

Triggering of Seismicity Remote from Active Mining Excavations

By

S. D. McKinnon

Department of Mining Engineering, Queen's University, Kingston,
Ontario, Canada

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Summary

Observations of seismicity and ground control problems in the Sudbury mining camp have shown that late-stage (young) sub-vertical strike-slip faults are sensitive to small mining-induced stress changes. The strength-limited nature of stress measurements made in the region indicates that these structures are in a state of marginal stability. Numerical continuum models are developed to analyze the behavior of such structures. In the models, shear strain localizations (faults) evolve such that there is close interaction between the fault system, stresses, and boundary deformation. Fault slip activity in these systems is naturally sporadic and reproduces the commonly observed Gutenberg-Richter magnitude frequency relation. It is shown that a relatively minor disturbance to such a system can trigger significant seismicity remote from the source of the disturbance, a behavior which cannot be explained by conventional numerical stress analysis methodologies. The initially uniform orientation of the stress field in these systems evolves with increasing disorder, which explains much of the scatter commonly observed in data sets of stress measurements. Based on these results, implications for stress measurement programs and numerical stability analysis of faults in mines are discussed.

Keywords: Triggering, microseismicity, stress analysis, rockbursts, fault stability.

1. Introduction

The majority of seismic events around deep hard rock mines occur close to excavation boundaries. These events are related to mining-induced stress changes leading to damage involving fracturing of intact rock or slip along pre-existing discontinuities. Extraction layouts leading to highly stressed structures such as pillars and abutments are particularly prone to induced seismicity. With appropriate calibration of rock mass strength, numerical stress analysis can be used to estimate the extent of fracturing and therefore the extent of near-excitation seismicity (Beck et al., 1997; Potvin and Hudyma, 2001; Beck and Brady, 2002). Characteristics of near-excitation seismicity

include swarms of events triggered by production blasts (which cause a rapid change in the stress field), followed by a gradual decay in event frequency to background levels over a period of hours or days. The regularity in the frequency and location of near-excavation events makes this type of seismicity a manageable mining problem.

A certain amount of seismicity also occurs further away from mining excavations and appears to be uncorrelated in time and space with mining activities. Events have been recorded hundreds of meters away from active mining. On the basis of source locations, it has long been recognized that these events are the result of slip on pre-existing structures such as faults, dykes or contacts (Smith et al., 1974; Gay et al., 1984). Although the number of events close to mining excavation boundaries vastly exceeds those further away, the latter are of great concern to mining since they tend to be of larger magnitude, increasing the risk of rockburst damage. Since neither their location nor magnitude can be predicted in advance, mines must consequently make more extensive use of heavier ground support to control potential rockburst damage than would be required if events were only located close to active mining excavations.

Due to the complex geometry and geological environment of most mines and the availability of numerous commercially supported codes, numerical stress analysis is the tool of choice for the majority of mining stability analysis. However, only a limited amount of success has been obtained in using numerical modelling to understand seismic events on faults and other geological structures. In particular, numerical stress analysis has not been able to explain the occurrence of seismic events remote from mining. Due to the widespread use of numerical stress analysis in the mining industry, it would be desirable to develop a methodology that would enable modelling to be used to explain both types of seismic events. The objective of this paper is to present an investigation into the cause of seismic events remote from mining and the implications for applying numerical stress analysis to the problem. As would be expected, this type of seismicity is strongly influenced by the geological environment in which the mine is located. Motivation for the approach to modelling mining-remote seismicity is taken from stress measurements and known geological controls of seismicity in the Sudbury mining camp, Fig. 1, which is a region of intensive mining activity in Ontario, Canada.

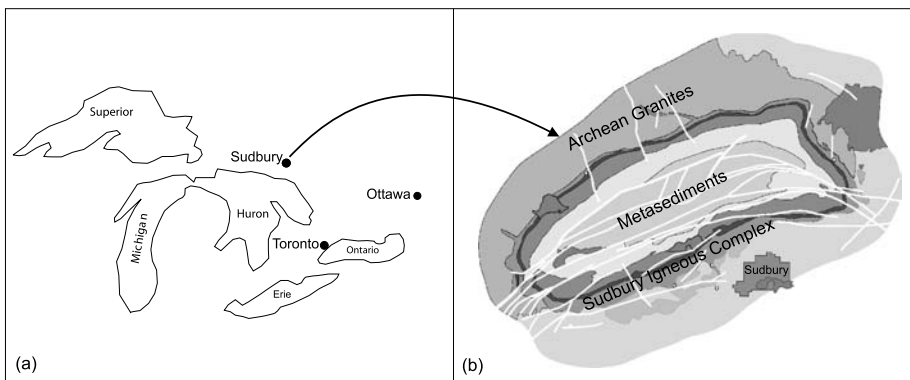


Fig. 1. **a** Location of the Sudbury Structure relative to the Great Lakes region of Eastern Canada, and **b** major geological features of the Structure

2. Structural Geology and State of Stress in the Sudbury Structure

2.1 Structural Geology

The mines of the Sudbury camp are located in a unique and complex geological formation called the Sudbury Structure. This section presents a brief overview of the geological setting and some details of those structures that have been associated with mining-induced seismicity.

The Sudbury Structure is approximately 60 km long, 27 km wide and roughly elliptical in shape, Fig. 1. It is comprised of three major components (Rousell et al., 1997): the Sudbury Basin, formed by a central sequence of metasedimentary rocks; the Sudbury Igneous Complex, a group of igneous units that surround and contain the metasediments; and an outer ring of shatter-coned and intensely brecciated footwall rocks. Much of the structure is believed to have been influenced by a catastrophic meteorite impact (Deitz, 1964), but the region has also undergone numerous episodes of tectonic deformation, each of which has left its structural imprint of faults, dykes, and folding. Details of the Sudbury Structure and its genesis can be found in Brocoum and Dalziel (1974), Shanks and Schwerdtner (1991), Rousell et al. (1997), and Boerner et al. (2000). In terms of the significance of geological structures to seismicity and stability in mines, Cochrane (1989) provides the most relevant information.

During the successive episodes of tectonic deformation, joints and faults formed in various orientations throughout the Sudbury Structure. However, based on fall of ground and seismicity data, Cochrane (1989) noted that the so-called late-stage faults and fractures were the most seismically sensitive structures to mining-induced stress changes. On the basis of crosscutting relationships, late-stage faults and fractures were found to be the youngest structures and to have formed contemporaneously. The faults are sub-vertical, strike between NE and SE, and show strike-slip displacement. They are generally gouge infilled with strong foliation in the adjacent rocks. Fracture zones associated with these faults are sub-vertical and strike NW to SE. Fractures occur in en-echelon patterns with the zones ranging from 5 to 10 m in width. Some of the fractures show clear evidence of strike-slip displacement but many are tight with little or no infilling material. Both faults and fractures are often found in close proximity but neither appears to crosscut the other.

On the basis of a Mohr-Coulomb failure mechanism, Cochrane (1989) determined that the orientation of late-stage faults implied a stress field with major principal stress axis oriented ENE, similar to the current stress field. However, no (small strain) mechanical explanation could be found for the orientation of the late-stage fractures.

In relation to seismicity, Cochrane (1989) noted the following significant behavior:

- Many rockbursts in the Sudbury mines occurred in openings remote from the vicinity of active mining excavations.
- Rockburst damage occurred at larger distances from the source along late-stage faults and fractures, rather than in excavations equidistant from the source. This supported the concept of triggering of events resulting from changes in the static stress field rather than seismic shaking.
- Failure prone structures were restricted to those features that were formed under the current tectonic stress field. Numerous openings excavated through and in the

vicinity of other major faults did not show any indication of stress-induced failures associated with those faults.

Although seismic monitoring in the Sudbury Structure does not predate mining activities, records from a small network of surface stations have shown that seismicity within the Structure clusters around active mines. The events occurring remote from active mining excavations are therefore still within the proximity of mines, and are not part of background neotectonic seismicity (Laverdure, 2005).

2.2 State of Stress in the Sudbury Structure

Based on a variety of stress indicators, the stress field in mid-continental North America is characterized by a horizontal major principal stress with an orientation

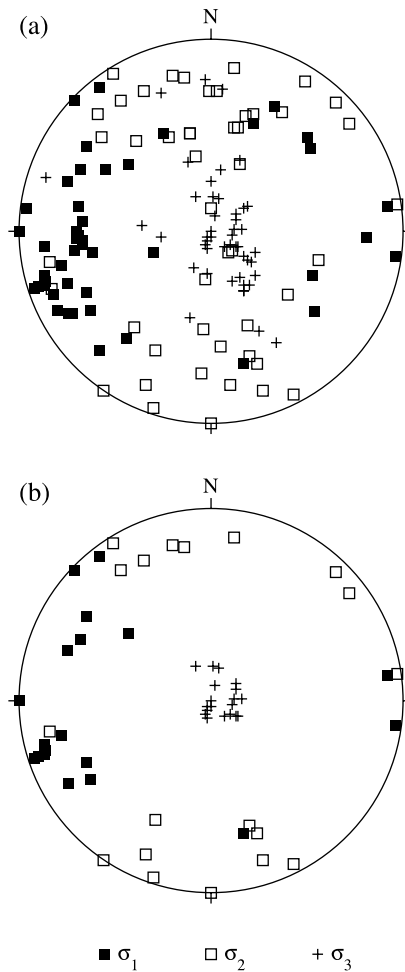


Fig. 2. Lower hemisphere projection of principal stresses, **a** Sudbury region stress measurements, **b** subset of measurements with minor principal stress within $\pm 20^\circ$ of vertical

approximately ENE (Zoback and Zoback, 1980; Zoback, 1992b). Arjang (1991) found a similar orientation for the major principal stress based on overcoring stress measurements made in mines in the Eastern Canadian Shield. Using a more extensive database of stress measurements, Arjang and Herget (1997) noted that although there are reasonable consistencies in factors such as the orientation of the major principal stress and the ratios of horizontal to vertical stresses, there was a very large scatter in the trend of the sub-horizontal major and intermediate principal stresses.

A significant portion of the stress measurements available in Eastern Canada were made in mines located in the Sudbury Structure. Poles of principal stresses measured in these mines are shown in the lower hemisphere projections of Fig. 2(a). Stress measurement data used in Fig. 2(a) were taken from Arjang (1998), plus unpublished data from INCO Ltd. (Galbraith, 2002). The minor principal stress is typically sub-vertical, which shows the least amount of scatter in orientation. The major and intermediate principal stresses generally dip sub-horizontally and have significantly higher variation in orientation compared to the minor principal stress. This is shown more clearly in Fig. 2(b), in which the data is restricted to those measurements with minor principal stress within $\pm 20^\circ$ of vertical.

When displayed in strength space, Fig. 3, the stress data is strongly suggestive of a linear envelope (for the regression line, $R^2 = 0.85$). There is also a reasonably high degree of correlation ($R^2 = 0.70$) between the magnitude of the two sub-horizontal

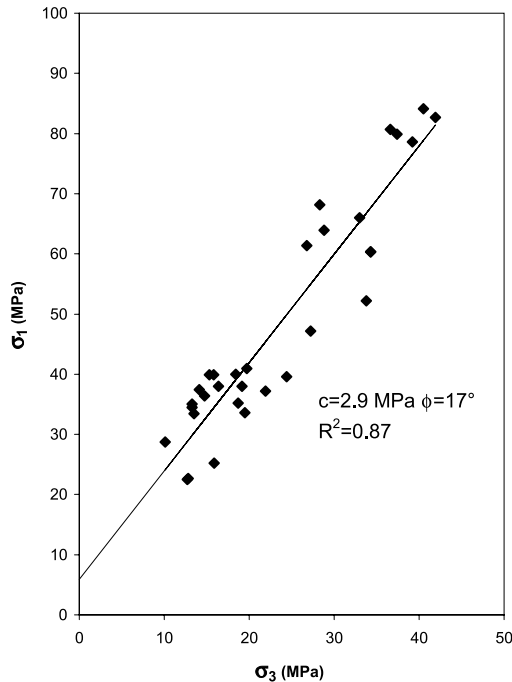


Fig. 3. Major and minor principal stress measurement data, Sudbury region. All stresses are negative (compressive)

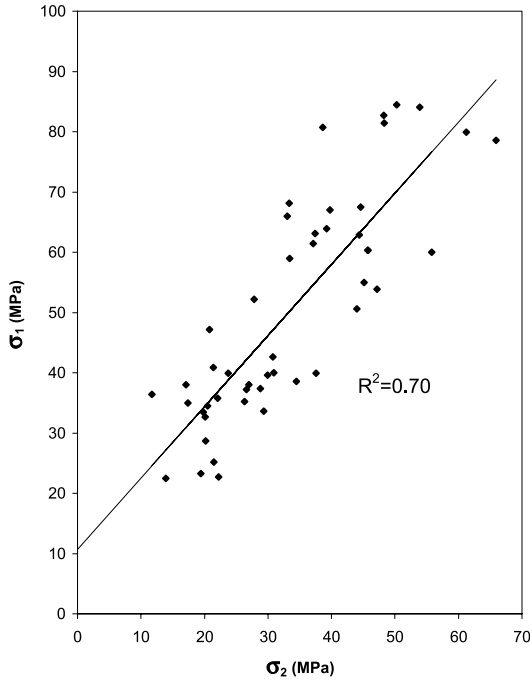


Fig. 4. Sub-horizontal principal stress measurement data, Sudbury region. All stresses are negative (compressive)

principal stresses, Fig. 4. The implication is that the state of stress is strength limited, similar to the strength envelope formed by laboratory compression tests. If stresses were not in a state of limiting equilibrium, they would not necessarily define a failure envelope. Since large scale structural discontinuities form the weakest link in the fabric of the rock mass, this correlation reflects a limiting equilibrium relationship between the state of stress and the strength of some of the faults. Simple Andersonian ranking (Anderson, 1951) of the principal stresses (the commonly used geological method of determining style of faulting that would be expected for various orientations of principal stresses) suggests that thrust faults would be the most likely candidates for marginal stability.

This leads to an apparent discrepancy between the type of faulting most favored in an Andersonian sense, i.e. stress measurements indicating a thrust faulting regime, and the apparent marginal stability of the late-stage strike-slip faults and fractures. Cochrane (1989) addressed this problem by noting that hydrofracture stress measurements made in the Paleozoic cover of the mid-continental stress province, Haimson and Doe (1983), indicated that at depth the vertical stress is greater than the minimum principal horizontal stress, suggesting that strike slip faults originated at depth and that subsequent erosion has reduced the vertical stress to the minor principal stress. The relationship between structures and stress conditions in Eastern Canada has also been complicated by repeated episodes of glaciation post-dating the formation of most structures, which suggests that the neotectonic stress field is not completely consistent

with the structural fabric. However, based on the strength-limited nature of the stress measurement data and the sensitivity of the late-stage faults and fractures to mining-induced stress changes, it would appear that these structures, as opposed to any other system, are in a state of marginal stability with the regional tectonic stresses.

This geological setting provided the framework within which numerical stress analysis was used to investigate the occurrence of seismicity remote from mining excavations. The observations of Cochrane (1989) show that geological structures are not equally sensitive to mining-induced stress changes, and that in the Sudbury Structure the most important structures to account for are the late-stage sub-vertical strike-slip faults. While the importance of other faults in the system is unknown at this time, the focus on the behaviour of the sub-vertical faults enables the numerical representation to be simplified to two-dimensions, as will be described in more detail below.

3. Review of Numerical Stress Analysis Applied to Mining-induced Seismicity

The standard approach to assessing slip on faults due to mining is well documented (CAMIRO, 1997). While the particular choice of numerical stress analysis code and method (continuum, discontinuum, boundary element etc.) may vary, the principles involved in assessing fault stability remain the same. The analysis sequence can be described by the following steps: the pre-mining state of stress is initialized, the new state of stress due to the mining geometry is computed, normal and shear stresses on the fault surfaces are resolved and compared to the assigned strength, and the potential for slip evaluated. Once the slip area has been computed, an estimate of maximum seismic moment and event magnitude can be made (CAMIRO, 1997).

If elastic continuum codes are used, faults are generally not incorporated into the models and therefore have no effect on the stress field. Slip on these virtual faults is generally assessed using the Excess Shear Stress (ESS) criterion (Ryder, 1987). Examples of this approach can be found in the work of Board (1996); Urbancic and Trifu (1998); Hanekom (2001); Beck and Brady (2002). Using discontinuum codes, faults may be incorporated explicitly into models. However, since fault surface displacement is typically equilibrated with the initial stress field, no history of deformation is accounted for and there is generally little influence of faults on the pre-mining state of stress. Examples of this approach can be found in CAMIRO (1997).

A more sophisticated approach has recently been proposed by Wiles et al. (2001). Using a boundary element method of analysis, observations of seismicity are used to prescribe a displacement on fault segments represented by displacement discontinuity elements. In this manner, a pre-strain is incorporated into seismically active fault segments, resulting in a local distortion of the stress field. This approach is promising, but is limited by the requirement that fault displacements can only be accumulated in the models based on estimates of slip computed from observations of seismicity. Significant seismic events resulting in rockburst damage can occur on faults with no prior history of activity. Also, this piecewise modification of the model is not well suited to the mine design process in which an assessment of risk is often required prior to extensive mining.

A common limitation of these methods, and in particular the issue of explaining seismic events remote from mining, is related to fundamental assumptions about fault strength, the state of stress, and the degree of stability of fault segments. The initiation of a homogeneous state of stress prior to mining and the superposition of the computed shear and normal stresses on fault surfaces (virtual or explicit) does not capture the critical interaction between the structures and the local stress field.

4. Numerical Modelling of the Evolution of Fault Systems

In order to numerically model a system of faults in a state of marginal stability, a number of approaches can be taken. It is tempting to make use of discontinuum codes, in which faults are modelled explicitly. However, there are problems related to the evolution of such systems, in particular the method of establishing compatibility of fault orientation, rock mass strength, and stress field orientation. The approach selected was to use a continuum representation starting from an initially intact material in which faults evolved as strain localizations in response to far-field (boundary) deformation. This ensured that faults would be correctly oriented relative to the evolving stress field, and that the stress field varied locally in response to changes in fault strength as a result of constitutive behavior such as slip weakening. The two dimensional finite difference code FLAC (Itasca Consulting Group Inc., 2002) was selected to carry out the stress analysis as it is well suited to modelling fractures and faulting in rock (Cundall, 1989; Hobbs and Ord, 1989; Cundall, 1990; McKinnon and Garrido de la Barra, 1998).

To enable faults to form in an initially elastic material, a strain softening constitutive model was used in conjunction with a large strain finite difference formulation for computing gridpoint displacements. A strain softening constitutive model was not essential, but sharpened the shear bands. The memory of where faults occurred in the material was provided by permanent deformation of the grid due to the large strain formulation. The two-dimensional nature of the code resulted in the formation of linear strain localizations, corresponding to strike-slip faults, which are the focus of the investigation.

4.1 Model Construction

A common problem with grid-based continuum models is the effect of grid characteristics on the formation of shear bands. Attempts to minimize these effects were made by various model construction strategies:

- Circular boundary models were used in order to minimize formation of shear bands at model corners due to stress concentrations.
- Relatively large numbers of zones were used in the models to facilitate the formation of shear bands, which typically span two or three zones. Models consisted of approximately 7000 zones.
- The initially square gridpoint geometry was randomized to eliminate regular channels of constant size zones. This reduced the tendency of shear bands to follow the alignment of grid axes.
- The Young's modulus of each zone was varied randomly about a mean value. This effect represented the heterogeneous nature of material properties. Randomizing

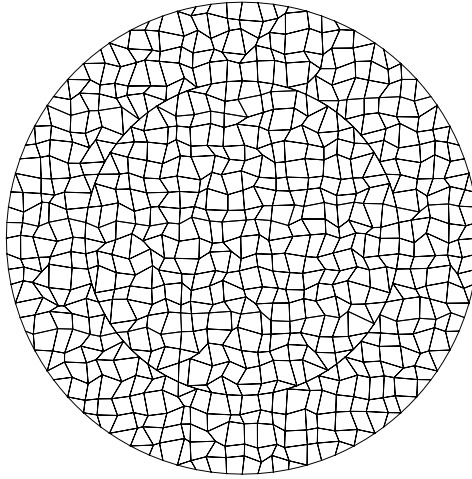


Fig. 5. Example of gridpoint randomization used to reduce grid effects on shear band formation

locations of displacement-induced stress concentration reduced grid triggering of shear band formation.

- An annulus of softer material approximately 5 zones wide surrounded the central model material. This material represented a resilient compromise between rigid displacement controlled and soft stress controlled boundary conditions, and was thought to be a geologically more realistic alternative to conventional boundary conditions.

A simplified example of the resulting model grid is shown in Fig. 5.

Similar numerical experiments were also carried out with substantially larger models than those described here. In those models, the density of shear bands was higher and fault growth (generally initiated in the interior of the models) could be tracked in more detail. However, the behaviour of these larger models was essentially the same as those described, leading to the same overall conclusions.

4.2 Material Properties, Initial and Boundary Conditions

Elastic properties for the models were chosen to represent a typical hard rock found in Ontario mines. These properties are listed in Table 1. It was found, however, that the

Table 1. Material properties

Property	Value
Uniaxial compressive strength $\sigma_{c(intact)}$	150 MPa
RMR	69
Young's modulus E_{rm}	30 GPa
Poisson's ratio ν	0.2
Cohesion c	4.3 MPa
Friction angle ϕ	55°
Tensile strength σ_t	0.5 MPa

main conclusions drawn from the models remained the same for other values of hard rock parameters.

The Young's modulus of each zone was varied randomly about a mean value of 30 GPa with specified variation chosen from a triangular distribution with a maximum deviation of $\pm 20\%$ of the mean value. The tensile strength was set to eliminate tensile failure, since the objective of the analysis was to promote the formation of shear bands representing strike-slip faults. The initial state of stress was set at the yield point of the material with a high mean stress of 25.0 MPa, major and minor principal stresses of 47.9 MPa and 2.1 MPa, respectively (compressive stresses positive). This avoided unnecessary cycling of the model from an unstressed elastic state, and avoided tensile failure. Note that these yield stresses are based on the rock mass properties shown in Table 1. The rock mass strength implied by the stress measurements shown in Fig. 3 applies to a larger scale and is not related to the engineering scale rock mass strength. However, the general conclusions from the results of these models do not depend on these details.

The prescription of appropriate boundary conditions was complex. In the crust, deformation is generally some combination of pure and simple shear. The proportion of each component of deformation is significant, as this determines the orientation of the principal stresses in the elastic regime. Using the definition adopted by McKinnon and Garrido de la Barra (1998), shown in Fig. 6, the orientation of the major principal stress for a particular combination of pure and simple shear is:

$$\psi = \frac{\pi}{2} - \frac{1}{2} \tan^{-1} \frac{1}{2 \tan \alpha},$$

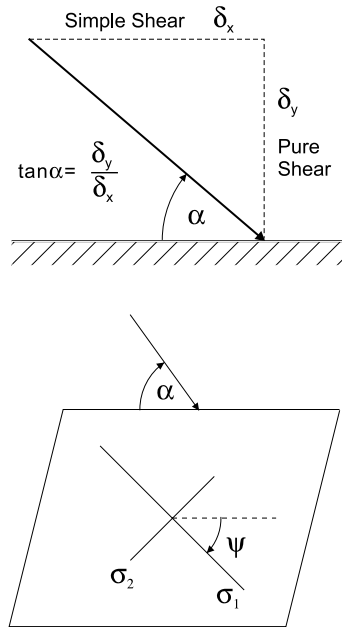


Fig. 6. Definition used for boundary displacement when combining pure and simple shear, and the resulting orientation of principal stresses (from McKinnon and Garrido de la Barra (1998))

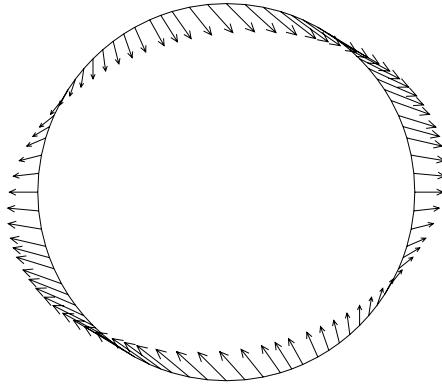


Fig. 7. Boundary displacement vectors used to reproduce equal proportions of pure and simple shear deformation

where ϕ is measured clockwise from the plane of simple shear displacement to the direction of the major principal stress (Fig. 6). Using an equal contribution of both pure and simple shear, i.e. $\alpha = 45^\circ$, the initial orientation of the major principal stress was computed as $\phi = 76.7^\circ$. Boundary gridpoint velocity vectors reproducing the initial state of stress and deformation are shown in Fig. 7. Gridpoint velocities were continuously adjusted such that they did not exceed a value of 1×10^{-5} m/step. This velocity corresponds approximately to the maximum fraction of the gridpoint spacing that can occur in one time step. By experimentation, this velocity was found to result in a small and controllable unbalanced forces at gridpoints.

5. Modelling Results

Four aspects of the modelled systems were of interest: fault evolution, characteristics of seismicity, triggering, and characteristics of the stress field in between faults.

5.1 Fault Formation

The fault pattern that developed in the modelled system, shown in Fig. 8(a), was similar in orientation to classical Riedel conjugate shears, i.e. close to the theoretical Mohr-Coulomb fracture angle of $45^\circ \pm \phi/2$ from the orientation of the major principal stress. Faults shown in this figure are represented by contours of accumulated shear strain.

Following initial fault formation, deformation in the model was accommodated largely on existing faults in preference to formation of new faults. Faults in an otherwise intact material represent weakness planes along which slip occurs more easily than formation of new faults. However, continuous slip caused fault terminations to interact with the softer annulus material surrounding the model. Resistance to fault slip gradually increased to the point where boundary deformation was accommodated more easily by formation of new faults. Deformation of the system therefore followed a complex pattern involving both slip on existing fault surfaces, and formation and slip

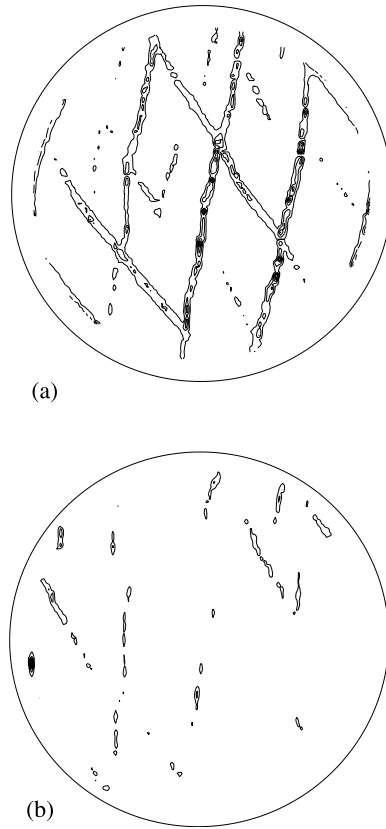


Fig. 8. **a** Faults, represented by contours of shear strain, and **b** current fault activity, represented by contours of shear strain rate

on new faults. The resulting relatively periodic spacing of faults that evolved over time tended to distribute boundary deformation throughout the system.

5.2 Characteristics of Seismicity

Fault activity was intermittent, with activity varying over time throughout the fault network. A snapshot of this activity is shown in Fig. 8(b). Contours in Fig. 8(b) are of shear strain rate, corresponding to those sections of the faults that were undergoing most rapid shear strain or slip. This behavior shows that even with constant far-field deformation, fault activity is not continuous.

This sporadic pattern of fault slip and formation was found to be the result of a complex interplay between kinematic restraint on fault slip, stress conditions, intact material strength, and the far-field boundary displacement. Intermittent slip (seismicity) was a natural consequence of this interaction, as boundary displacement was distributed throughout the model by these mechanisms. Asperities on fault surfaces

and complicated slip weakening constitutive models were not required in order to reproduce intermittent slip in the system. Since all of the faults were participating in slip over time, their stability was marginal. This aspect of the system is critical to triggering of seismicity (slip) remote from mining.

Since the time-scale for observing seismicity in mines is short compared to the mechanism of distributing far-field strain through intermittent slip on faults, short-term observations of seismic activity may indicate that certain faults are inactive. This conclusion could be misleading, in that faults participating in distributing strain may be currently quiescent but could become active at any future time. Since a region generally consists of structures that have formed through a number of episodes of tectonic activity, the modelling results indicate that those most likely to become seismically active or have the most sensitivity to mining-induced stress changes, are those that have formed or are being formed in the neotectonic stress field, i.e. those at or close to the Mohr-Coulomb fracture angle relative to the major principal stress. In a new area of mining, this result could help to discriminate which of numerous fault systems would have higher risk of seismicity.

Seismicity, both in mines and the earth's crust, has been found to follow the well-known Gutenberg-Richter magnitude frequency law (Gutenberg and Richter, 1954), in which the log of the cumulative number of events larger than a particular magnitude is linearly related to magnitude. Numerically, this relationship has typically been replicated using spring-block models (Burridge and Knopoff, 1967; Pelletier, 2000), often involving complex friction laws. The continuum representation presented here is shown to also reproduce this significant characteristic behavior. It also reproduces mechanical aspects of real systems, including boundary conditions and stresses, that are not accounted for in spring-block models.

In the finite difference scheme used, there is no real seismicity. However, shear strain rate, which is a measure analogous to seismicity, occurs through acceleration of gridpoints in shear bands due to out-of-balance forces resulting from stresses exceeding the yield strength of the material. This is analogous to fault rupture. In the model, the history of maximum unbalanced force throughout the deformation process provides a measure of seismic activity. For the model used to generate the fracture pattern shown in Fig. 8, the history of maximum unbalanced force is shown in Fig. 9. The general background of activity is punctuated by what appears to be random larger events. By sorting this history into a cumulative number of events as a function of magnitude, the characteristic linear G-R form of Fig. 10 results. The slope of this line is generally referred to as the b value. For crustal earthquakes its value is normally close to 1.0, but in Fig. 10 the computed b value is approximately 5. This difference occurs since unbalanced force is a gridpoint variable, which is not representative of the actual length of the fault segment undergoing slip in the model. Because of this, there is an overabundance of smaller "events", resulting in a steeper slope and hence higher b value.

The formation of shear bands in the type of system modelled here has been studied by Poliakov and Herrmann (1994), using a code of similar type to FLAC. They found that the formation of fracture networks was a self-organized critical (SOC) phenomenon (Bak and Tang, 1989; Grasso and Sornette, 1998), and that the length distribution of fractures was fractal, i.e., it formed a power law

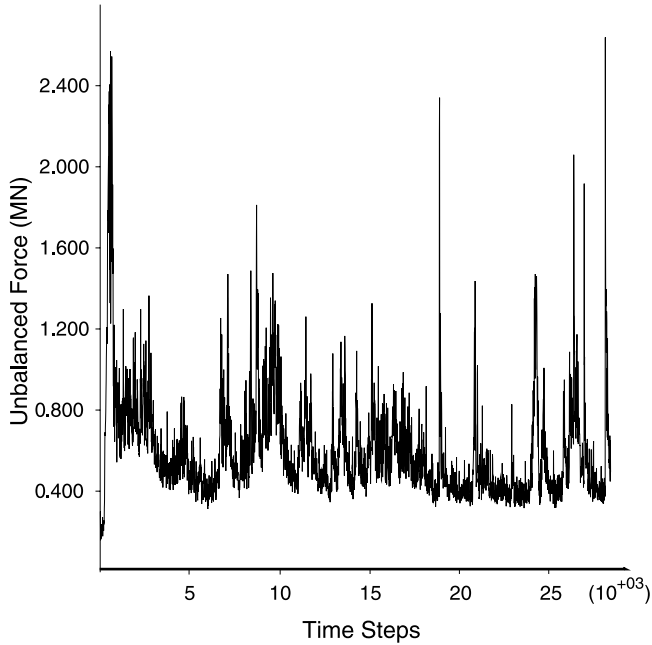


Fig. 9. History of maximum unbalanced force in the grid at each time step during deformation

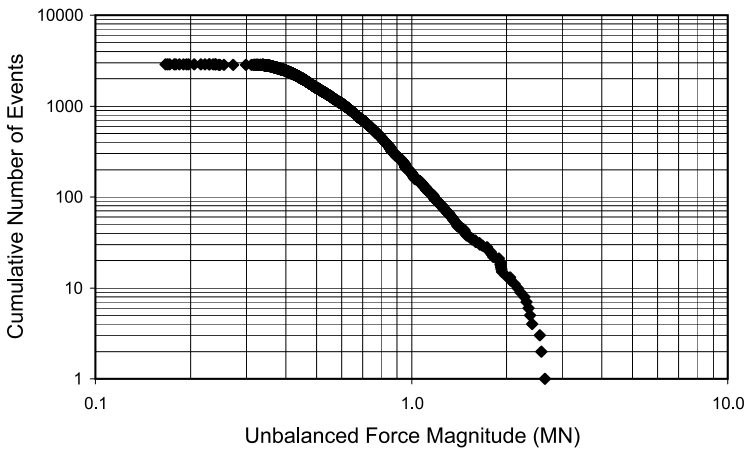


Fig. 10. Magnitude-frequency plot of maximum unbalanced force history

relationship. The similarity between the models used by Poliakov and Herrmann (1994) and those used in this study, plus the G–R form of gridpoint unbalanced forces indicates that the model spontaneously evolved into a SOC state. In the next section, it is shown that the marginal stability of faults in a SOC state

results in sensitivity to small changes in the stress field, and hence remote triggering of seismicity.

5.3 Triggering of Seismicity Remote from Mining

Since unloading due to mining is very rapid relative to the rate of geologically induced deformation, the effect of mining in the system was approximated by reducing the stresses in a small section of the model instantaneously. Stresses in four adjacent zones were reduced by 50%. The area of these four zones was very small in comparison to the area of the model (less than 0.1%) and, in an elastic system, would cause only minimal local influence. For comparison purposes, a control model in which no mining occurred was also developed. Fault slip activity in the control model at 500 time steps beyond the state shown in Fig. 8(b) is shown in Fig. 11(a). Fault slip activity in the model in which mining was simulated, after the same number

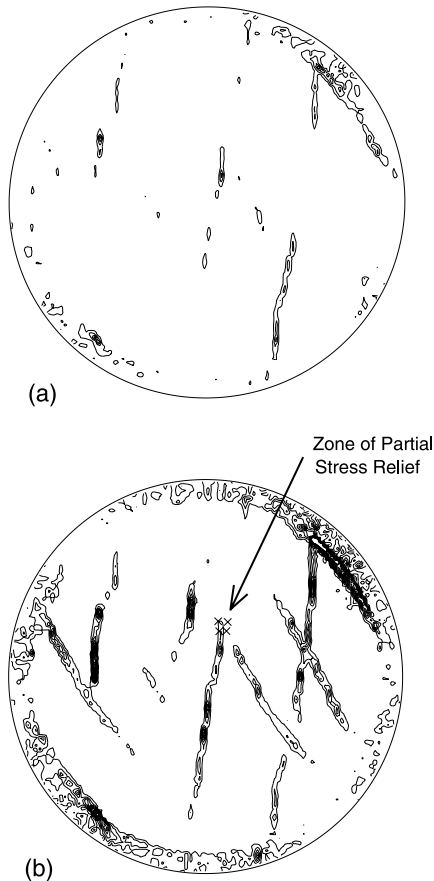


Fig. 11. **a** Shear strain rate in model with additional 500 time steps, and **b** same model including zone of partial stress relief to simulate effect of mining

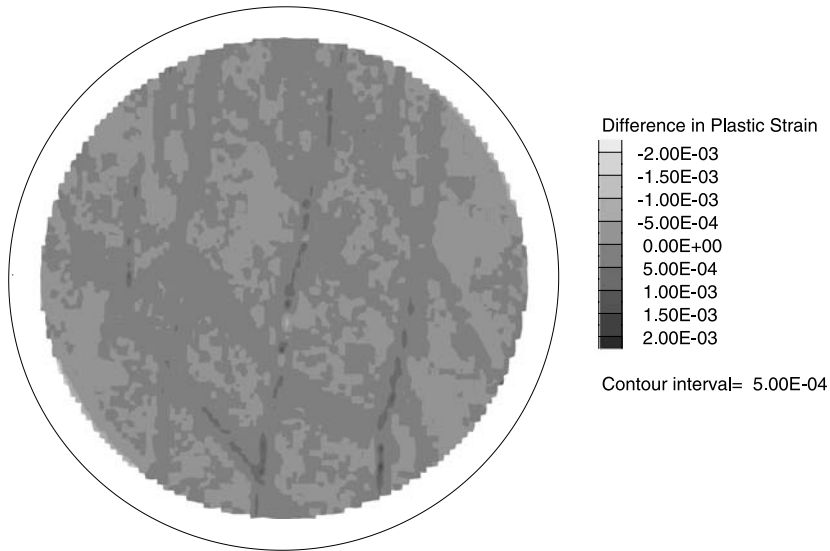


Fig. 12. Difference in plastic shear strain between models with and without mining, following 500 time steps beyond the state shown in Fig. 8

of time steps, is shown in Fig. 11(b). Crosses in the latter figure show the location of the zones that were partially stress relieved. Since the contour limits are the same in both figures, mining clearly triggered a much higher level of activity on faults in this system.

The extent of the effect of mining can be seen by comparing the difference in plastic shear strain between the control model and the model with mining. This is shown in Fig. 12. The effect was not restricted to those faults close to mining. Pervasive strain differences indicate that mining triggered a permanent difference in how the entire system evolved. This is a completely different effect than would have occurred in an elastic material, in which the induced strains would be restricted to the immediate vicinity of mining.

Similar results were obtained using a model in which the boundary deformation from the state shown in Fig. 8(a) was subsequently frozen and all residual internal gridpoint motion was relaxed prior to mining. This replicated the effect of a halt in tectonic motion while maintaining confinement, illustrating that it is not necessary for faults to be actively driven in order to be seismically sensitive to small stress changes. It is therefore possible for locked-in stresses from a prior period of tectonic activity to cause certain faults to be sensitive to seismic triggering. This behaviour required that the prior state of stress not be completely relaxed.

This result has some relevance to the Sudbury Structure situation in which the late-stage strike-slip faults appear to be most sensitive to mining-induced stress changes, but where the neotectonic stress field favors thrust faulting. After the period of late-stage strike-slip fault formation, the mechanism responsible for

reducing the vertical stress to the rank of minor principal stress has apparently not reduced the state of marginal stability on the late-stage strike-slip faults and fractures.

5.4 Influence of Fault Slip on Stress Field

In addition to changes in the stress field within fault zones (shear bands), stresses are also modified outside of faults in the form of principal stress axis rotations plus magnitude changes. Figure 13 shows an example of how the intra-block stress field varied adjacent to shear zones. Additional models showed that the effect on stress field was more pronounced as fault strength-loss was increased. More quantitatively, a history of mean major principal stress orientation (+ve clockwise from east) from this model is shown in Fig. 14(a), and the corresponding change in standard deviation of the orientation is shown in Fig. 14(b). With increasing deformation and fault slip, the stress field becomes increasingly disordered.

These results were used to interpret the scatter in principal stress directions in the Sudbury Structure measurements, shown in Fig. 2. The larger scatter in the sub-horizontal principal stresses compared to the minor (vertical) principal stress can be partially explained by the effect of faults. If the sub-vertical late-stage strike-slip faults are currently active in their accommodation of regional tectonic deformation, displacement along those features would lead to scatter in the orientation of stress components in the orthogonal plane, which for strike-slip faults is the sub-horizontal plane, (see Fig. 2(b)). Although scatter in the orientation of principal stresses is common with overcoring stress measurements, this source of error would be equally distributed amongst principal stress components. The significantly higher scatter in the horizontally as opposed to vertically oriented

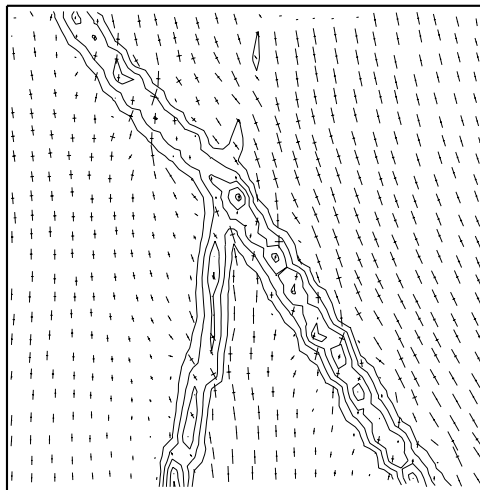


Fig. 13. Principal stress tensors adjacent to faults in a portion of a non-strain softening model

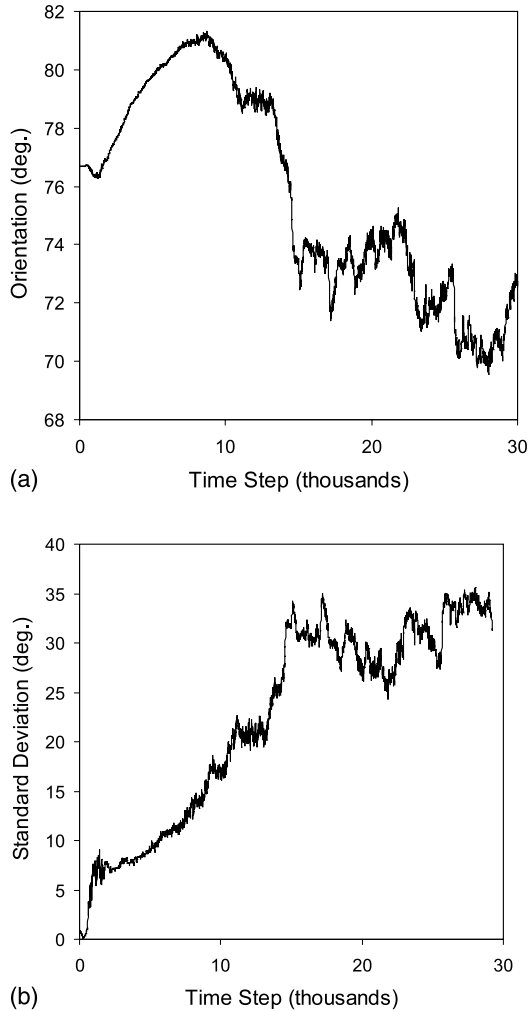


Fig. 14. **a** Mean orientation of major principal stress with deformation and **b** change in mean orientation. +ve clockwise from east, non-strain softening model

components of the stress field is consistent with the interpretation of marginally stable strike-slip faults.

6. Discussion

The influence of faults and other geological discontinuities on stress fields has been known for some time. In the engineering literature, Hyett et al. (1986) discussed conceptually their scattering effect on stress measurements and noted the influence of the geological history on the characteristics of the stress field. Cuisiat and Haimson (1992) discussed the influence of discontinuities on stress field in the context of scale effects. Stephansson and Brown (1988) reviewed the results of numerous stress

measurement programs and described the difficulties in reliably defining the state of stress in discontinuous rock masses due to the scattering effect. Martin and Chandler (1993) describe perturbations in stress field orientation and magnitude at the URL due to geological structures. More recently, Christiansson and Janson (2003) discussed the effect of various geological factors on the scatter of stress measurements. Similarly, in the geological literature, it has been recognized that major structures can divide the stress field into “domains”, across which the stress field may differ e.g. Rebai et al. (1992); McKinnon and Garrido de la Barra (1998); Pascal and Gabrielsen (2001); Martinez-Diaz (2002). Fault stability and triggering of earthquakes has been attributed to small changes in static stress; see Scholz (2002) for a review. In all cases, however, faults have been treated as independent discontinuities immersed in a uniform stress field, i.e. the complex relationship between deformation history, the stress field, and the resulting state of stability, have not been modelled.

In analyzing stress data, it has been common practice (particularly in the engineering literature) to develop a practical, and therefore simplified, description of stress fields. This is driven by the need for application of stress measurement results to engineering design, and in particular, to prescribing boundary conditions for numerical stress analysis. Thus, while it has been recognized that geological structures perturb the stress field, they have been viewed as static entities causing only local perturbations. The models described in this study have shown that the stress field variation in the vicinity of faults is part of a more interactive dynamic relationship between sets of faults in a system. The seismic sensitivity and stability of the two representations of faults is quite different. The prevalence of high horizontal compressive stress environments globally (Zoback, 1992a; Wong, 1993) would indicate that these results are widely applicable.

6.1 Implications for Stress Measurements

In order to develop a representative stress tensor for engineering purposes, the standard methodology is to carry out multiple (normally overcoring) measurements in boreholes at different locations. The stress tensor fit to the data is typically assumed to be a linear variation with depth, e.g. (Arjang and Herget, 1997). See Amadei and Stephansson (1997) for a comprehensive overview of stress measurement interpretation. Statistical treatment of stress measurements is based on the premise that an average stress condition exists, the mean stress can be recovered, and the error in its measurement estimated. The model results described here indicate that the concept of an average stress field may in some geological conditions be misleading.

This can be demonstrated using simulated stress measurements from the model previously described. Averaged over the entire system, the mean orientation of the stress field is largely preserved, Fig. 14(a). This average hides the fact that stability of faults varies throughout the system according to the flow of the stress field, which as shown in Figs. 13 and 14(b) can have significant local variation. On a local scale, the variation in orientation of the stress field may lead to the formation of compressive bridges across specific sections of a fault. If the stress field in that region were measured, a stability analysis would indicate a high degree of stability against slip due to the clamping action. However, the results of the numerical models indicate that

this does not imply that the fault would be insensitive to mining induced stress changes. Elsewhere in the fault system, the flow of stress may result in relatively low stability and high sensitivity to mining induced stress changes. Slip induced on distant sections of the fault system could lead to a cascade of stress and stability changes on previously stable sections. When considering stresses and stability, the overall state of the system must be considered. The models indicate that a minor disturbance to a system in an overall state of marginal stability can propagate over large distances and that seismicity is dependent on more than simply the state of local stress.

It would therefore be inappropriate to fit simple depth-dependent stress models to measurements made in such environments. However, from a practical point of view and due to high cost, it would not be feasible at most mines to carry out sufficient stress measurements to capture these variations. How then can the stress field be characterized for use with conventional numerical stability analysis? Currently, there is no simple answer, but knowledge of the existence and cause of the stress field variation points to characteristics of suitable techniques.

In order to map the flow of the stress field within a rock mass, a methodology enabling stress field data to be extracted from many points within a volume would be more appropriate. Gephart's (Gephart and Forsyth, 1984; Gephart, 1990) method for obtaining seismically derived principal stress orientations is such a technique. The method makes use of focal mechanism solutions of multiple seismic events, and finds the best fitting stress field consistent with computed and observed slip directions. Although the method only enables relative principal stress magnitudes to be obtained, the flow of stresses near geological structures could be used to constrain numerical models attempting to incorporate their effects (Connors et al., 1993; Urbancic et al., 1993). For example, if no distortion of the stress field were noted in the vicinity of a structure, it could be inferred that it was not affecting the stress field and could therefore be excluded from a stress analysis model. A large effect on the stress field would indicate that it was a significant structure and should be incorporated into a model. Calibration of the strength of the structure could be carried out using the seismically derived stress field flow.

6.2 Implications for Numerical Modelling

The results of this study have significant implications for numerical modelling of geological structures in mines in order to determine the impact of mining on seismicity. The "static" method of initializing a uniform stress field within the rock mass does not lead to the interaction between stress field and geological structures that appears to be required for remote seismic triggering to occur. Although continuum models were used in this study to generate such structures, it will not normally be possible to evolve the correct system of faults in a model that would correspond to structures found in a particular mine. How then can numerical models be developed to assess the effect of mining on fault stability?

Faults are physically characterized by measurable parameters such as orientation, infilling, surface roughness etc. In addition to this, some form of fault system classification related to their inter-connectivity with other faults or their relation to the stress field would be useful. The purpose of such a system would be to discriminate between

those faults that would most likely be sensitive to seismic triggering and those that would not. Their numerical treatment would be different.

Remotely triggered seismic events described in this study appear to be a self-organized critical phenomenon. Since such systems exhibit chaotic behaviour and sensitivity to model initial conditions, it is currently not possible to predict this form of seismicity deterministically using numerical models. If, on the other hand, a fault system is poorly aligned with the neotectonic stress field, deterministic stability analysis would most likely be possible using conventional methodologies (e.g. by using the ESS criterion), provided the local stress field could be adequately determined. This highlights the importance of developing a reasonable understanding of the geological history and the tectonic setting of a rock mass, from which the structures most critically aligned with the neotectonic stress field should be identified as a priority.

The most complex aspect of models to address is the stress field. There are currently no established procedures whereby the stress field can be brought to a pre-mining state of equilibrium in which the stress field varies in accordance with a marginal state of stability that may exist on numerous structures. A simple reduction in the strength of faults to a state of marginal stability would not lead to the variations in stress field flow that is a characteristic of a naturally evolved system. Seismic monitoring will likely play a significant role in calibrating fault strength and the method outlined by Wiles et al. (2001) appears to be a significant step in that direction, possibly used in combination with a stress field flow mapping technique using Gephart's stress inversion method (Gephart and Forsyth, 1984; Gephart, 1990).

Calibration of numerical models is frequently done using observed rock mass behaviour. This may include calibration of fault strength based on observed seismic events, and calibration of rock mass strength based on the extent of microseismic activity around stopes. The results of the analysis described in this study imply that some care must be exercised in using seismicity on faults to calibrate fault strength. Due to the complexity of stress field magnitude and orientation that may exist around marginally stable faults (which may not be known) the use of triggered events for calibration purposes (using the traditional method of initializing a uniform stress field and computing fault slip and event magnitude as a function of fault strength) could be misleading. However, identification of fault systems that may have marginal stability would still be valuable; positioning of significant long-life excavations such as shafts, crusher stations, repair bays etc. near these structures could be avoided.

7. Conclusions

- Mines in the Sudbury Structure have shown evidence of triggered seismicity remote from active mining excavations. Structural mapping (Cochrane, 1989) has shown that faults which formed or are being formed in the neotectonic stress field, have the greatest degree of seismic sensitivity to mining-induced stress changes. Structural mapping and seismic monitoring are important in identifying fault systems and locations of faults that are seismically sensitive.
- Stress measurements made in the Sudbury Structure indicate that the stress field is in a state of marginal stability with rock mass strength. Based on their observed

sensitivity to mining induced stress changes, it is inferred that the late-stage fault and fractures are only marginally stable.

- Numerical models used in this study show that a fault system evolved from a far-field tectonic displacement will be in a state of marginal stability. Fault slip is intermittent in these systems. Although not all faults are active at any given time in accommodating the far-field displacement, they become active over time.
- Intermittent fault slip occurs naturally in these systems under constant boundary deformation without requiring complex constitutive models or the use of asperities or barriers on the fault surfaces.
- Triggering of remote seismic events is a characteristic of marginally stable faulted systems. Excavations do not have to intersect sensitive faults in order to trigger seismicity. Due to the marginal stability of faults, long-range triggering of seismicity can occur with only minor changes to the stress field.
- In marginally stable systems, the stress field can have significant variation in both magnitude and orientation. This may be difficult to distinguish from scatter normally attributed to measurement error, but as shown with data from the Sudbury Structure, the scatter may not be equally distributed amongst principal stress components. In this case, the components of stress with the largest scatter may be used to infer which faults have the least degree of stability.
- The conventional method of initiating a uniform state of stress in elastic models used for stability analysis does not account for the history of deformation that has occurred on faults, does not lead to a metastable balance between strength and stress field, and cannot explain seismicity that occurs remote from active mining excavations.
- The interactive nature of marginally stable fault systems precludes their analysis using conventional stress analysis methods, since slip on these faults will be sensitive to small changes in stress and the initial conditions of local stress field orientation and magnitude will not be known. Classification of faults on the basis of likely sensitivity to mining induced stress changes (which could be based on their orientation relative to the neotectonic stress field) will help discriminate those faults whose stability may be assessed using conventional stress analysis methods and those that cannot.
- Identification of rock masses in which faults may be seismically sensitive can have benefits in terms of assisting support strategy and location of critical excavations.
- Stress measurement analysis techniques which attempt to fit simple depth dependent stress tensors to the data loose information that may be important in characterizing these natural stress field variations. A volumetrically based stress field inversion method, such as the Gephart's (Gephart and Forsyth, 1984; Gephart, 1990) seismically based technique could provide significant insight into the spatial variation of the stress field around marginally stable structures. Information on the stress field flow could be used to calibrate fault strength in numerical stress analysis models.
- These conclusions are specific to environments which are undergoing active tectonic compression.

These conclusions are based on inferred evidence for marginal stability (stress and seismicity data) that has been supported by the results from relatively simple two-dimensional numerical stress analysis. While the models may have reproduced some of the complexities of real systems, this does not constitute proof that the real system

is behaving in that manner. However, the conceptual framework provides a means of interpreting the observed complex behaviour, and can be tested with additional observations from other regions.

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Author's address: Dr. Stephen D. McKinnon, Department of Mining Engineering, Queen's University, Kingston, Ontario, K7L 3N6, Canada; e-mail: sm@mine.queensu.ca