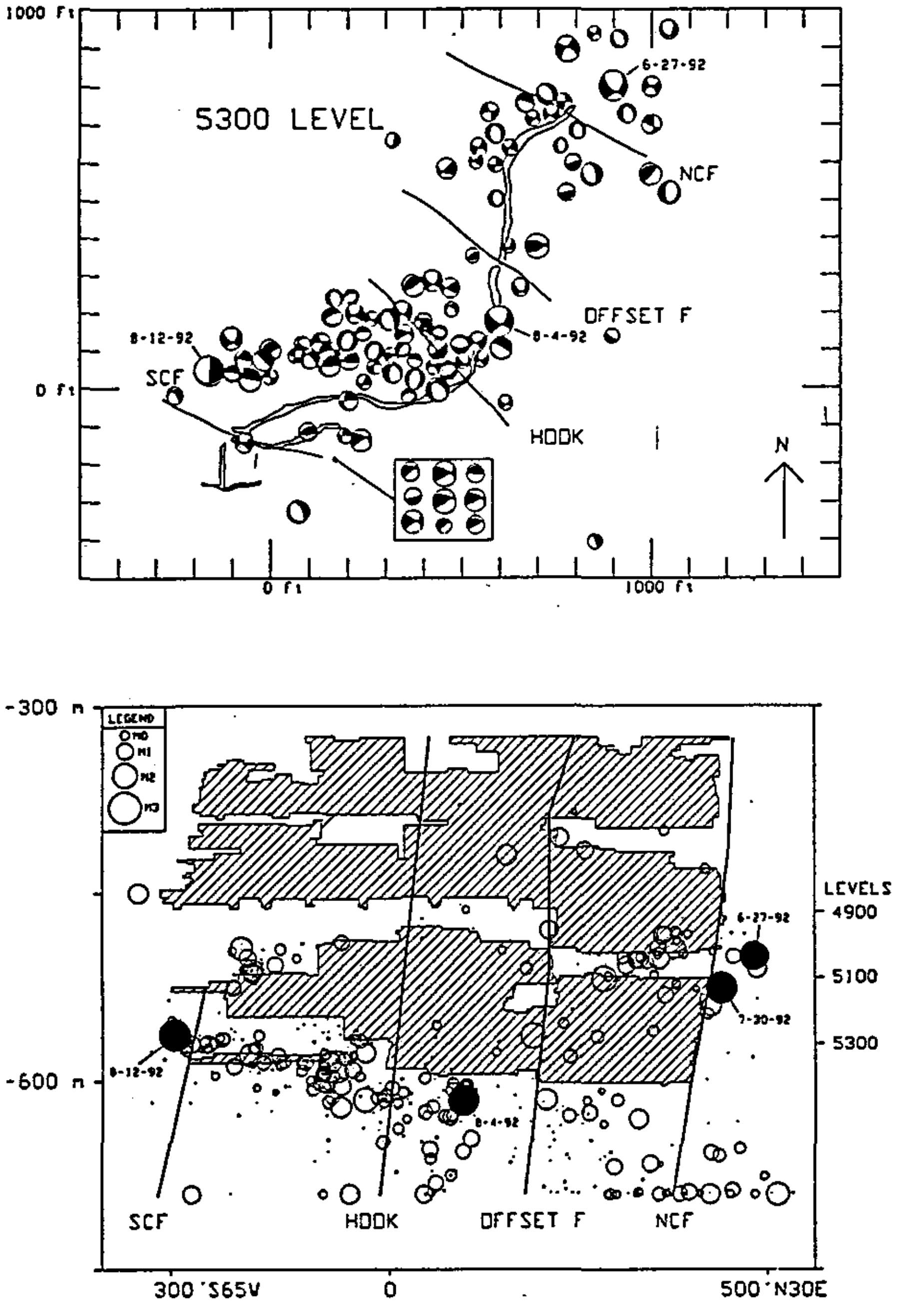


Figure 11. ***Seismic event locations for the period of May 1 to September 30, 1992, projected onto longitudinal and plan sections the Lucky Friday Mine (The diameter of circle corresponds to magnitude. Major rockbursts are noted; shaded regions are mined and backfilled.) [Lourence et. al., 1993]***

The seismicity resulting from one face advance increment is shown in the section given in Figure 12. As seen, the seismicity occurs in the western (footwall) of the orebody in a wide arc emanating from the face and extending several hundred meters into the wall. The curious result of the analyses is that the seismicity is restricted primarily to the immediate vicinity of the face or in the western wall. The large seismic events are found almost exclusively in this region, while the minor seismicity in the eastern (hangingwall) is of lower magnitude. This behavior agrees well with the field observation that seismicity is restricted to the footwall region. The modeling implies a source mechanism related to bedding plane slip as illustrated in Figure 13. A shearing mechanism preferentially occurs in the footwall since beds are unfavorably oriented with respect to the stresses (arching) around the longwall face. In the hangingwall side, the beds near the face (where stress drops are large) are clamped by high normal stresses (negative ESS as shown in the previous figure), thereby preventing slip. The slip which does occur in this region of relaxed normal stress behind the face is characterized by fracture opening, resulting in smaller energy releases.

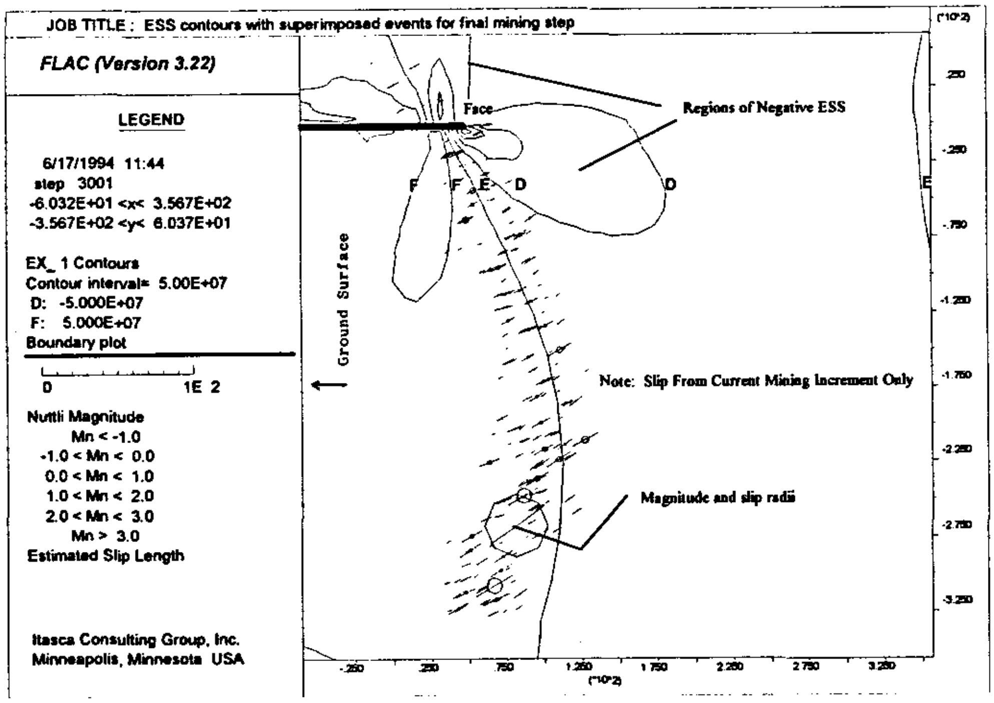


Figure 12. Close-up view of events with superimposed contours of excess shear stress (Events follow the contour of positive ESS.)

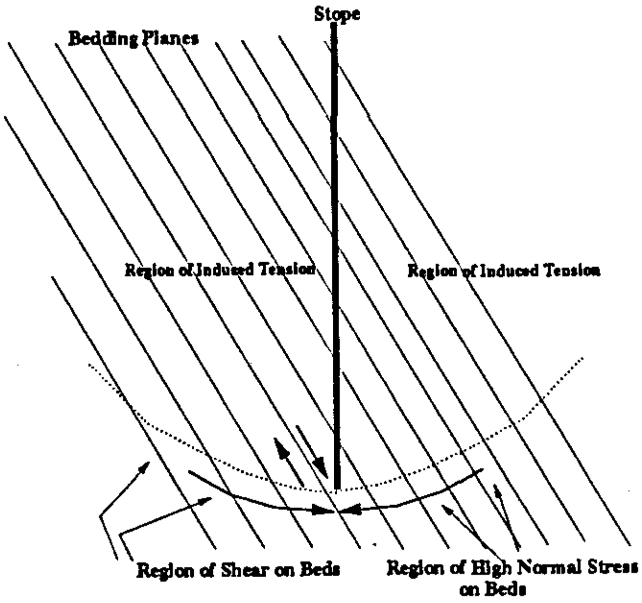


Figure 13. Schematic illustration showing proposed mechanism for seismicity in footwall (northwest wall) (Shearing occurs on bedding planes in left side of orebody while clamping occurs in opposing wall.)

A parametric evaluation was conducted of the frictional properties of the bedding, with static friction values in the range of 25 to 30° and dynamic friction angles of 25 to 28°. The frequency-magnitude response is shown in Figure 14. It is seen that the numerically-predicted value of the b slope is approximately 1.1, with a maximum event magnitude restricted to approximately 2.5 to 3 M_L. This restriction in magnitude of the bedding slip events appears to be a function of the stress state and bedding orientation around the face, and not a function of the continuous length of the bedding structures. These conclusions have obvious practical implications, the most important of which is with respect to location of the stope development. Unfortunately, a shaft was sunk in the early 1980s in the footwall to minimize development length. However, the ramp development was placed directly in the region most susceptible to large-magnitude bedding events, thus locating mining in the area of greatest damage potential.

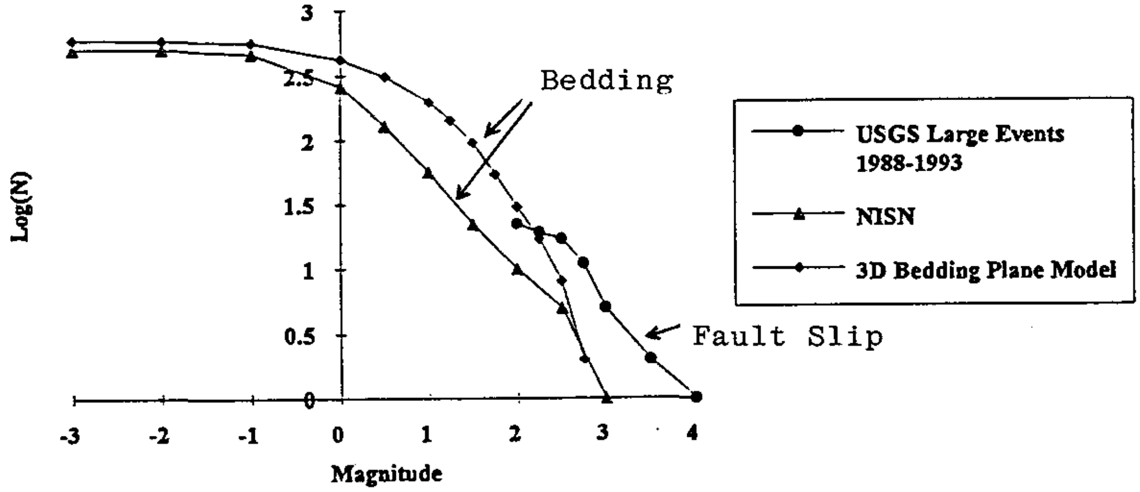


Figure 14. Frequency-magnitude plot for the Lucky Friday Mine, 1992-1993, North Idaho Seismic Network and 3D Model (Large events monitored at the USGS in Newport, Washington, from 1988-1993, are also shown.)

A separate three-dimensional explicit slip analysis was conducted to examine the potential for producing events in excess of magnitude 3 M_L on the terminating fault structures. The 3DEC program (Itasca, 1994) was used for this purpose. The analysis shows that these fault structures are poorly aligned with respect to the northwest orientation of the principal stresses which tend to arch around the ends of the orebody, resulting in large induced shearing stresses on the structures. Modeling was conducted over a span of four years of longwall face advance. When the change-over was made from overhand to underhand mining, sill pillars were left along the faults. These pillars have proven to be extremely difficult to extract. The modeling showed that these pillars, even though relatively narrow in height, act as local asperities on the faults, and tend to clamp them until they fail violently. The resulting large (> 3 M_L) events may be a result of the combined failure of the pillars along the fault traces, allowing violent slip over large surface areas. The practical conclusions to be gained from this analysis are:

(1) that even small pillars left against the faults here can effectively clamp them locally; however,

(2) when they do eventually fail as the face is advanced, excessively large events can result.

It is recommended that fault-locking pillars not be left in place at the Lucky Friday Mine.

5.0 Conclusions

The work described in this thesis was prompted by the need for analytical or numerical methods which could be used to assess the seismic potential of a rock mass when subjected to a specific mining method or sequence. In particular, it was concluded that techniques are needed which:

(1) are based on relatively simple concepts and which can be applied relatively quickly;

(2) help identify the seismic mechanisms and the relative impact of changes to mining methods or geometries on alleviation of the problem — as opposed to attempts to make exact predictions of future rockbursts;

(3) take into account the geology of the mine and the statistical nature of rock mass fracturing; and

(4) can be "calibrated" against data obtained from commonly used waveform-digitizing systems.

A numerical methodology for estimation of mine seismicity was discussed here which is based on two fundamental ideas regarding rockbursting, as follows.

1. Rockbursts are primarily the result of shear failure of a rock mass, either along pre-existing discontinuities or within the intact rock itself.

2. Rockbursts are essentially random phenomena, whose occurrence and severity depend largely on the interaction of the mining-induced stress field with the statistical nature of the geometry of rock mass fracturing.

The method developed was shown to produce seismic response which appears to correlate well with observed seismic response. The ESS method, itself, has been criticized as being highly conservative in nature when applied in a general manner. The work presented here illustrates the value in verification of the model against field data in choosing physical properties of the structures to avoid overly-conservative results. Comparison of the model to the observed response of the Lucky Friday Mine indicates that the model can be highly useful in capturing the essence of the seismic source mechanisms, and that it can be used as a basis for making mining decisions.

Finally, the primary objective of this research was to develop an engineering tool which could be used for **comparative** analyses of seismic potential of various means of mining a block of ground. It is felt that further experimentation with the method must be made before conclusions can be drawn as to the general applicability of this method.

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