

Investigating Factors Influencing Fault-Slip in Seismically Active Structures

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ABSTRACT: As Canadian mines progress to greater depths, magnitudes of induced stresses increase, becoming high enough to cause rock mass damage and failure during excavation. In addition, depending on the orientation of key geological structures in relation to the in-situ stresses, induced shear loading can be developed on these structures, creating the potential for: a) remobilization of existing geological structures, b) formation of new seismically active structural zones, created through rock mass damage and coalescence along such structural zones, and/or c) interaction between existing and newly created structures. Numerical analyses were carried out to investigate four possible factors that might cause fault slip on controlling structures, namely: (a) unclamping, (b) day-lighting, (c) stress rotation and (d) pillar shear. Application to an underground mine in the Sudbury Basin allowed verification of these factors and the proposal of two alternative mine planning methods to limit fault slip on key structures: (1) pillar clamping and (2) stope sequencing.

1 INTRODUCTION

As many Canadian hard-rock mines are progressing to greater depths (> 2.5 km), improving our understanding of the rock mass damage and failure processes around underground openings excavated within a brittle rock mass under high in situ stresses, has been an important research topic over the last decade.

At great depth, magnitudes of induced stresses substantially increase, becoming high enough to cause rock mass damage initiation and failure during excavation. In addition, the strain energy accumulated in pre-existing major fault and shear zones can often trigger severe rockbursts. Based on the magnitude of microseismic events and rockbursts experienced underground, two general zones of stress-induced rock mass failures have been typically observed in underground hard rock mines relative to the proximity of the excavations and the confinement conditions. In a simplified manner, these zones can be classified as rock mass failure developing under low and high confinement, as illustrated on Figure 1

1.1 *Low Confinement*

At great depth, rock mass damage and failure in the vicinity of an excavation develops under low confinement conditions (i.e., reduction of radial stress and increase of tangential stress) and has been described by two scenarios: a) stress-induced failure with spalling and slabbing, and b) structurally controlled gravity-driven failures (Kaiser et al., 2000).

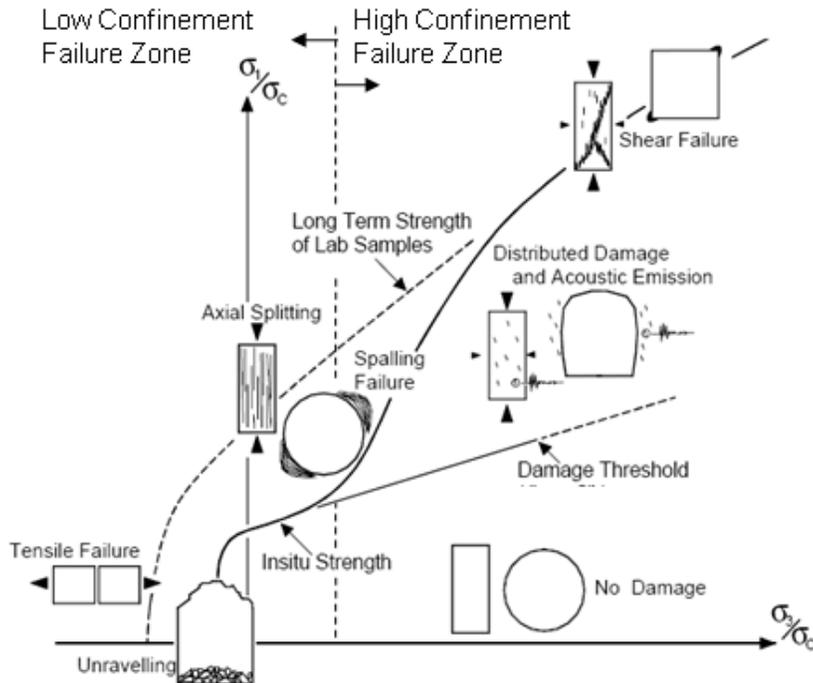


Figure 1: Schematic representation of rock mass brittle failure under low and high confinement conditions (adapted from Diederichs, 1999 & 2003).

Interpretation of the stress-induced damage processes, in a sparsely to moderately jointed high m_i rock mass (e.g., $GSI > 70$ and $Q > 20$) under low confinement, has been proposed to begin by the nucleation and propagation of extension fractures (i.e., tensile fractures formed under a compressive stress field), within the blocks of intact rock inside the rock mass (Castro and McCreath, 1997a). These extension fractures tend to grow in the direction of the major principal induced stress and, consequently, develop sub-parallel to the excavation boundary. Within the near-surface zones of the rock mass surrounding an opening, where damage has initiated, the damage process weakens the rock mass and causes a local reduction in rock mass stiffness. Weakening in this context refers to the formation and propagation of many new extensional micro- and macro-fractures extending through the intact blocks within the rock mass, thereby creating new release surfaces. After damage to the intact rock has progressed sufficiently, macroscopic failure will eventually occur. The macroscopic mode of failure and the actual rock mass "peak" strength [or system strength (σ_c)_{sys}] at which failure develops, are reflections of both the rock material characteristics and the characteristics of the specific field loading system. Important system characteristics may include: confining pressure, opening geometry, loading system stiffness, loading rate, method of excavation, type and time of installation of support, loading path, rock mass fabric (including the orientation and characteristics of the major geological structures, e.g., faults, shears, dykes), amongst others (Castro et al., 1995).

In areas of high in-situ stress and in places where no regional faults or shears exist, the movement of wedges and blocks along pre-existing, generally non-continuous discontinuities has only a minor effect on rock mass damage initiation, because the blocks are either clamped by the confining stresses or do not initially have the kinematic freedom to allow translation or rotation. The damage process thus begins by fracturing through intact rock material inside the rock mass; for example, by breaking rock bridges between existing discontinuities. As a result, valid information can be extracted from laboratory testing of intact rock as a basis for defining an initiation criterion for rock mass damage (Castro, 1996).

As a design tool, zones with the potential for rock mass damage initiation (DI) around deep excavations can readily be approximated by performing elastic numerical analyses and applying the deviatoric stress approach represented by:

$$(\sigma_1 - \sigma_3) = \sigma_{DI} \approx 0.4 \text{ to } 0.5 \sigma_{ci}$$

where σ_1 and σ_3 are the major and minor principal induced stresses respectively, σ_{DI} is the threshold stress for damage initiation and σ_{ci} is the uniaxial compressive strength of the intact rock measured in the laboratory (Castro, 1996, Castro et al., 1997b, Martin et al., 1999 and Diederichs, 1999).

As damage accumulates, it progressively changes the internal structure of the rock mass by the formation and propagation of new extension fractures and release surfaces, which increase the kinematic freedom for movements of blocks along combined surfaces including the existing discontinuities and the newly forming damage zones within the previously intact blocks of rock.

When the deviatoric stresses $(\sigma_1 - \sigma_3) = (\sigma_c)_{sys}$ reach approximately 0.6 to 0.8 σ_c , estimated using elastic numerical analyses, more specific zones of potential rock mass failure can be expected (Castro et al., 1997a). This transition in conditions, represented on Figure 1 by a sigmoidal failure criterion, has been represented in elastic and plastic numerical analyses using a bi-linear failure envelope cut-off for the occurrence of stress-induced slabbing in brittle rock masses (Kaiser et al., 2000), by a modified pair of Hoek-Brown spalling failure curves (Carter et al., 2008) and most recently using a S-shaped failure curve-fit (Kim & Kaiser, 2008).

Under low confinement, structurally controlled gravity-driven failures around open stopes have been addressed by applying the empirical stability graph method, initially proposed by Mathews et al. (1980) and revised and updated by many, including Potvin et al. (1988), Suorineni (1999, 2000) and Mawdesley (2004). The influence of a single fault in close proximity to a stope wall has been investigated using this stability graph approach and adding a parameter F (Fault Factor) when estimating the modified stability number, N^* (Suorineni, 1999). However, there has not been sufficient research investigating stress-induced fault-slip failure in regions with low confinement conditions, which on many occasions occur associated with the release of strain energy in the form of a rockburst.

1.2 High Confinement

Although significant progress has been made towards the estimation of strain bursting and the application of enhanced ground support in deep underground mines (e.g., Camiro, 1996), new research development is required to improve our understanding of fault-slip types of rockbursting, particularly in a Canadian setting (e.g., Vertical Retreat Mining type of deposits). These bursts are usually of high magnitude and can cause severe rock mass failure around underground openings, particularly when they occur relatively distant from the excavations. In such fault-slip bursts, because of high confinement, it appears that shear loading controls rock mass failure.

While there is some knowledge from geological and earthquake studies and from rock mechanics work carried out for the deep mines of South Africa, notably by Ortlepp (1978, 2000) and others; because geological conditions vary from mine site to mine site, it is currently not possible to anticipate in Canadian mines where and when a fault-slip type of rockburst will occur during production mining.

In many situations, mining complications are generally experienced only when the orientation of key geological fabric in relation to the in situ stress induces shear loading on incipient, pre-existing structures. When this happens in a typical mine environment it creates the potential for: a) mobilization of pre-existing geological structures, b) formation of new seismically active structural zones (or deformation bands), formed through rock mass damage (extension fracturing) and fracture coalescence along these structural zones (corridors or bands), and/or c) interaction between existing and newly created structures.

Recent experience in one Canadian mine (Bewick et al., 2009), lead to the realization that our understanding of the factors and mechanisms influencing rock mass failure under high confinement was limited. Some research modelling analyses using 2D numerical codes were

therefore implemented to investigate possible factors that might cause fault slip on controlling structures under low and high confining conditions. This paper discusses the four factors that were identified from the analyses, viz: (a) unclamping, (b) day-lighting, (c) stress rotation and (d) pillar shear. Each of these factors is examined in more detail in Section 3.0 with relation to how each improved the understanding of the geologic structure controls that can lead to rock bursting.

2 FORMATION OF NEW FAULTS OR SHEAR ZONES

Analysis of the mining induced seismicity that developed at Garson Mine in Sudbury indicated that the majority of microseismic events experienced in the last 2 years neither occurred immediately after a stope was mined nor were located close-to or around a stope, drift or excavation boundary; instead they tended to occur along new and/or along pre-existing major geological structures. Using a seismic plane clustering algorithm (Vasak et al., 2004), it was found that a preferred orientation existed of seismically active planes with the dominant active planes dipping 35°-55° to the South. In addition, several known geologically interpreted structure zones that interconnected with these preferred planes were also mobilized within an overall corridor of more seismically active features, designated the 45° Structure Zone (Bewick et al., 2009). Further seismic analyses showed that structure-structure intersection and interaction played a key role in the spatial linking of the various parts of the zones with increased seismic activity occurring by transfer between the structures as mining progressed.

Based on geological analysis of the seismic plane clustering data using stereographic projections, it became apparent that the 45° Structure Zone constituted a “thrust or reverse” fault type of feature. This inference could also be drawn from evaluation of the in-situ stress state at Garson, based on standard Anderson (1951) fault mechanics. In the Anderson theory of faulting, thrust faults typically are assumed to form in the plane parallel to σ_2 , when the major principal in situ stress is horizontal and the minor principal in situ stress is vertical, and when the minor principal induced stress σ_3 remains more or less constant and the major principal induced stress σ_1 increases.

However, ironically even though the presence of a pre-existing structural fabric offset had been postulated from exploration drilling interpretation as something of this sort of orientation appeared responsible for ore-zone offsetting, no significant features along these trends could be identified from underground mapping, neither within the defined projected 45° Structure Zone nor bounding it. Instead, only quartz veins in an en-echelon geometry were observed underground, and only in a few locations. The hypothesis put forward for further examination was that the 45° feature was not a fully formed reverse fault, but existed only in embryonic form as a band of en-echelon tension gashes (of similar geometry, but different scale to the features illustrated on Fig. 2). As such, the possibility existed that the main fault structure only would be represented underground by sporadic tension gashes that likely would be infilled with quartz or other mineralization, and only where significant tensile/extension fractures had allowed injection of hydrothermal fluids. If so, as almost all of the infill appeared to be siliceous this possibly also might make the 45° zone stronger and more brittle than the adjacent rock mass and, consequently, it would also concentrate stress towards it.

This sort of induced macroscopic shear structure (or deformation band) formation is not unknown (ref. Gay & Ortlepp, 1979, Ortlepp 1978 & 2000, McGarr, 2002, Schultz & Balasko, 2003, Shipton et al., 2006). In the case of South African mines, such features have been labelled as “shear fractures or ruptures” forming ahead of advancing stope faces and clustered about the plane of the tabular mining (Ortlepp, 2000, Fig. 2).

As described by Gay and Ortlepp (1979), “*The shear zones are themselves made up of smaller, en echelon shear planes, which are connected by subsidiary conjugate shears and extension fractures. These shear planes become diffuse and are replaced by extension and bedding-plane fractures at the boundaries of the fault zone.*”

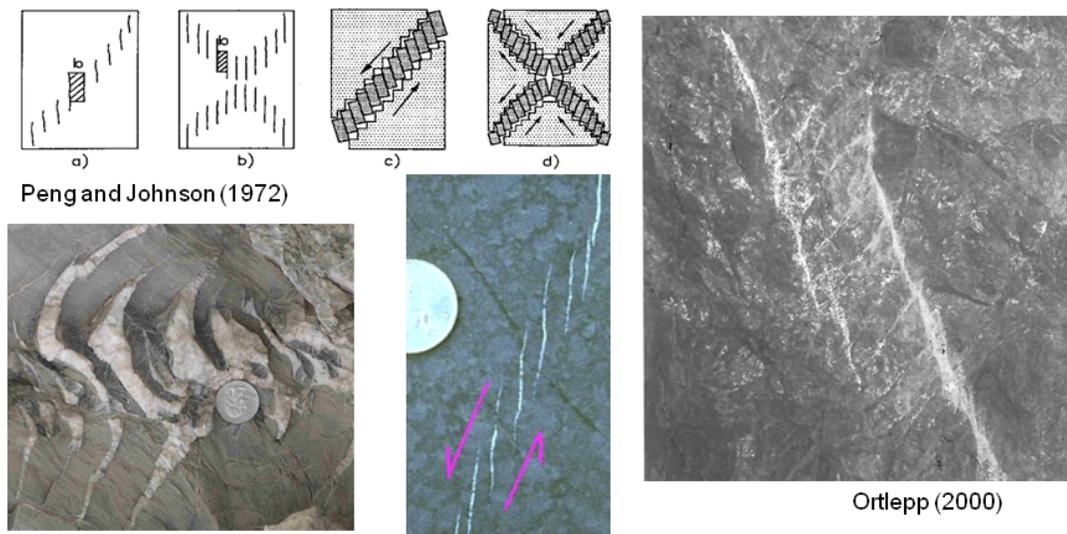


Figure 2: Typical embryonic fault zone fabrics analogies with an idealized conceptual model with the nucleation of extension cracks (or fractures) followed by the formation of an en-echelon fabric under shear loading.

In addition, the microscopic observations of the shear planes suggested the following sequence of events resulting in the formation of such faults: (1) development of extension fractures in the region of planes of maximum shearing stress, (2) coalescence of extension fractures to form conjugate shear planes, and (3) rapid movement along the more favourably oriented of these shear planes to form the major gouge zones and feather fractures (Gay and Ortlepp, 1979). Again, similar to observed under low confinement, the formation of a macroscopic shear zone or deformation band appears to initiate by the nucleation and growth of extension (induced tensile) fractures, but in the case of high confinement, they develop within a shear zone / shear rupture (Ortlepp, 2000) / deformation band or principal slip zone (Shipton et al. 2006) (Fig. 3).

However, there is debate on the magnitude of induced stresses needed to create such structures in intact rock (McGarr, 2002). While it is clear that the magnitudes of induced stresses that can occur when mining under high compressive stresses can over time and with increasing mine extraction, mobilize the formation of “new” fault zones; it is not clear how much influence pre-existing structural geology has on controlling this development. Nevertheless, such faults have been shown to have developed either by an increase of stresses ahead of an excavation front or by a reduction of stresses around mined out stope walls. In such cases, most of these newly generated faults have tended to be thrust type (σ_3 remains constant and σ_1 increases), however a representative group are normal (σ_1 remains constant and σ_3 decreases).

If it is assumed that seismicity is being generated from slip and/or re-opening and shear movements along pre-existing geological structures, such a tendency would to a large extent be dependent on the frictional characteristics of the contact being sheared and the ratio of shear (τ) to normal (σ_n) stress acting on the surface, as expressed by $T_s = \tau/\sigma_n$.

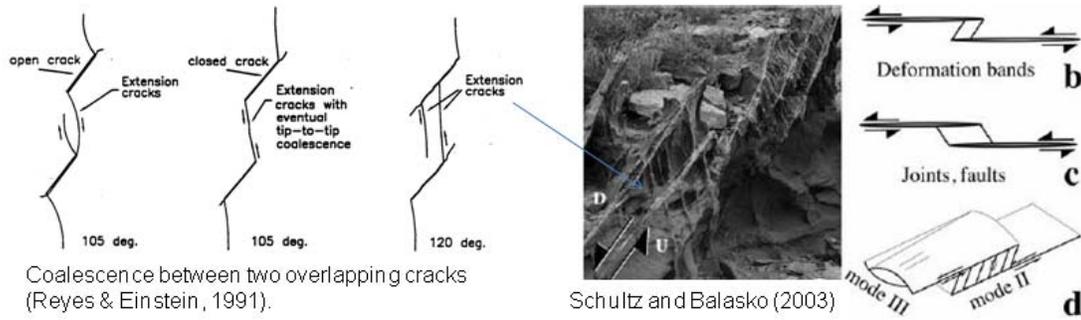


Figure 3: Examples of extension fractures within a shear zone or deformation band observed in the laboratory with gypsum samples (Reyes & Einstein, 1991) and in sandstone outcrops in the US (Schultz and Balasko, 2003).

The ease with which such shear will occur will in turn have a direct effect on the magnitude and extent of generated seismicity. Where slip is easily accomplished, little build-up of stored strain energy occurs. By contrast, if slip is restricted (by large asperity perturbations on the sliding surface, for example), large build-up of strain energy can develop; with sudden release once a certain threshold (or degree) of strain has been reached. A useful measure that can be utilized for ranking geologic structures on the basis of their likelihood to build large strain energy prior to shear release is therefore to calculate their potential dilatancy. The dilation tendency of any given fault or geologic contact margin is relatively straightforward to compute because it is mainly dependent on the normal stress acting on the structure and the natural waviness or undulation of the surface under examination. Thus, assuming similar planarities for the structures of concern, a first order estimate of dilation tendency can be made for a given stress field (stress magnitude and orientation) and for a given fault orientation (dip and dip direction), as follows:

$$T_d = (\sigma_1 - \sigma_n) / (\sigma_1 - \sigma_3)$$

where the shear and normal stresses have been resolved in the plane of the geologic structure and where the dilation tendency T_d , as calculated from this expression, varies from 1 for faults with the highest dilation tendency (more likely to build strain energy) to 0 for faults with low tendency for dilation on shearing (i.e., more easily able to slip without large delayed strain release).

Based on this assessment using the Garson in situ stresses, it was found that maximum dilation tendency would occur on horizontal and sub-horizontal surfaces, as these would be more or less perpendicular to σ_3 (which is oriented near vertically at Garson - Fig. 4). The analyses however, suggested that the maximum likelihood for shear band development across the mine-wide fabric might be for structures oriented at 45°. Dilation in such a zone might then preferentially occur on embryonic flat structures, potentially eventually coalescing into a true fault structure, such as recognized by Ortlepp and others, and which might occur initially as an offset shear band (e.g., Schultz and Balasko, 2003); the inference being that, a hierarchy of potential shearing (and hence seismicity) might well develop, simply dependent on structure orientation with respect to prevailing stress state.

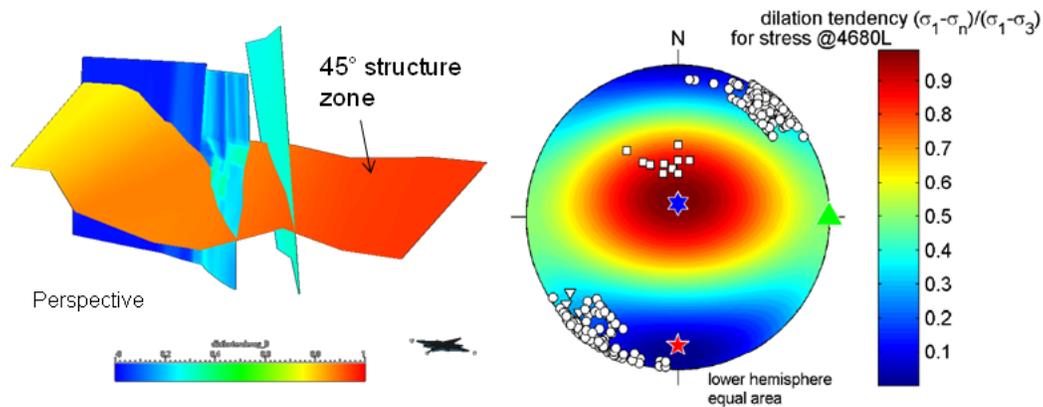


Figure 4: Dilation tendency for the 45° Structure Zone.

3 POSSIBLE FACTORS INFLUENCING FAULT-INDUCED SLIP

Given this postulated engineering geological model (EGM) of feasible structure creation and seismicity, a number of possible factors were examined as potential causative mechanisms for inducing fault slip on key geological structures, (ref. Bewick et al, 2009 for more details on the Garson mine EGM). The four factors considered of importance in controlling seismicity development viz. (1) unclamping, (2) day-lighting, (3) stress rotation and (4) pillar induced shear were each examined to check for (a) potential fault slip initiation if pre-existing structure was unfavourably oriented, or (b) for creating embryonic shear bands where intact rock predominated within the mine wide area.

Based on this examination, it was found that generally there were some spatial relationships evident between mining activity and seismic activity, which suggested that failure of structural features was triggered mostly by their unloading (decrease of their apparent shear strength due to mining induced stress change).

1. *Unclamping*: Two scales of unclamping can be considered: Local Unclamping occurs when the induced tensile stress field, created by mining one or a few stopes, overlaps a nearby pre-existing geological fault. If sufficient reduction in the normal stress acting across the fault plane occurs, such that it is reduced below a certain threshold level, fault slip occurs. If the fault in such a hypothetical situation exists close to the mining excavation, a free-face is available close to the slip location where energy can be radiated. Generally, this is where any rockburst damage would be concentrated. Based on back-analysis of the data collected as part of the Garson study, it was found that typically, the size of the rockburst resulting from fault slip induced by local unclamping could be related to the volume of the triggering excavation and the area of free face available for the rock mass to dilate into.

Regional Unclamping occurs when the extent and size of mining excavations becomes sufficiently large that the overall induced tensile stress field in the adjacent country rock mass overlaps one or more faults, resulting in an unclamping effect on faults existing within this region and occurring away from any actual mining excavations. The mechanism of slip is the same as for localized unclamping of the contained fault structures within the de-stressed zone, but in this case there is no nearby free face. Where regional de-stressing develops and faults become “unclamped”, seismic activity can develop at significant distances from any mining and seemingly in an area unconnected to the mining operations. As found from the Garson experience, where this sort of phenomenon occurred, faults were observed to slip as a consequence of regional unclamping in zones nowhere near, or intersecting the mining excavations. Based again on recent Sudbury experience, the size of rockburst resulting from such forms of regional unclamping appear to be related to the

amount of strain energy previously stored on the source fault before it slipped, which is extremely difficult to determine.

Discussion: Local Unclamping versus Regional Unclamping Rockbursts

Although, in general, the occurrence of the local unclamping fault-slip bursts can be more frequent than regional bursts, because they are of somewhat lower magnitude compared to regional unclamping fault-slip bursts, their occurrences can be, in general, managed during mining operations. This could include, for example, de-stress blasting of specific areas, installation of enhanced support (e.g., with additional energy absorption capacity) considering the potential for a strain type of rockburst to occur and/or adjusting re-entry time and decay period after stope blasts. The regional type of fault slip bursts by contrast, although not frequent, are much more dangerous due to their magnitude (i.e. amount of stored energy released) and location away from the mine openings. They tend to cause severe damage to the rock mass and ground support in more than one location and often, since their occurrences cannot be anticipated, present a major hazard for the mine. In addition, their occurrences can also trigger other seismic events causing even wider spread damage.

2. *Day-lighting*: When an actual mine stope intersects a geological fault (Figure 5). Local unclamping of a fault may also be accompanied by concurrent, or subsequent, day-lighting of the fault, providing freedom for the fault to slip into the excavation void. When this happens, it does so with the release of a large amount of strain energy, often accompanied by a large seismic event. This is particularly true if the fault has already been subjected to earlier mining induced movement that may have resulted in a large, locked-in, shear stress remaining in place along its surface. In many cases, day-lighting faults could slip before the advancing drift face or mining front reaches them, due to localized basic unclamping, suggesting that enhanced support is required to be installed say, at least 15 m prior to approach of a fault zone.

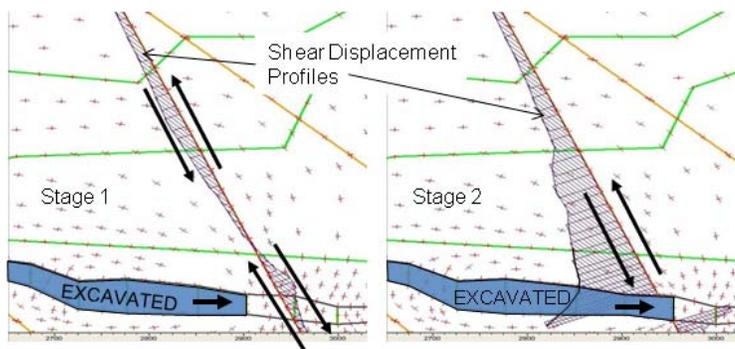


Figure 5: Day-lighting of a fault allows the release of shear slip.

3. *Stress Rotation*: As mining progresses, typically the stress field ahead of the active mining face curves around the void created by the stope which, in turn, causes rotation of the stress tensor in the area around the face, as shown in Figure 6. This can result in a situation where the major principal induced stress can switch from being oriented normal to the fault plane (where it would provide positive clamping to the fault plane, e.g., Stage 1 on Figure 6) to becoming more parallel with the fault plane (where it would tend to exert a shearing effect which could induce slip, e.g., Stage 2, Figure 6). It also highlights a popular misconception that it is always best to mine perpendicular to a given fault. Depending on the induced stresses, this may not be the best direction to cross the fault.

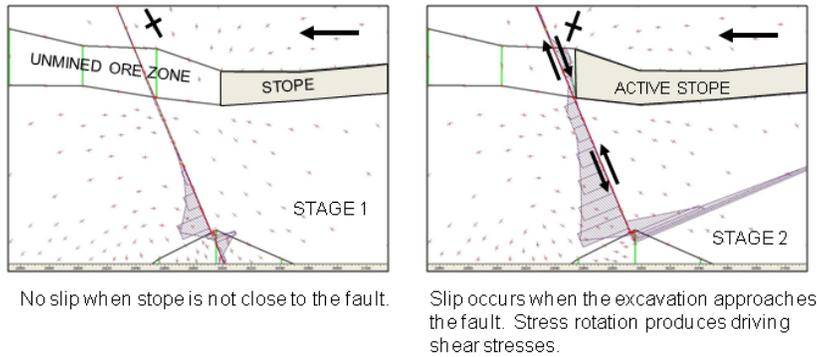


Figure 6: Fault slip caused by stress rotation due to approaching excavation.

4. *Pillar Shear*: Pillars intended to help clamp faults can, in some circumstances and particularly in the case of a day-lighting fault, inhibit displacement of the rock mass on one side of the fault whilst leaving it free to move on the other, creating a situation likely to induce rather than restrain fault slip. Figure 7 shows how the positioning of pillars relative to a fault location can play a vital role in controlling the stability of the fault. In the left hand diagram, mining took place without any pillars being left in the stope. Significant left-lateral shear slip is seen on the fault to the south of the stope but no shear slip is seen on the region of the same fault to the north of the stope. In the right hand diagram, pillars are left in the stopes (shown in black). While the eastern pillar clamps the fault and prevents most of the slip that was previously observed to the south of the stope, it also supports the rock mass north of the fault on its eastern side allowing the rock mass on its western side to dilate into the stope void, with accompanying shear slip on the fault in that region.

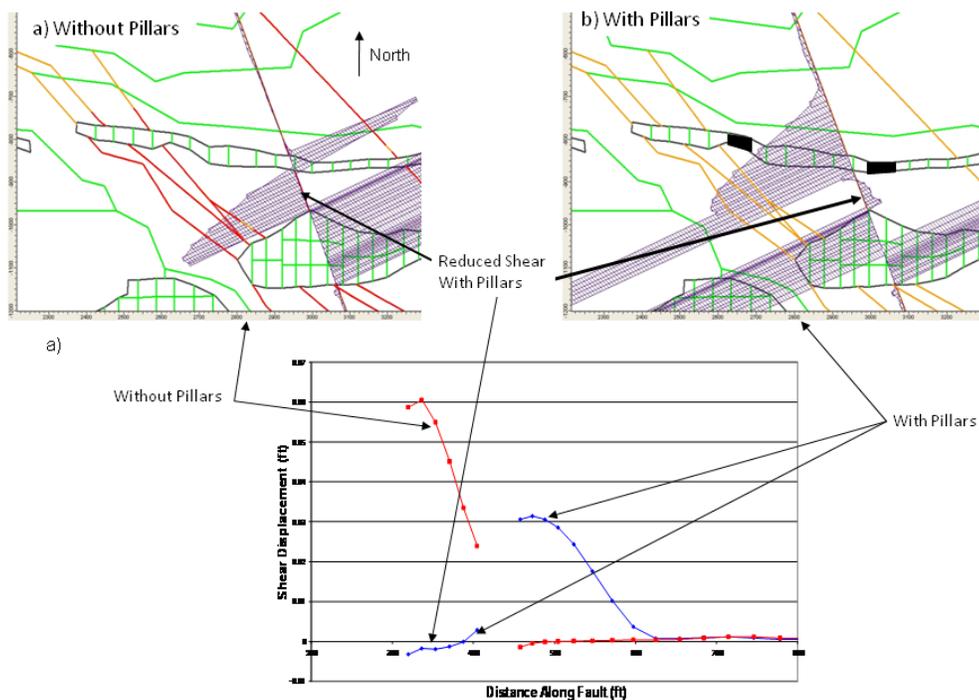


Figure 7: Placement of pillars could assist in minimizing fault-slip.

It is important to note that also, while each of the four fault slip factors [unclamping (local and regional), day-lighting, stress rotation and pillar shear] can act in isolation, very often two or more of the factors operate together, complicating the implementation of mining solutions to mitigate the likely adverse effects created by the induced movements.

3.1.1 Possible Mining Solutions to Control Fault Slip

Based on careful scrutiny of the various models created to analyze key active structures at Garson mine, two methods of preventing, or limiting, fault slip on the NW fan of splay faults (Bewick et al., 2009), namely: (1) pillar clamping and (2) stope sequencing were considered:

1. *Pillar Clamping:* Theoretically, leaving pillars to limit stope spans reduces the tensile zone around any stoping. This, in turn, would tend to reduce the amount of potential unclamping (reduction in normal stress) that can develop on any faults in the vicinity of the stoping. However, in practice this is not always as easy to achieve and requires very careful planning of pillar layouts (temporary and permanent) if these pillars are to function well. If the pillars eventually have to be removed, this may lead to a much more adverse situation, as pillar extractions could result in very sudden large drops in clamping stress, which could cause even larger seismic events than those prevented by the original pillar layout. The use of backfill has merit for aiding control of such structures but for it to be effective a very good quality, stiff backfill would have to be used. If permanent pillars are planned, de-stressing the pillars should be considered to reduce the potential for pillar burst, but ideally it should be done after the pillar has already been loaded, passing, for instance, the damage initiation stage.
2. *Stope Sequencing:* Advancing production mining in different sequences or in different directions can be used to advantage as a method for limiting the potential for individual faults to slip (e.g., Figure 8).

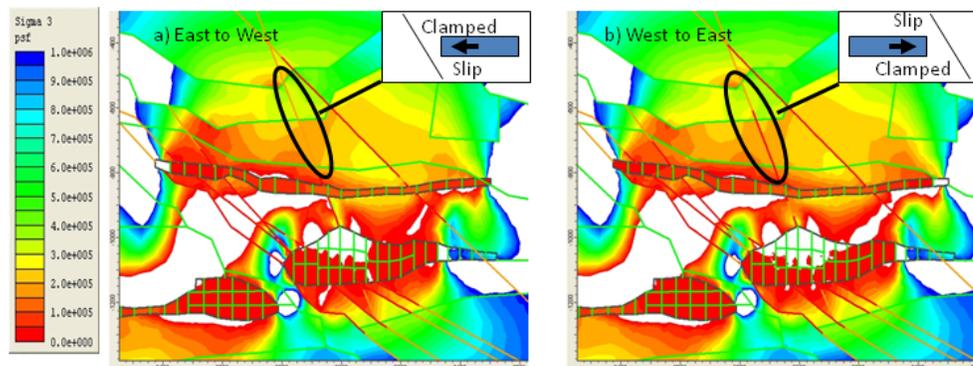


Figure 8: Evaluation of mining sequence on potential induced fault-slips.

4 FINAL REMARKS

Stress-induced rock mass damage and failure can occur both under low and/or high confinement conditions. In both conditions, the damage process seems to almost always initiate by pre-conditioning the rock mass prior to actual failure by the creation of networks of new extension fractures. Once sufficient damage or pre-conditioning has occurred to the rock mass, then overall loading and geometric system adjustment tend to exploit these damage zones through several mechanisms, thereby inducing actual “failure”.

Under low confinement, observations in the laboratory and at mine scale suggest that the onset of rock mass damage begins by the nucleation of extension fractures (formed by induced tensile stresses in a compressive stress regime) that tend to grow approximately parallel to the direction of the maximum induced principal stress (Castro, 1996). Under low confinement, the presence of pre-existing discontinuities (e.g., joints and bedding planes) appears to exert little influence on the process of nucleation and propagation of the new extension fractures.

In regions of high confinement, by contrast, macroscopic fault or shear zones may form as mining develops, such as those formed ahead of tabular stopes in South Africa (Ortlepp, 1978). Several terms have been used in the technical literature to describe the formation of this type of macroscopic shear zone, such as: shear rupture, deformation band or principal slip zone. In this paper, because of morphology similar features have also been termed somehow interchangeably as “an embryonic fault zone”, a “seismically active structural zone” and/or in one specific case at the Garson mine as “the 45° Structure zone”.

Using the South African experience that these major structural features (or zones) tended to only show significant damaging signs of shear displacement near stoped zones, where the kinematic conditions for shear deformation were most favourable, for shear release, numerical simulations were carried out to investigate four factors that could help identify potential for adverse fault-slip, as described in Section 3.0.

Similarly to the low confinement conditions, the damage process for the formation of these macro shear zones may also start by pre-conditioning the rock mass with the nucleation and growth of extension fractures. Such extension fracturing would likely tend to be a clean surface exhibiting no signs of shear displacement and being associated with high dilation in the direction normal to its propagation. The difference to the low confinement case, however, seems to be that when under high confinement, these extension fractures rather than immediately coalescing, they may develop in an en-echelon pattern, within a zone (corridor or deformation band) created under an overall shear loading or stress condition.

Except for a few observations from deep mines in South Africa (Ortlepp 1978, 2000, (Fig. 2) McGarr, 2002, and from surface outcrops (e.g., Schultz and Balasko, 2003, Fig. 3), these fault or shear zones have not been mapped or described as such in Canadian underground mines. However, their formation may have been recorded by microseismic systems and described as fault-slip types of rockburst, as in general they inevitably generate high magnitude events when they fail.

In this paper, it is proposed that in addition to their being created essentially from “scratch”, on some occasions they may exploit previously weakened geological zones. This is evidenced by en-echelon patterns of pre-existing extension fractures that have already been formed and filled with quartz (or dykes) in the geological past. Such features could now be reactivated by shear loading to create a new macroscopic shear rupture in response to changes in induced stresses created by mining.

More research is however required to better understand such rock mass behaviour under high confinement conditions around large VRM stopes in Canadian mines.

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