

Mining of orebodies under shear loading Part 1 – case histories

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The conditions for rockbursts occurrence are traditionally identified as: high stress, high extraction ratio, strong brittle rocks, folding, faulting and unfavourable excavation geometry. Some rockbursts cannot be explained by any one or a combination of these factors. Salamon (1983) stated that a disconcerting feature of rockbursts is that they defy conventional explanation. Based on detailed review of case histories, this paper identifies oblique loading of orebodies by the major far field principal stress as a cause of rockbursts. Orebodies subjected to this loading condition are termed orebodies in shear. Orebodies in shear are subjected to compressive and shear loads. This paper shows it is risky to generalise that tabular orebodies have their axis perpendicular to the major far field principal stress. This study identifies characteristics of orebodies in shear and the consequences of not taking this loading mechanism into account in the planning, design and mining of such orebodies.

Keywords: Orebodies in shear, Stress orientation, Case histories, Rockburst, Dilution, Orebody geometry, Mine planning, design

Introduction

Background

The factors previously identified as favourable conditions for the occurrence of rockbursts include high extraction ratio, strong brittle rocks, depth (high stress), and discrete geological structures such as faults and shear zones. Hedley (1992) states the following factors as causes of rockbursts: hard brittle rocks, mining depth, structural features (joints, faults, dykes), dip of orebody, and stoping sequence and mining rate. Blake and Hedley (2003) summarise the causes of rockbursts as follows:

‘Most of the hard-rock mining districts throughout the world that experience rockbursting have many similarities. They are in an initially high stress environment owing to depth, tectonic forces, or a combination of both. The shape of the orebody is tabular and thickness of the vein or width of the seam is usually <5 m. The direction of the major principal stress is usually perpendicular to the tabular dimension. The extraction ratio is high, usually >80%. The wall rocks, and often the vein or seam material, are very hard, brittle, and strong, as well as being old geologically – mostly of the Precambrian age (greater than a billion years old). In addition, the geology is often very complex with respect to folding, faulting and metamorphism.’

Not all the causes of rockbursts are known. Blake and Hedley (2003) state that rockbursts occurred at a depth of 150 m at the Director Fluorspar Mine in Newfoundland and on the surface in granite quarries in

Vermont. Homestake Gold Mine in South Dakota did not experience rockbursts until at a depth of 2100 m after operating for a century. Blake and Hedley (2003) report that the worst rockburst in North America occurred in the Solvay Trona Mine in Wyoming in 1995 with a magnitude of 5.2 local magnitude (M_L). These observations contradict current understanding of causes of rockbursts. Salamon (1983) states as follows:

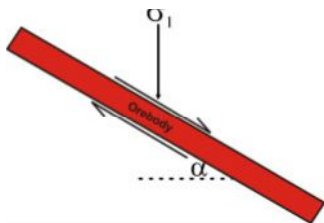
‘A disconcerting feature of rockbursts is that they defy conventional explanation.’

The geometry of an orebody as it relates to the principal stress orientation has been paid little attention as another cause of rockbursts. Mining engineers have been given the wrong impression that most orebodies have the major principal stress perpendicular to the strike. Ariang (1991) concluded that a common feature at mines with near vertical orebodies is that the maximum horizontal principal stress acts perpendicular to the strike while the minimum horizontal stress is aligned on-strike. Blake and Hedley (2003) states that for tabular narrow vein (width, <5 m) orebodies the direction of the major principal stress is usually perpendicular to the tabular dimension.

Orebody geometry is controlled by its genesis and can be complex or consist of multiple lenses at different orientations. These characteristics also influence the magnitudes and orientations of *in situ* stresses. For these and other reasons the major *in situ* principal stress may not be aligned perpendicular to an orebody but oblique to it. Because most orebodies are complex and most occur as multiple lenses, we conclude that there are more orebodies with major far field stresses oblique to them than has been suggested. Further details of causes of oblique loading in orebodies are discussed in the section on ‘Causes and evidence of shear loading in orebodies’.

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1 Schematic of shear loading mechanism due to major principal stress being oblique to orebody dip: α is dip of orebody in degrees

Experience at the Geomechanics Research Centre (GRC) (Kaiser and Suorineni, 2005) over the past 10 years from three orebodies with major far field stress oblique to the strike or dip shows several characteristics that differentiate them from those having major far field stresses perpendicular to the strike or dip. It was observed that these orebodies were characterised by unusually frequent seismic activities at locations where they were least expected during mining. In addition to the severity and frequency of seismicity in these orebodies, they are also associated with major dilution problems. Despite these major problems associated with mining orebodies with major far field stresses oblique to the strike or dip, little information exists in the literature on any detailed studies to understand and mitigate the problem. In mine planning and design, less attention than expected is paid to situations where the major far field or driving stress orientation is oblique to the orebody axis.

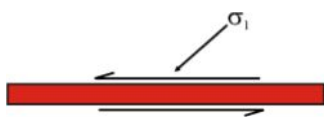
Definition of orebodies under shear loading and knowledge gap

When the major far field *in situ* or driving stress is oblique to the dip (Fig. 1) or strike (Fig. 2) of an orebody, it subjects the orebody to both compressive and shear stresses. In this paper, these orebodies are termed orebodies in shear.

When mining orebodies under shear loading, depending on the mining method and planned extraction sequence, pillars and excavations will be subjected to both compressive and shearing stresses. As explained above, planning of the extraction of orebodies in shear assuming that they are loaded in pure compression as suggested by Arjang (1991) and Blake and Hedley (2003) can result in unintended consequences. Orebodies under both compressive and shear stresses behave very differently from those subjected to pure compression. However, except for a few isolated cases, shear loading is rarely identified as a source of rockbursts in mines.

Objectives and approach

Geomechanics input to mine planning and design is required for the establishment of stope and pillar dimensions and sequencing, type and timing of backfill,



2 Schematic of shear loading mechanism due to major principal stress being oblique to orebody strike (plan view)

overall direction of mining advance and the overall mine infrastructure layout. These parameters are established either empirically, numerically or a combination of both. Empirical approaches are based on observations and experience. One limitation of empirical approaches is that the mechanics of the problem is always unknown. This can be offset if they are applied to cases similar to the ones on which the database and experiences are based. On the other hand, the success of numerical modelling approaches strongly depends on an understanding of the physics of the problem. The limitation of this approach is that the input parameters are rarely known exactly. In both cases, therefore, one has to understand the environment in which he is working to successfully apply the approach.

In this paper, case histories of problems encountered such as rockbursts and high dilution during mining of some orebodies are critically reviewed to show that shear loading was the major cause of the problems, and hence to create awareness in the mining industry that in mine planning and design, the generalised assumption suggested by Arjang (1991) and Blake and Hedley (2003) that the major far field principal stress is often perpendicular to the orebody axis is not always correct. Blanket application of the assumption that major far-field stresses are perpendicular to orebody strike or dip when in fact they are oblique to the orebodies can result in adverse safety issues and economic losses, as will be shown in the section on 'Case histories'.

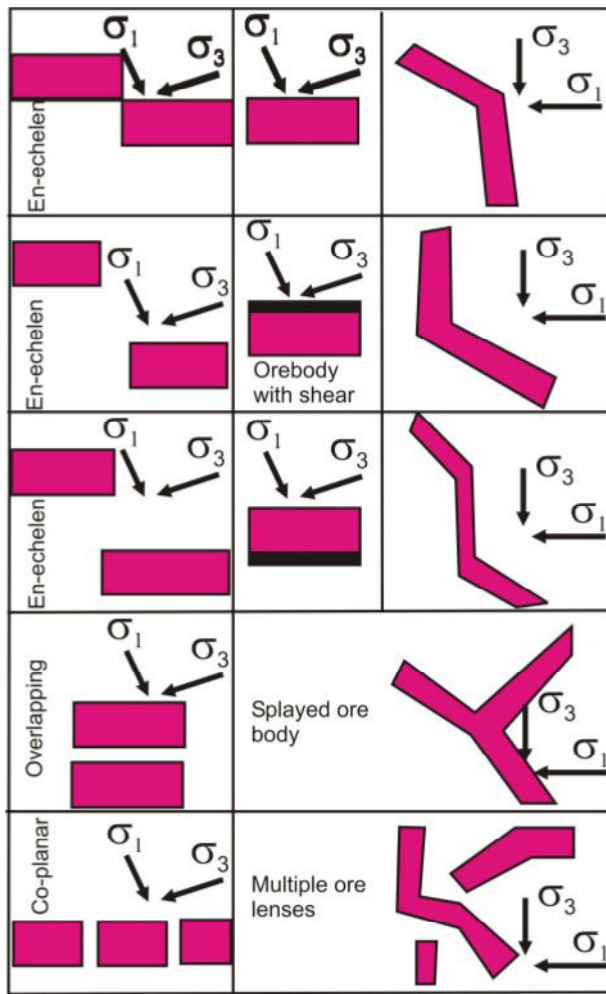
This paper is Part 1 of a two part paper focusing on the characteristics and consequences of shear loading from case histories, to create awareness, identify characteristics of this loading mechanism, and point out the risks of not accounting for it in the planning and design for the extraction of such orebodies. Part 2 will focus on developing fundamental knowledge on the behaviour of orebodies under shear loading. The next section discusses hints that an orebody or some orebody lenses in a mine may be subjected to shear loading.

Causes and evidence of shear loading in orebodies

Complexity of orebodies

Francis *et al.* (1997) states that orebody complexity relates to such parameters as the morphological, grade, geotechnical and geological characteristics. These parameters are related to the orebody genesis. Thus, understanding the genesis of mineralisation is vital for planning the orebody extraction method and sequence.

Brown and Rosengren (2000) states that poor detailed knowledge of the orebody geometry in underground metalliferous mines can result in dilution or incomplete recovery or both. This is more so when in the mine planning and design stages the varying orebody geometry is not related to the *in situ* stress state. Generalisation of the orebody – *in situ* stress relationship will result in different stability issues as some parts can be under shear loading and others not. Figure 3 shows a matrix of different orebody geometries and how loading mechanisms by the driving stress can be different in different parts of the orebody. The orebody geometries in Fig. 3 can be grouped into discontinuous and continuous. Discontinuous orebodies can be co-planar or offset (en-echelen) (column 1). Continuous orebodies can be single



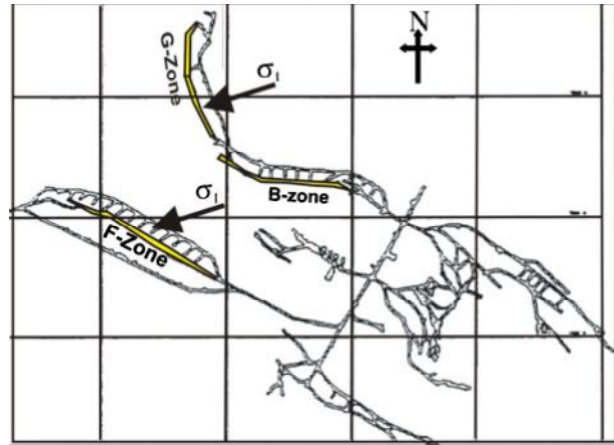
3 Matrix of orebody geometries (modified from Mgumbwa, 2011)

linear (column 2), splayed and or arcuate (column 3). Vein type deposits often present the most complex orebody geometries, and are more prone to being loaded in shear. In columns 1 and 2, mining direction will dictate whether the hangingwall or footwall stability state is affected. This scenario will be demonstrated in the section on 'Case histories' using the Lac Shortt case history. The stability states will be more adversely affected by the presence of discrete geological structures as shown in column 2. Local structures directly affect the stability of nearby stopes at all mining stages, while regional structures affect mine stability at higher extraction ratios (Suorinen and Kaiser, 2008).

Many mines have more than one orebody. These orebodies often have different orientations. In such cases the orientations of the axes of the orebodies relative to the major far field or driving stress will be different resulting in some ore lenses being loaded in pure compression and others compression and shear as shown in Fig. 4.

Misinterpretation of stress measurement data

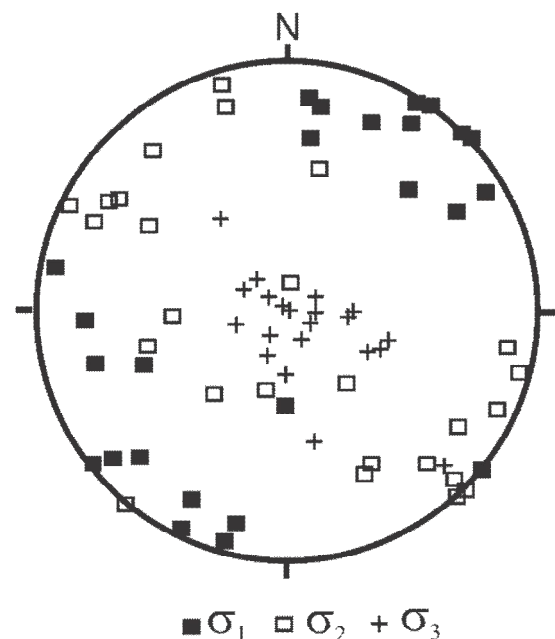
Regional and local stress measurement results often show great variability in both stress magnitudes and orientations (Arjang, 1996; Arjang and Herget, 1997; Herget, 1988; Fairhurst, 2003). Grabinsky *et al.* (1997) state that even in the most homogeneous geomechanical domains, the stress magnitude can vary by ± 15 to



4 Multiple ore lenses in different orientations in mine (modified from Corcum, 1997)

$\pm 30\%$ about the component's mean value and direction can vary by ± 15 to $\pm 30^\circ$ about the mean orientation as shown in Fig. 5 for stress measurement data in the Gardillac Fault Region.

Statistical treatment of stress measurement data is based on the assumption that an average stress condition exists, that the mean stress can be recovered and that the error in its measurement can be estimated (Suorinen and Kaiser, 2008). Using numerical modelling, McKinnon (2006) concluded that this concept might be misleading in some geological environments. A margin of error of $>15^\circ$ in the major principal stress azimuth can obscure actual orebody-stress relationship and lead to the general conclusion that orebodies are mostly loaded perpendicular to their axes (see Arjang, 1991; Blake and Hedley, 2003) when they are not. An azimuth variation of $>15^\circ$ results in significant shear



5 Scatter in orientations of *in situ* stresses from stress measurements along Cadillac Fault in Quebec: $\sigma_1 = 4.98 + 0.043z$ MPa, $\sigma_2 = 2.31 + 0.033z$ MPa, $\sigma_3 = 0.021z$ MPa; z is depth in metres (data from McKinnon and Labrie 2007)

stresses to make orebodies behave differently compared to when they are loaded in pure compression.

In order to minimise the risk of mischaracterising orebody–stress relationships, it is suggested that *in situ* stress measurements be complemented with borehole and excavation breakout surveys to determine the true orientations of the stress tensor, when possible. Also, rather than using mean stress orientations, the use of modes and median values should be examined, as these are better representations of central tendencies in skewed data (Suorineni and Kaiser, 2008).

Case histories

This section presents case studies on some of the consequences and implications when mining orebodies under shear loading without recognising the shear loading phenomenon and planning to mitigate the consequences in such mining environments. The mines discussed were identified based on factual published information and the observations of abnormal behaviour after the fact. The orebodies in these mines were found to fulfil one or a combination of the following conditions:

- Major far-field stress is oblique to the strike or dip.
- The orebodies may be continuous or discontinuous.
- For discontinuous orebodies, the configuration may be coplanar or en-echelon with offsets.
- Pillars are loaded in shear, causing them to be burst prone.
- Orebodies are ‘narrow veins’ with a width less than or equal to 5 m, in conformity with the suggestion of Blake and Hedley (2003).

The descriptions on these case studies focus on the impact of shear loading on the failure mechanisms of pillars, stopes and offsets. Efforts were made to describe the failure mechanisms as they relate to the orebody geometry, *in situ* stress regime, geology, rock mass properties and mining practice. Three underground hard rock mines in Canada and one in Chile are presented to show the impact of shear loading on mining orebodies in shear. A German potash mine at which the shear loading concept was first applied to explain the severity of a rockburst is described to show how shear loading can cause rockbursts even in soft rocks.

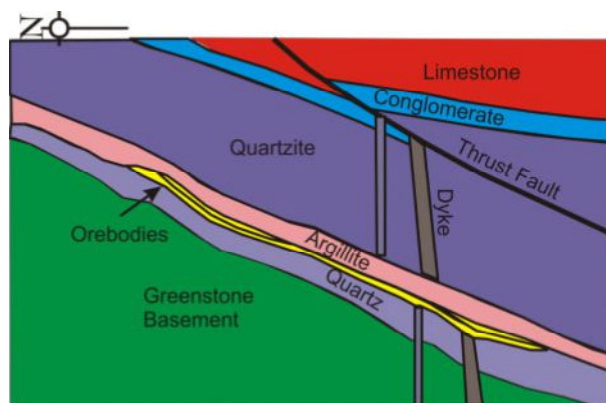
Quirke Mine

Location and geology

This case history is well documented in Coates *et al.* (1973), Hedley *et al.* (1984), Hedley (1992) and Blake and Hedley (2003). It shows how change in pillar alignment resulted in shear loading and affected pillar stability.

Quirke Mine is an abandoned uranium mine, located approximately 13.5 km north of Elliot Lake, Ontario, that was owned and operated by Rio Algom Ltd. The mine was in operation from 1956 to 1960, and again from 1968 to 1990, during which time it produced 44 million tons of ore from two separate shafts (Coggan, 2001).

The uranium bearing conglomerate reefs at Elliot Lake are deposited on the north and south limbs of a broad syncline. Figure 6 is a north–south cross-section looking east, showing the geology of Quirke Mine and the far field stress state. The orebody thickness varied



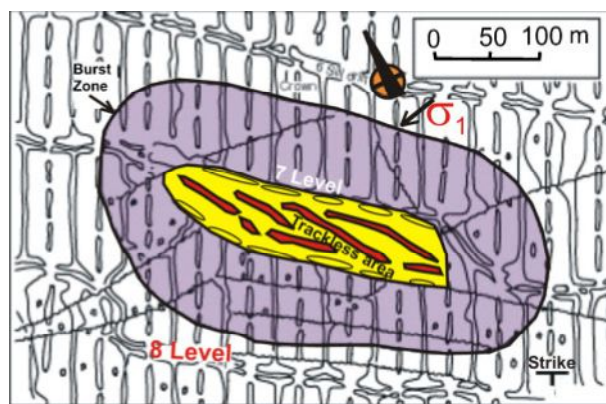
6 Simplified geology of Quirke Mine (modified from Hedley *et al.*, 1984)

between 2 and 5 m, dipping south at about 15–20°, and persisting to a depth of 1050 m.

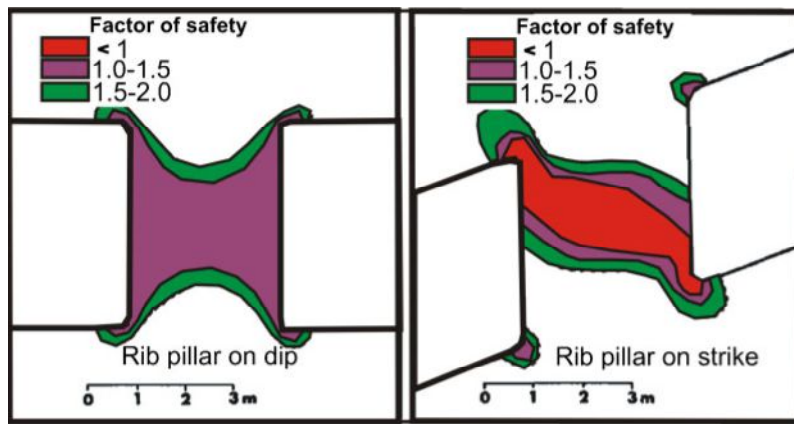
The strengths of the orebody, hangingwall and footwall rocks ranged from 210 to 230 MPa. The premining state of stress was defined by a vertical principal stress equal to the depth. In the east–west direction (orebody strike) the horizontal stress was about 2 to 2.5 times the vertical stress, and in the north–south direction (dip) was about 1.5 times the vertical stress (Coates *et al.*, 1973). Because of the orebody geometry, competence of the orebody and host rocks, room and pillar mining method was selected as the main extraction method. Rib pillars were used. The extraction ratio ranged from 70 to 80% depending on the depth and reef thickness.

In the central part of the mine plan (Fig. 7) a local roll in the orebody with a dip of 15° produced a distance of 180 m between the 7 and 8 sill drifts. This would have resulted in stope lengths too long to be effectively recovered with slushers as was the practice at the mine. Hence, the top 60 m was converted to a trial trackless area with the pillars aligned 45° to strike rather than dip to enable movement of machinery. Both the on dip and realigned pillars at 45° to orebody strike had the same width to height ratios.

After changing the pillar orientation mining was successfully executed up to completion in 1977/78 without any significant ground control problem in the trackless area.



7 Central part of mine plan between 7 and 8 level drifts showing trackless area with re-aligned pillars and rockbursts zone: major far field principal stress σ_1 direction relative to orientations of pillars is superimposed (modified from McKinnon and Labrie 2007)



8 Stability of rib pillars aligned on dip and strike (Hedley *et al.*, 1984)

Ensuing ground control issues

Four years after mining the trackless area pillar deterioration started in the 7 level sill drift, which was directly above it. The rib pillars in the trackless area crushed non-violently following about 200 mm of roof convergence (Hedley *et al.*, 1984). The area of pillar deterioration expanded slowly, without violent failure to include the bottom of the 7 level stopes, and all of the trackless area. On 10 March 1982 a small rockburst was reported to have occurred in the 7 level sill pillars, resulting in snapping of bolts. A series of rockbursts (2–3 M_L) then ensued. The rockbursts became frequent and expanded rapidly outside the trackless area as shown in Fig. 7. A summary of the ensuing ground control problems at Quirke Mine 4 years after mining the trackless area is given by Hedley *et al.* (1984) as follows:

- Rockbursts initiated in the sill and crown pillars on the 7 level near the trackless area.
 - Violent failure appeared to have occurred in the sill and crown pillars, and where extra large rib pillars were left.
- Relatively non-violent failure appeared to have occurred in the slender rib pillars, especially those in the trackless area (about 6 m high by 3 m wide).
- The quartzite beds in the roof spanned the affected area without major breakdown. Roof falls that occurred appeared to have been controlled by geological structure and triggered by vibrations from nearby seismic events. No rockbursts were observed in the roof, but there were some in the haulage drifts in the footwall.
- The area of pillar deterioration expanded gradually over a period of about two years.
- Accelerating convergence rates coincided, and in some cases preceded increasing seismic activity.

Hedley *et al.* (1984) attributed the cause of the rockbursts to the pillars being re-aligned on strike causing them to be weaker than others, and the low angled, mud coated thrust fault and a vertical mud coated fault passing through the trackless area which could have affected the stress distribution. Note that the trackless area pillar realignment resulting in a change in the pillar loading mechanism is not mentioned, and the cause for the pillars being weaker is not identified. The former will be discussed in the next section while the latter will be the primary objective of Part 2 of this two part series.

Impact of shear loading

It is considered likely that the re-aligned rib pillars at 45° to the strike of the orebody and to the major far field

principal stress resulted in their being loaded in shear along the short axis as shown in Fig. 7, causing them to be weaker. They then yielded gradually, shedding their load to the neighbouring pillars aligned on dip. The neighbouring rib pillars with high width (W) to height (H) ratios (squat pillars) then failed violently.

Hedley *et al.* (1984) conducted stress analysis on the Quirke Mine case. Two identical pillars at the same extraction ratio with one pillar being aligned on dip and the other on strike were analysed. The results are shown in Fig. 8. It can be seen that the on-dip rib pillar is stable with an average safety factor of 1.2 across the centreline, while for the pillar on strike, failure extends across the complete pillar width from the top left hand corner to the bottom right hand corner. Thus, the rockburst problem which occurred at Quirke Mine was initiated because of the 45° alignment of the pillar geometry in the trial trackless area. This inappropriate alignment resulted in adverse shear loading conditions that eventually caused the domino pillar bursting at Quirke Mine.

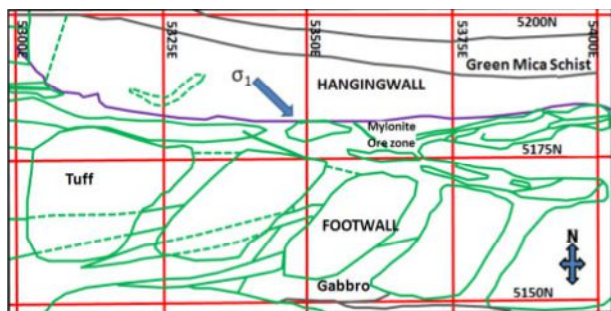
Lac Shortt Mine

Location, geology and mining practice

The Lac Shortt Mine was an 800 t/day gold mining operation located near the town of Desmaraisville, Quebec. It was owned and exploited by Minnova Inc., and later by INMET until its closure in 1992.

A detailed description of Lac Shortt case history can be found in Ecobichon *et al.* (1992), Coulombe and Nantel (1992) and Falmagne (2001). This case history shows how not taking shear loading into account in mine planning and sequencing resulted in elevated risks of seismicity and high dilution. Proactive measures could be taken to manage the seismicity and dilution if the oblique loading of the orebody was accounted for in the planning, design and sequencing of extraction.

The Lac Shortt Mine orebody was a typical example of a uniform orebody loaded obliquely to strike by the major far field principal stress. The deposit was tabular in shape with an average dip of 80° to the north. The width varied between 3 and 10 m with an average economic width of 5.5 m. On the property scale, the orebody was closely associated with two subparallel faults of opposing dip and carbonatite intrusions which were features thought to have contributed to the anomalous high *in situ* stresses encountered at the mine. Figure 9 is a simplified geology of the mine at the 700



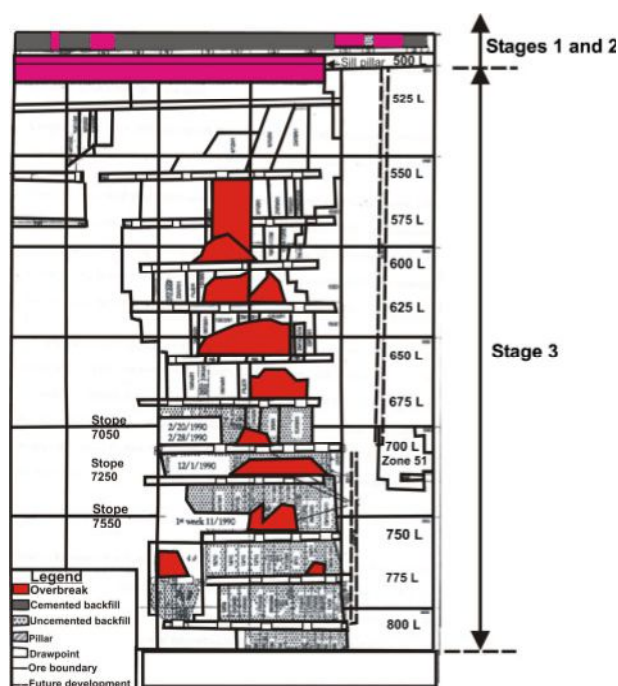
9 Simplified plan view of geology of Lac Shortt Mine as seen on 700L (modified from Falmagne, 2001): major far field principal stress orientation relative to orebody is superimposed

level showing the orientation of the major far field principal stress relative to the strike of the orebody.

The maximum principal stress was inclined at 45° with respect to the strike of the orebody. K ratio in the NW–SE direction is about 4 and in the NE–SW direction is 2. The high k ratio of 4 is unusual in the Canadian Shield where it is on average 2. Falmagne (2001) gives a summary of the mechanical properties of the major rock units at Lac Shortt Mine. Uniaxial compressive strengths ranged from 60 MPa (in the green mica schist when loaded parallel to foliation) to 280 MPa in the ore.

The orebody at Lac Shortt was mined in three stages, the first two between 500 and 50 m below surface (upper zone), and the third phase from 830 to 500 m level (lower zone) (Fig. 10).

The upper zone was mined using open stoping with alternative primary stopes filled with cemented rockfill and secondary stopes filled with cemented sand fill (McCreath and Kaiser 1992). The mining in the upper zone resulted in secondary pillars that were rockburst



10 Vertical cross-section showing ground control problems and mining stages at Lac Shortt Mine (modified from Falmagne, 2001)

prone. Hence, because of the lessons learnt in this zone, the mining method for the third phase at depth was changed to a modified AVOCA mining method with delayed backfill (Ecobichon *et al.*, 1992). These mining methods were based on the orebody geometry and mechanical properties. As pointed out earlier, the relative orientation of the major far field stress to the orebody axis is in general often ignored, and emphasis placed on stress magnitudes only. The consequences of this limitation on mine performance in terms of safety and economics (based on the Lac short case study) are discussed in the next section.

Ground control issues experienced

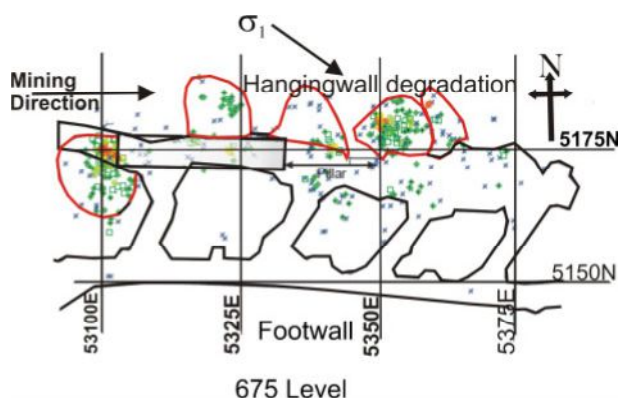
Mining at Lac Shortt was characterised by high stress conditions responsible for rockbursting during secondary pillar mining, at a depth of 250 m. Falmagne (2001) summarised the ground control problems encountered at Lac Shortt Mine as:

- deterioration of footwall and orebody developments, stope dilution, major falls of ground and caving of stopes
- sill pillar rockburst at shallow depth of ~ 250 m, and common shakedown failures were wide spread (Fig. 10).

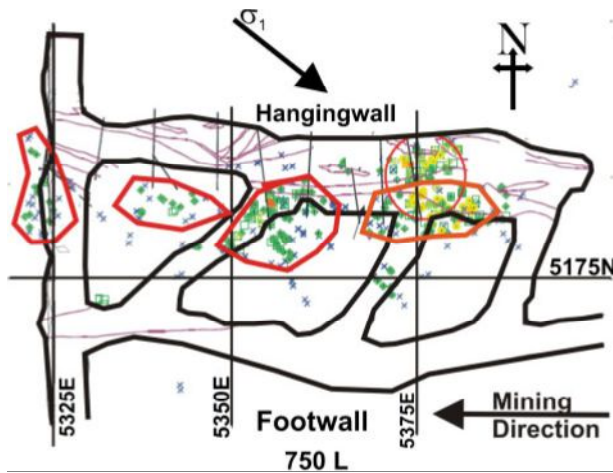
In 1989, a rockburst occurred near the shaft and in the footwall development necessitating the installation of a seismic monitoring network (Ecobichon *et al.*, 1992). A review of seismic activity from microseismic monitoring indicated the rockbursts were either in hanging wall or footwall depending on mining direction. The governing factor of this finding is identified and discussed in the next section.

Impact of shear loading

The ground control problems at Lac Shortt Mine were unique. The conclusions from the microseismic monitoring can be related to the fact that the major far field stress was inclined at 45° to the strike of the orebody. Figures 11 and 12 show the directions of mining and locations of intense microseismic activities. The two figures show that depending on the mining direction the hangingwall or footwall is continuously degraded as the mining front advances. Falmagne (2001) indicated that the mining direction at Lac Shortt Mine had an impact on the location and intensity of the rock mass degradation, and therefore on the stability of the openings.



11 Plan view showing effect of mining from east to west: hangingwall degradation (modified from Falmagne, 2001)



12 Plan view showing effect of mining from west to east: footwall degradation (modified from Falmagne, 2001)

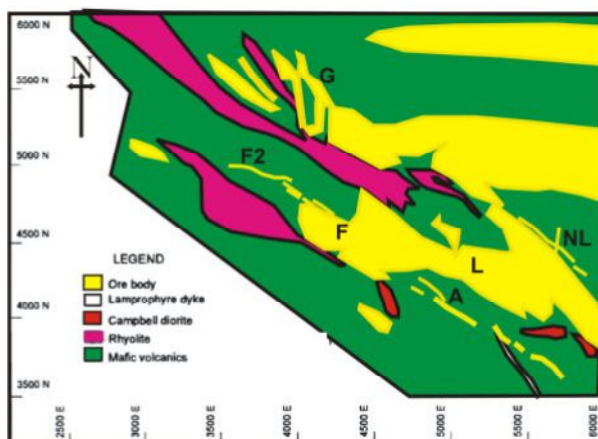
F zone at Campbell Red Lake Mine

Location, geology and mining practice

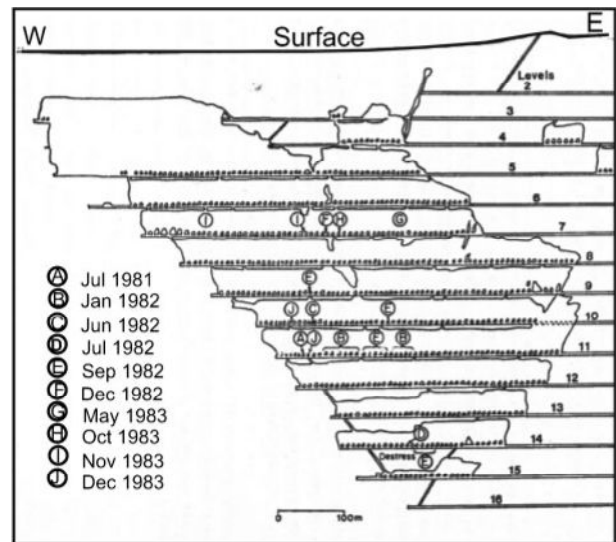
Campbell Mine is in Balmertown on Highway 125, 4 km east of the town of Red Lake. It is an underground gold mine within the District of Kenora in Northwestern Ontario, and has been in operation since 1949. The mine has changed hands since 1944 when the deposit was discovered by Dome Exploration, a wholly owned subsidiary of Dome Mines Limited. Dome Exploration optioned the property the same year, and Campbell Red Lake Mines Limited was incorporated. Formerly wholly owned by Placer Dome Inc., the mine is now owned by Goldcorp Inc.

The F zone is an isolated orebody to the west of the inclined shaft. Various consultants' reports (Blake, 1984; Hedley *et al.*, 1985; Golder Associates, 1999) on the F zone following the first rockburst in this area of the Campbell Mine contain detailed descriptions of the mine, mining practices, and the problems encountered during mining.

The detailed geology of Campbell Mine is in Zhang *et al.* (1997) (Fig. 13). The ore thickness in the F zone varies between 0.3 and 1 m. The dip of the orebody is 75° to the south. The orebody host rock is andesite. The mechanical properties of the major rock units at the



13 Plan view showing simplified geology of Campbell Mine as seen on 19 level (modified from Zhang *et al.*, 1997): letters represent different ore zones



14 Vertical section showing F zone sequence of boxhole pillars deterioration between 1981 and 1983 (Hedley, 1992)

Campbell Mine can be found in Delgado and Raffield (2003).

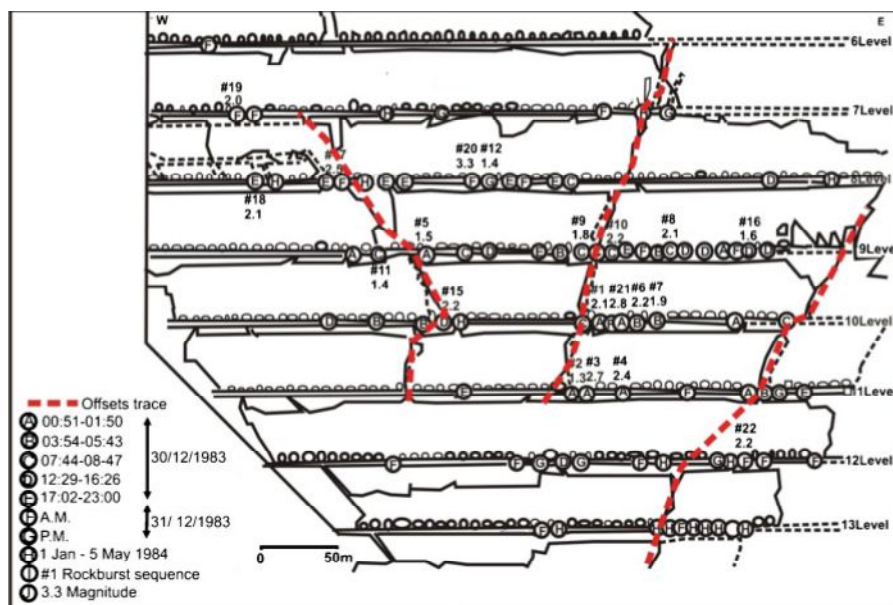
Delgado and Mercer (2006) give a summary of the Campbell Mine geology and mechanical properties of the major rock units. The major lithological units are andesite, ultramafic and rhyolite rocks of good to very good quality rock masses. Uniaxial compressive strength values range between 126 and 250 MPa, with an average of ~180 MPa. Based on a series of *in situ* stress measurements, the major far field principal stress is approximately east–west with a k ratio of 3 in this direction at 1000 m (current depth of mining in the F zone). In the north–south direction the k ratio is ~1.7. These k ratios decrease with depth. Delgado and Mercer (2006) note that observations indicate the *in situ* stress field rotates, and can be locally disturbed near lithologic contacts (e.g. dykes, faults, andesite ultramafic contacts, etc.).

The mining method in the F zone of Campbell Mine changed over the years to suit the ground conditions. Initially, the main mining method was shrinkage stoping with box hole pillars and 6.1 m wide sill pillars. By 1992 mining below 600 m was by overhand cut and fill with deslimed tailings as backfill. Current production is from cut and fill and longhole stoping.

F zone ground control problems

Figure 14 shows the overall pattern of ground control problems in the F zone. Problems started with the deterioration of the boxhole pillars, leading to the first rockburst on the 11 level in 1981. The rockbursts then spread in the boxhole pillars between the 7 and 14 levels within a 30 month period (Hedley 1992). A major rockburst occurred on the 8 level on 31 December 1983 that was felt on surface and 200 km away from the source. This rockburst was preceded by smaller events between levels 7 and 10 (the first event on level 10) on 30 December 1983, with aftershocks on levels 10 and 12 (Fig. 15). The extent of damage was widespread in the F zone resulting in production shut down in the section of the mine.

Based on underground visual observations and computer modelling, Hedley (1992) concluded that the



15 Vertical section showing F zone sequence of major seismic activities between 1981 and 1983: numbers indicate rockburst sequence (modified from Hedley, 1992)

major rockbursts occurred in the sills rather than in the boxhole pillars and that the driving force appears to be the change in potential energy as the hanging wall and footwall suddenly converged, when ore was mucked from the 12 level stope. The boxhole and sill pillar strengths used in the models were based on the Elliot Lake pillar equation assuming andesite cube strength of 100 MPa. The boxhole pillars W/H ratio was 2.2 while the W/H ratios of the affected sill pillars were between 2.9 and 5.8.

Hedley (1992) states that the vast majority of the major seismic events occur where the sill pillars are 6 m wide on dip, with very few events occurring where the sill pillars are 15 m wide.

Re-assessment of F zone

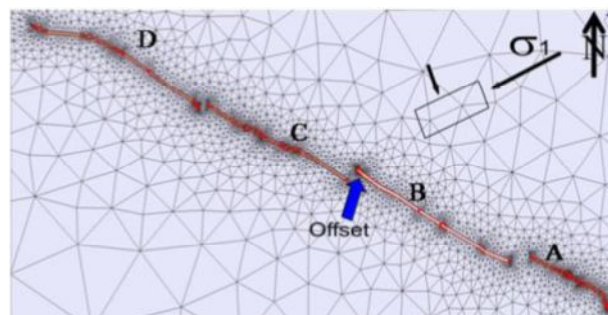
As pointed out above, mining in the F zone led to major rockbursts that prevented full ore extraction and resulted in production shutdown. The sills and boxhole pillars in the F zone are high grade ore. In 2004, the GRC was approached on how to safely and economically mine the sills and boxhole pillars between 4 and 15 Levels by longhole drilling and blasting.

The F zone of Campbell Red Lake Mine is described by Arjang (1991) as having the major far field principal stress perpendicular to strike. All previous consultants' analyses and reports assumed that the major far field principal stress is about 90° to the strike of the orebody. The historical burst records and *in situ* stress measurement data were reviewed by the authors. An underground tour was also undertaken to observe the mine infrastructure performance, and to interview mine personnel on their experiences at the mine. Following the reviews, it became clear to the authors that contrary to Arjang (1991) and previous consultants' conclusions the major far field principal stress is normal to the orebody strike, it was in fact 25° to it (Kaiser and Suorineni, 2005) (see Fig. 16). Figure 16 shows details of the F zone orebody geometry and how it relates to the major far field principal stress. A unique feature of the F

zone orebody is that it is inclined relative to the major far field stress and consists of four en-echelon primary ore lenses with offsets of various geometries. Loading of the offsets in shear further exacerbated the stability problems in the F zone.

The oblique loading of the orebody by the major far field principal stress subjected the orebody to compressive and shear loading. Based on the GRC experience at Quirke and Lac Shortt mines discussed in the sections on 'Lac Shortt Mine' and 'F zone at Campbell Red Lake Mine', the F zone orebody was in shear, and that accounted for its abnormal behaviour at such a shallow depth of <1000 m below surface.

Numerical modelling of the F zone with the major far field stress oblique to it showed that the offsets were highly stressed (Fig. 17) and burst prone. Comparison of the offset patterns with the rockbursting history and sequence in Fig. 15 shows that the offsets formed the seeds of the bursting sequence in 1981 that escalated in 1983. The shear loading mechanism of the offsets and sills made them weaker compared to if they were loaded in pure compression. Why pillars loaded in shear are weaker than if they are loaded in pure compression will be discussed in detail in Part 2 of this paper.



16 F zone showing oblique loading by major far field principal stress and offsets between ore lenses (Kaiser and Suorineni, 2005)



17 Three-dimensional numerical modelling results for F zone showing high stress concentrations at offsets (Suorinen et al., 2007)

El Teniente Mine

Location and geology

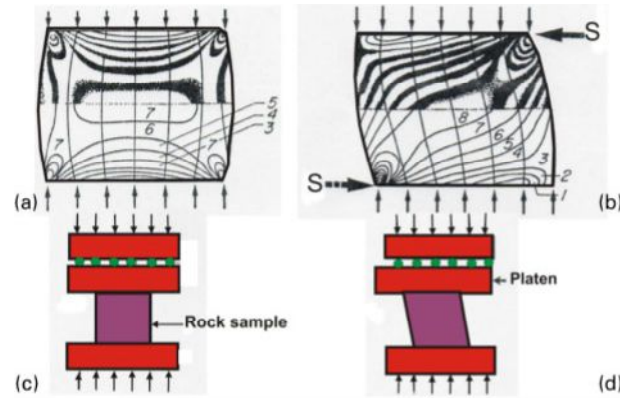
This case study is heavily drawn from Kvapil et al. (1989). El Teniente is one of the five mining divisions of Codelco. It is located 80 km south of Santiago. El Teniente produces 404 035 t fine copper per year and is the largest block caving mine in the world.

The El Teniente ore deposit was formed by very dramatic and intense tectonic processes resulting in high *in situ* stresses. The deposit shape is roughly triangular in plan view, with a height and base length of 3 and 1.5 km respectively, persisting to a depth of >1.0 km. The maximum principal stresses in the central part of the mine are approximately in northwest direction while in some northern parts of the mine the stresses are in east-west direction. The rock mass of the primary ore is andesite with pockets of diorites while the secondary ore consists of soft Braden Formation. Further details of the *in situ* stresses and mechanical properties of the major rock units can be found in Kvapil et al. (1989).

Rockbursts started to occur when mining entered zones of hard primary diorite that were under very high stresses. Between 1976 and 1980, a series of rockbursts occurred in one of the production zones resulting in short and long term disruption of mining activities. As at 1980, it was a commonly held belief that rockbursting does not repeat itself in a given area since one burst releases large quantities of potential strain energy. Time lapse following the occurrence of a rockburst in a given area further dissipates the remaining energy potential. Following these assumptions, a new mining level was developed 12 m below the former production level destroyed by a rockburst in 1980. On 17 December 1987, the new level was again destroyed by a more massive rockburst than those that occurred between 1976 and 1980. The rockbursts in the two levels occurred mainly in pillars at stress levels less than the compressive strength of the pillars (Kvapil et al., 1989).

Cause of unusual rockbursts at El Teniente

Based on a detailed study and the observation of underground failure modes at El Teniente, it was concluded that the pattern of rockbursts occurrence at El Teniente could not be explained with traditional knowledge. The



18 Demonstration of shear loading effect on pillars compared with loading in pure compression using a, b photoelastic modelling and c, d uniaxial testing (after redrawn from Kvapil et al., 1989)

rockbursts occurred mainly in the pillars between the drifts. The damage in the pillars was not symmetric but concentrated in specific zones in the pillars. The failure occurred at stress levels below the compressive strength of the pillars.

To determine the cause of these unusual rockbursts, Kvapil et al. (1989) hypothesised that in triaxial compression rock accumulates a much higher strain energy than the same rock in uniaxial compression, and that in shear the same rock will accumulate still less energy before failure. Kvapil et al. (1989) used photoelastic modelling and pure uniaxial compression loading and a combined compression and shear loading (Fig. 18) to prove their hypothesis. They concluded that a change in loading mechanism from pure compression to compression and shear changed the properties and behaviour of rocks or for that matter any solid. Such a change in properties will make the rock behave as a more brittle material and fracture by rockbursting.

Thalmann Potash Mine disaster

The Thalmann Potash Mine disaster on 8 July 1958 resulted in the collapse of Merkers (Kvapil et al., 1989; Whyatt and Varley, 2008). A 4.8 M_L rockburst destroyed Merkers and generated microseismic activity 2000 km away from the source. Shear loading was for the first time used to explain the cause of this rockburst. Kvapil et al. (1989) note that, all the characteristics of the damage of this rockburst bear resemblance to the El Teniente Mine experience discussed in the section on 'El Teniente Mine'. While in some exceptional cases rockbursts can occur in soft rocks, the Thalmann case is very unusual, and defies conventional knowledge on favourable conditions for rockburst occurrence. It is intuitive to conclude that the shear loading mechanism would have changed the potash behaviour from ductile to brittle for the rockburst to occur. This is the subject for discussion in Part 2 of this paper.

Implications of shear loading for mine planning and design

The case histories presented unambiguously show that the magnitudes of the far field principal stress alone are not sufficient for mine planning and design. They also show that the present generalisation that most orebodies,

particularly tabular orebodies are oriented perpendicular to the major far field principal stress is not correct, and can be misleading.

The orientation of the major field stress relative to the orebody axis is critical for the safe and economic extraction of orebodies and should always be taken into account in mine planning and design. The case histories show that improper establishment of the orebody geometry major far field stress relationship can result in ground control problems where they are least expected, if the design was based on the wrong assumption.

More favourable ground conditions could be created and many of the disasters avoided or at least minimised if in the mine planning and design stages the engineers in the various case histories had established that the orebodies at hand were subjected to both compression and shear loading, and more importantly had the awareness that orebodies under shear loading require a different mine planning and design approach to avert ground control problems.

In the case of the Quirke Mine case study, the domino pillar failure from rockbursting could be averted by using higher pillar width to height ratios in the trackless area when the pillar orientation was changed from dip to essentially strike pillars. For the Lac Shortt situation, an east west mining direction could limit damage to hangingwall to safe expensive critical mine infrastructure in the footwall. Alternatively, proactive measures could be taken by using strong support in the footwall infrastructure if engineers were aware of the consequences of the shear loading. Similarly, the Campbell Mine ground control problems could be properly managed knowing that to maintain pillar stability, bigger boxhole and sill pillars should be used. This observation was made clear by the fact that sill pillars wider than 6 m remained stable while those smaller failed.

Knowledge of orebody geometry–stress relation is vital in planning and design of an underground infrastructure and maintaining safe and economical extraction sequence. Fairhurst (1986) states that a more effective design strategy is to give greater emphasis to the overall effects of interaction between stress states, rock mass properties and excavation geometry. Orebody geometry affects the layout and location of underground infrastructures. The mining induced stress, stress concentration and distributions around underground openings need to be clearly understood in order to establish safe and economic local and global ore extraction sequences.

Conclusions and recommendations

The complex geometries of orebodies, the occurrence of orebodies in multiple lenses within a mine, and inaccuracies in the determination of actual *in situ* stress orientations imply that there are more orebodies under shear loading than generally assumed. The generalisation that most orebodies have their axis perpendicular to the major far field stress is misleading.

The orientation of the major far field principal stress or for that matter the driving stress, relative to the orebody axis should be recognised as one of the causes of rockbursts. At present the driving stress orientation relative to orebody axis is not considered as one of the factors that cause rockbursts.

There is lack of awareness in the mining community of the consequences of having an orebody loaded in shear. This paper has unambiguously demonstrated that special attention should be paid to orebodies loaded in shear.

The case studies presented identify the following as characteristics of orebodies under shear loading.

- Tabular orebodies are most often affected by shear loading.
- In shear loaded orebodies ground control issues that arise cannot be explained with conventional knowledge.
 - Rockbursts can occur where they are least expected.
 - Soft rocks such as potash can burst when loaded in shear.
 - Rockbursts can reoccur in the same area
 - Rockbursts can occur at shallow depths
 - Pillars designed and guaranteed to be stable assuming they are loaded in pure compression can fail if the actual loading mechanism is shear.
- Pillars in these orebodies tend to fail in asymmetrical manner due to different stress distributions caused by combined compression and shear loading.
- In orebodies under shear loading, the location of damage (footwall or hangingwall) in continuous tabular orebodies depends on the mining direction.

It is suggested that since stress orientation is an important factor, and orientations from stress measurements are so variable, orientations from stress measurements data be complemented with underground observations from borehole and excavation breakouts to determine the actual *in situ* stress orientation, whenever possible. Also stress modelling for the design of critical elements (pillars) should include a sensitivity analysis on the relative critical field stress direction.

Acknowledgement

The authors are grateful to Vale and the Natural Sciences and Engineering Research Council of Canada (NSERC) for funding the research.

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