Global Approach to Managing Deep Mining Hazards

R.P. Bewick, P.Eng.
Golder Associates Ltd. Sudbury, ON, Canada

B. Valley, Ph.D.
MIRARCO, Sudbury, ON, Canada

S. Runnalls, P.Eng., J. Whitney, P.Eng., & Y. Krynicki, P.Eng.
Vale Inco Garson Mine, Sudbury, ON, Canada

ABSTRACT: Recent experience in structurally complex mining environments suggests that sudden shear deformation along large scale structural features/zones can occur in unexpected areas and at distances >200 m away from active mining areas. As mines move deeper the risk for unexpected major seismic events (>2.0 Mn) to occur increases. The mechanics of sudden seismic energy release in structurally complex environments cannot be explained by case by case focused studies, but requires the implementation of a global or holistic understanding of the structures, their characteristics, and interactions. Only then can the complex dynamic between structures, mining induced perturbation and occurrence of seismic events be captured. Thus permitting risks to be mitigated by implementing strategic geomechanical management practices in order to minimize hazardous ground exposure to mine personnel and ensure stakeholder value is maintained. This paper discusses the use of a Global Approach consisting of creating an engineering geology model based on integrating both geologic data, seismic data, and numerical modelling.

1 INTRODUCTION

A series of fault slip seismic events have occurred at Garson mine. The events have occurred during development advancement exposing faults, after the extraction of single stopes due to mining induced stress change, and due to time effects after delays of many days during which no mining had been conducted. This paper discusses the study completed consisting of a global or holistic approach aimed at mitigating some of the risks associated with the structurally controlled rockbursts at Garson. The approach consisted of the following:

- Building an Engineering Geology Model (EGM) to gain a more informed understanding of the mechanisms involved in the observed rock mass behaviour at the mine and identify seismically active structures;
- Numerical modelling to provide guidelines for stope sequencing that attempt to manage induced stresses in relation to the main geological structures (fault zones, shears, and dykes identified as seismically active from the EGM) in order to mitigate negative (stress-structure) interactions; and
- Improvements to the tactical approach which included discussion, for example, on ground support designs that will withstand the observed ground behaviour and response to mining.

Focus is placed on the building of the EGM and limited discussion on the numerical modelling completed to further characterize Garson mine. Numerical modelling completed to assess various sequence options, etc., and improvements to the tactical approach are not discussed (ref. Castro et al. 2009 for more insight into the numerical modelling completed).

1.1 *Background*

Garson mine is located in the south east area of the Sudbury Basin (Ontario, Canada). Mining occurs in two main ore bodies (the #1 Shear and the #4 Shear) which are copper-nickel-sulphide and occur within shear zones that (as well as the ore bodies) strike approximately east-west and dip steeply south.

A simplified geologic model is shown on Figure 1 and the rock mass qualities of the main units are summarized in Table 1. The north or footwall progresses from norite (NR, purple), to greenstone (GS, green), and finally to meta-sediment (MTSD, yellow). A generally WNW-ESE striking, bifurcated sub-vertical dyke of olivine diabase (OLDI, brown) cuts the series. The #1 and #4 shear ore bodies (extending to depths of 5600 ft and 6000ft respectively) are shown in dark and light pink.

The current active mining block at Garson is between 4700L and 5100L (levels denote depth in feet below surface). The in situ stresses at a depth of 5100ft are assumed to be approximately: σ_1=74 MPa, σ_2=47 MPa, σ_3=42 MPa with the major principal stress (σ_1) oriented in the horizontal and the minor (σ_3) in the vertical direction (Cochrane, 1991, Maloney & Cai, 2006). Both transverse and longitudinal modified slot and slash open stope mining methods are employed. The typical planned stope dimensions are 100x50x40ft. The stopes are extracted in two or 3 blasts and then tight filled with a mixture of pastefill and waste rock.

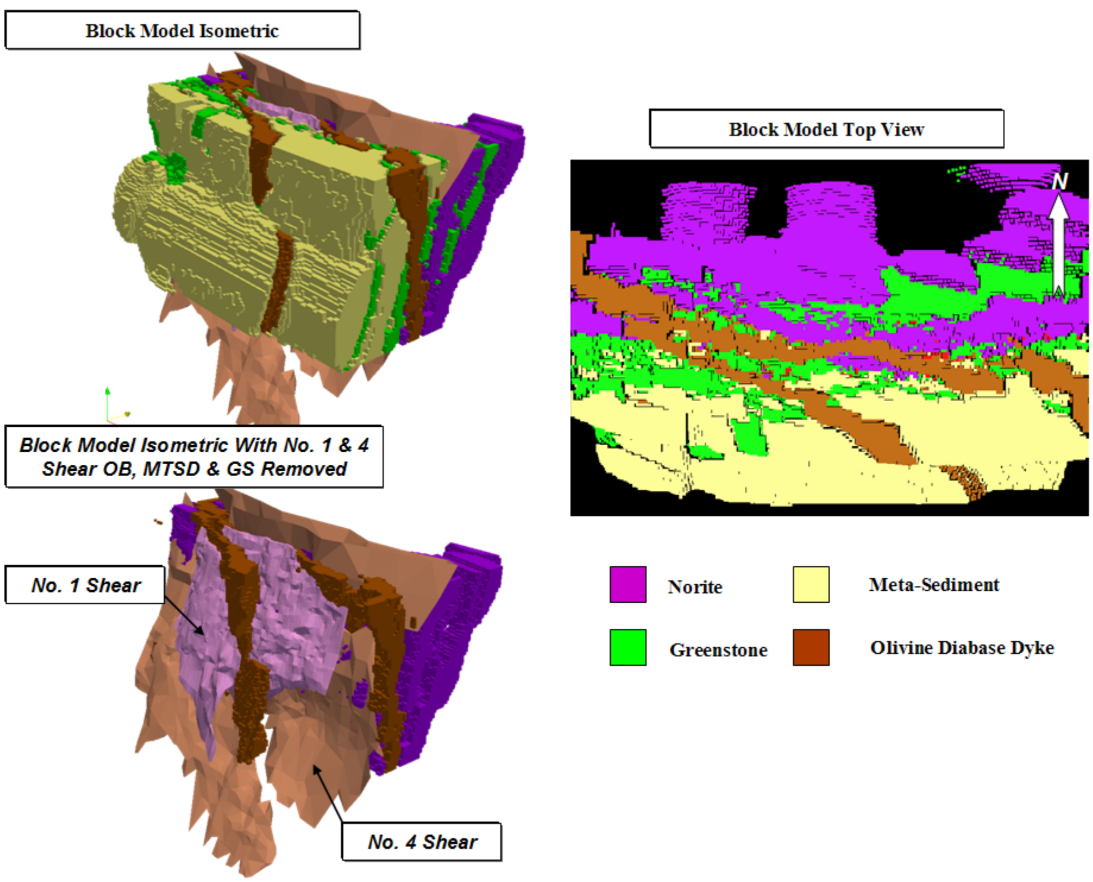

Figure 1: Generalized Garson mine geology.

Table 1: Summary the major rock types and their geomechanical classification

Rock Type	Q' Range	GSI Range
Norite	11 to 33	70 to 80
Greenstone	5 to 17	65 to 75
South Limb Olivine Diabase	No observation	55 to 75 (Estimated)
North Limb Olivine Diabase	20 to 50	90 to 100
Massive Sulphide	30 to 38	65 to 75
Meta-Sediments	0.4 to 2	20 to 35

2 COMPREHENSIVE ENGINEERING GEOLOGY MODEL

Data collected at Garson mine between years 1999 to 2007 were compiled in order to gain a more informed understanding of the mechanisms involved in the observed rock mass behaviour. The data included principally — but not exclusively — the exploration drillhole database, level mapping, seismic data, and interpreted faults zones. All data were loaded and processed in a common platform in order to extract valuable information and to build a comprehensive EGM. The data was compiled to assess:

– Location, orientation, and character of major structures (level mapping, interpreted fault zones, block model structural interpretation, etc.);
– Potential local stress orientation (level mapping, interpreted fault zones, seismic data, numerical back analysis, etc.);
– Areas of high stress concentration (core disking, seismicity, numerical modelling, etc.);
– The spatial and temporal repartition of the seismicity (seismic time links, mine sequencing, etc.); and
– The relation between seismicity, geological structure and the mining activities (i.e. assessment of seismically active structures and spatial links/interactions).

2.1 *Geologic Model*

The main focus of the geological analyses was on the brittle tectonic aspects of the geological data set. This included the characterization of fracturing and faulting on various scales.

2.1.1 *Background Fracturing and Structural Trends*

Two sources of data were used to extract the structural trends:

– i) the features mapped underground by the mine's geology department which included location and orientation of joints, veins, faults and shears as summarized on Figures 2a, b, c and d; and

– ii) the interpretation of major discontinuities using a geological block model built by compiling and interpolating the drillhole database (consisting of approximately 7500 holes) as summarized on Figure 2e. The major discontinuities and offsets of the lithological block model were interpreted on successive horizontal and N-S vertical slice sections. Finally, interpreted discontinuities were linked between sections in order to extract their locations and orientations.

The major and secondary trends for the various types of structural data are listed in Table 2. The dominant trend present is an NW–SE sub-vertical orientation. This orientation is well known in the Sudbury Basin and is parallel to the trend of the typical transverse faults (Roussel, 1981) or late-stage faults (Cochrane, 1991). The secondary trend present in the fault data is a NE–SW orientation. There is systematically a slight obliquity between joint/vein and fault/shear data. This is possibly explained by remnant or current embryonic fault patterns including Riedel's type of shearing associated fracturing (Riedel, 1929) or shear related tensional veining (e.g.

Beach, 1975). The third trend represents E–W striking structures dipping to the south at an angle of approximately 35° (shears) to 60° (interpreted discontinuities). Finally, some sub-horizontal shears, joints and interpreted discontinuities are also present.

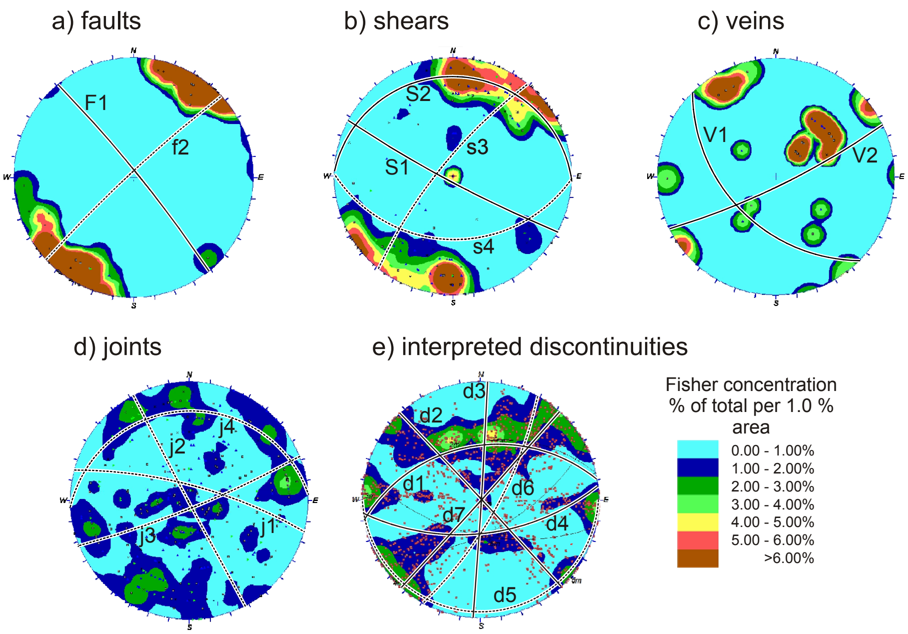

Figure 2: Stereographic projections (lower hemisphere, equal angle) of mapped a) faults, b) shears, c) veins, d) joints and e) block model interpreted discontinuities.

Table 2: Summary of the structural trends for the various structural data. Uppercase labels are for dominant trends and lowercase labels for secondary trends (e.g. all lower case for the joints signifies equal dominance)

Type	Label	Dip Direction	Dip	Strike
Faults	F1	036°-066°	89°-82°	NW–SE
	f2	317°	85°	NE–SW
Shears	S1	189°-227°	80°-86°	NW–SE
	S2	010°	00°-05°	horizontal
	s3	309°	76°	NE–SW
	s4	181°	34°	E–W
Veins	V1	229°-221°	33°-58°	NW–SE
	V2	154°	81°	NE–SW
Joints	j1	015°	75°	E–W
	j2	242°	89°	NW–SE
	j3	158°	83°	NE–SW
	j4	357°	16°	E–W
Interpreted Discontinuities	d1	350°	41°	E–W
	d2	046°-048°	89°	NW–SE
	d3	092°-095°	89°	N–S
	d4	153°-194°	58°	E–W
	d5	180°	03°	horizontal
	d6	119°	73°	NE–SW
	d7	131°-133°	89°	NE–SW

2.1.2 *Discrete feature characterization*
In addition to the general structural trends, major features were identified and characterized in detail as shown on Figure 3. These features are the following:
- 2500 structure zones;
- 45° structure zones;
- 3500 fault zones and parallel structure; and
- OLDI dyke (North and South Limbs).

2.1.2.1 2500 Structure Zones
The 2500 structure is historically well-known at the mine. It is a NW–SE striking, sub-vertical fault zone. Using the provided data, the 2500 was characterized (internal architecture) as shown on Figure 3b. The 2500 structure model suggests that the structure zone ranges in thickness from approximately >50 ft to <1 inch on some of its splays. The configuration as mapped into the 3D model suggests that the structure is steeply dipping with an approximately SE-NW strike and sub-parallels the south limb of the OLDI dyke, but does not specifically cut it. The obliquity between measured fault orientation underground (red patches on Figure 3b) and the general fault envelop also suggests that the structure is not one discrete plane, but a series of anastamozing gouge filled shears that weave somewhat such that the zone widens and thins along strike. In some areas, there are suggestions of lenses of more competent rock within the zone. In other cases, particularly where the zone is wide, the structure is characterized by weak disposition with overall strength in the range of R0 to R1 (UCS < 5 MPa) according to ISRM strength estimation, and with low RQD values. The thick gouge filled ductile zones in combination with the thin relatively brittle (rock bridged) zones are likely the reason for the structures large release of energy during slip as the thin less ductile zones would allow for energy to build up and fail violently.

2.1.2.2 45° Structure Zones
A series of 45° south dipping parallel structures were identified from drillhole intercepts and ore body geometry by the mine's geology department. One intercepts the current active mining area (green structure on Figure 3a). The disposition of these structures is consistent with thrust or reverse faults based on Sudbury Basin and/or Garson stress state orientations. Curiously, no significant features on these trends had been identified from underground mapping although their presence was postulated from exploration drilling interpretation as something of this sort of orientation appeared responsible for ore-zone offsetting. The possibility must therefore be entertained that such features have not yet become fully formed reverse faults, but rather they occur as a band of en-echelon tension gashes. As such, they likely are infilled with quartz or other mineralization. If significant jointing has opened up in a tensional sense, the zone may have been strengthened and could be more brittle than the adjacent rock mass.

2.1.2.3 3500 Structure Zones
Two other fault zones, roughly parallel to the 2500 structure were identified; (1) the 3500 structures; and (2) the 'parallel' structure (dark green structure on Figure 3a). Little is known about the internal architecture of these zones, but their orientations suggest that they may have been generated by the same tectonic settings of the 2500 structures and thus will have similar dispositions. However, they seem to be less developed in terms of width, presence of gouge, etc.

2.1.2.4 Bi-Furcated Diabase Dyke
Observations of the dyke model as shown on Figure 4a & b suggested that the dyke "undulates" along strike in both the north and south limbs and contains holes (i.e. is non-continuous).

The "undulation" is more evident in the north dyke limb. While such "undulation" might be conceivable in a crenulation style folded geological environment (i.e. something similar to a boudinage style of geometry), in the structural framework that seems to be suggested by the stereonets (Figure 2) and by the interpreted horizontal and vertical slice sections (ref. 2.1.1 point ii), it would seem more likely that the "undulations" in the dyke geometry reflect multiple fault offsets.

The non-continuous and 'undulating' dyke block model is of significant mining concern as such holes could become stress focal points and the offsetting dyke geometry acts to also concentrate stresses. Principally, such holes, if truly present, would exert significant influence on nearby stress conditions due to the marked stiffness contrast between the OLDI (north limb GSI ≈ >85 and E_m ≈ >70GPa) and the surrounding GS and NR rock units (GSI ≈ >65 and E_m ≈ >40GPa).

The data from the lithologic and RQD block models (lithologic block model shown on Figure 1) fits well to the interpreted mine geology dyke wireframe geometry (not shown), strongly suggesting that zones of the dyke were actually missing (Figure 4a). While it was recognized that this could be an artefact of the block model due to areas with limited drillhole density and in fact this was actually found to be the case in some areas, it was clear that this was not the case everywhere. Specific checks indicated that in some zones, drillholes were found right through the suspected dyke contact but logged as NR or GS.

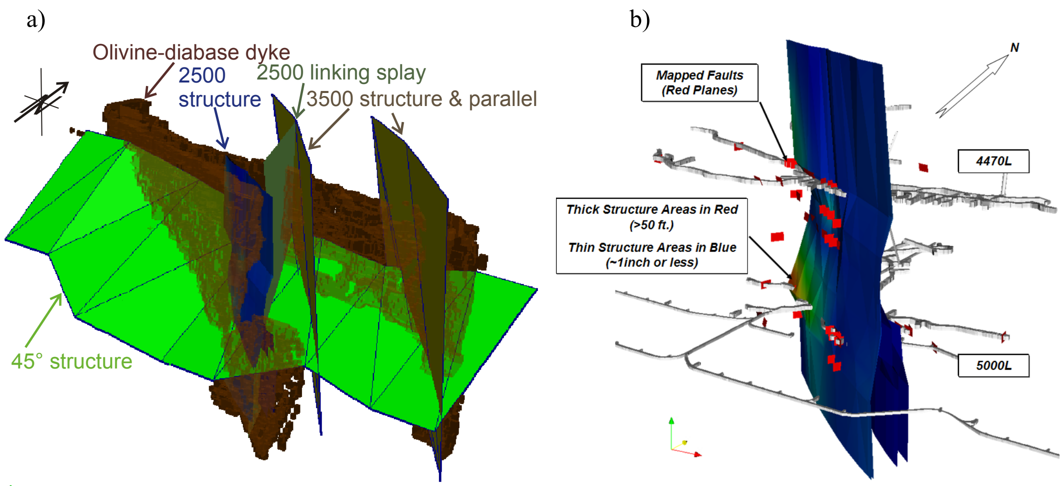

Figure 3: a) View of the main structures at Garson mine in the active mining area. b) Detail of the 2500 structure model. Mapped geologic major structure planes (red) oriented normal to the structure are hypothesized to be tensional openings due to shear along the 2500 structure.

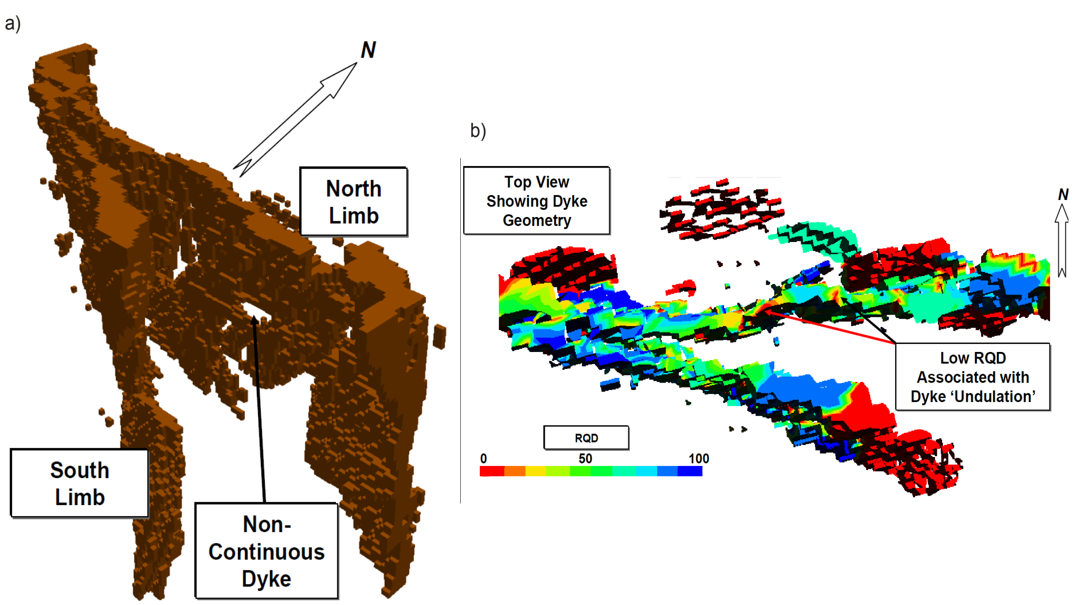

Figure 4: a) Olivine-diabase dyke geometry. b) Top view of the dyke, colored by RQD.

2.2 *Seismic Analysis*

Both micro-seismicity and larger scale seismicity that has resulted in damage to mining excavations has been recorded and observed at Garson. Such seismicity is not uncommon around mining excavations at depth, but what is unusual about the seismicity at Garson is that it has not always been located in the immediate vicinity of any mining excavations (see Figure 5a). Further, there appeared at first that there was no clear apparent relationship between the excavations themselves and the locations of the seismic activity. The majority of the mining induced seismicity was not located around the boundaries of the stopes as would have been expected.

The structure of the seismic cloud was further investigated using various techniques. Particularly, a coarse analysis was completed where seismic density was computed and linear trends were extracted. The strike directions of the high density seismic trends are presented on Figure 5b. There is a strong similarity with the orientation of the dominant structure at Garson mine (Figure 5c). This clearly suggests a strong structural control of the occurring seismicity. A seismic plane clustering algorithm was also applied to the data (Vasak et al., 2004, Kaiser et al., 2005). The orientation of the seismic active planes (Figure 5d) shows a dominant trend for 35°-55° south dipping planes. This is in agreement with the observation that a large amount of seismicity focuses on the 45° south dipping structure zones (Figure 5a).

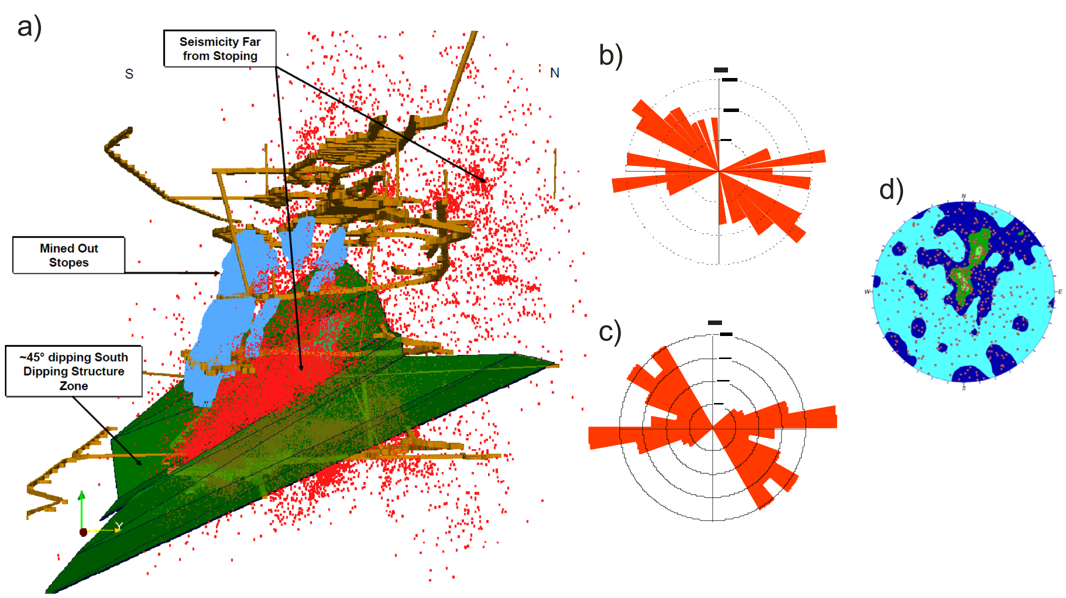

Figure 5: a) Location of microseismic-events relative to mine infrastructure. b) Rosette diagram of high density seismic trends. c) Rosette diagram of the strike of the main structures at Garson mine (see also Figure 3). d) Sterographic projection of the orientation of the seismically active planes (lower hemisphere, equal angle).

A finer analysis of the seismicity showed that structure-structure intersection and interaction played a key role in the spatial repartition (i.e. the spatial location and organization/patterns) of the seismic activity. Particularly, the following interactions were identified:

1) Interaction within the dihedral formed by the north and south OLDI limb, the 2500 structure and the 45° structure (Figure 6a, b);
2) Interaction between the south OLDI limb, the 2500 structure and the 45° structure (Figure 6c, d);
3) Interaction between the 2500 parallel structure, the north OLDI limb and the 45° structure (Figure 6e); and
4) Interaction between the 2500 parallel structure and the 45° structure (Figure 6f).

The analysis of the repartition of the seismicity with time suggests that seismic activity is transferred between the structures as mining progresses as suggested by the time links on Figure 6 (two right images). Time links are lines joining seismic events in chronological order. In the right-images presented on Figure 6 (time period from 14-Jul-07 to 01-Aug-07), time links clearly highlight the remote interaction between zones a, d, and e and the vertical interaction with the 45° structure zones (lower right image in Figure 6). However, the details of the mechanisms underpinning these activity transfers are not understood at this time.

Generally, the spatial relationships between mining activity and seismic activity suggest that failure of the structural features is triggered mostly by their unloading (decrease of their apparent shear strength due to mining induced unloading).

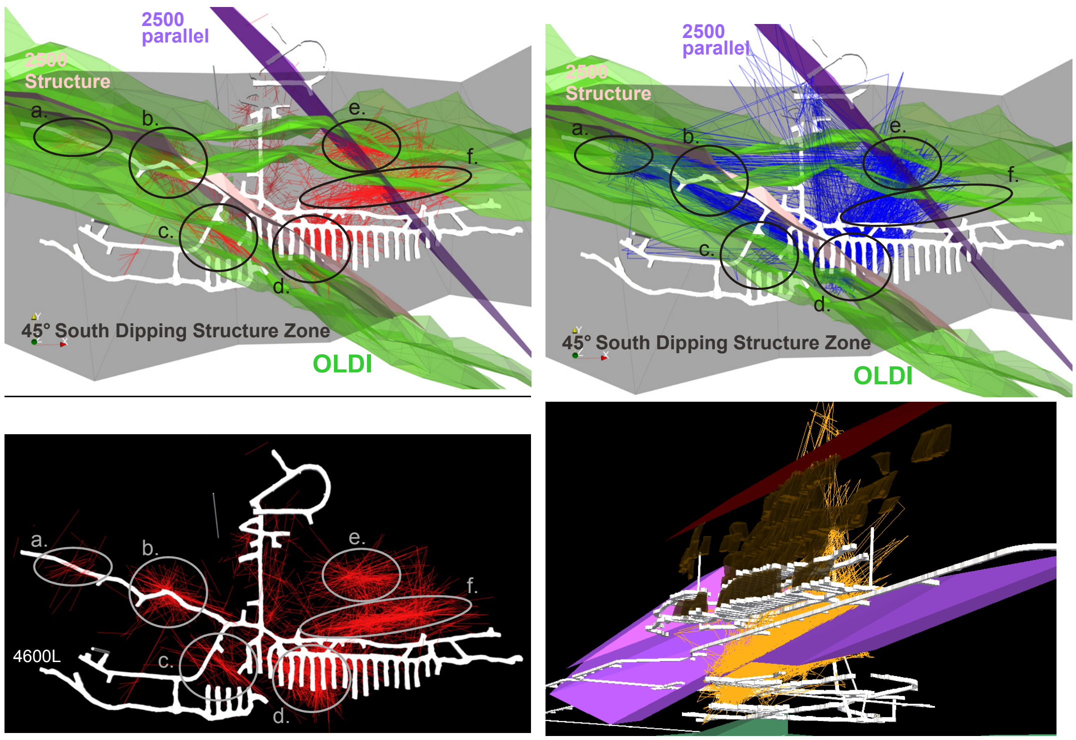

Figure 6: Relationships between Line-of–Intersection (LOI) of the seismically active planes (in red, left images) and the main structures. 4600L is displayed for reference. The LOI permit the visualization of the interactions within the micro-seismic pattern. Right images: time links (in blue and orange) on filtered seismic data for the period 14-Jul-07 to 1-Aug-07.

3 NUMERICAL MODELLING

This section highlights two numerical modelling exercises to illustrate; (1) a back-analysis completed to further confirm the role of the 45° structure zone's significance in the seismicity at Garson; and (2) modelling using displacement boundary conditions to more realistically account for the stiffness differences between the materials and faults to identify potentially highly stressed areas of ground.

3.1 *Example Case History: Simultaneous Bursting on 4470, 4600, and 4700L*

Simultaneous bursting occurred on 4470L, 4600L, and 4700L on January 23, 2007 in the north limb of the OLDI dyke. At 22:05, the OLDI dyke became seismically active around the 2670 cross cuts (the main entrance drifts to the levels) on 4470L, 4600L and 4700L. On 4470L, minor cracking and spalling of the shotcrete was recorded through the OLDI dyke near the south side of the north limb by the norite contact. The damage on 4600L was moderate cracking and spalling of the shotcrete throughout the dyke, displacement of approximately 2 tons of dyke material from the back near the dyke's northern boundary and displacement of 5 tons of dyke material from the back near the dyke's southern boundary. On 4700L, severe cracking and spalling of the shotcrete throughout the dyke was recorded with displacement of over 10 tons of dyke material from the east wall just south of the norite/dyke contact, 5 to 6 tons displaced from the back in the middle of the dyke, and 2 to 3 tons of dyke material displaced from the back near the dyke/norite contact.

While the 45° structure zones were known to the mine, they were previously thought to not play a large role in seismicity generation. In creating the EGM, value was gained as all of the events appeared to coincide with the location of the potential south dipping 45° structural zone crossing directly between 4600L and 4700L, defined from geologic interpretation and cross correlated by seismic activity (Figure 7 left).

3.2 *2D Fault Slip Assessment*

A back-analysis of the case history outlined above was completed using both Phase^2 (©RocScience 2006) and UDEC (©Itasca) to determine if slip could have potentially occurred along the 45° structure zone and be the potential cause of the simultaneous bursting.

The analysis of the mining sequence (Figure 7 right) leading up to the January 23, 2007 event showed a change in the direction of shear displacement thus a large magnitude of displacement along the potential structural zone. This further suggested that the potential south dipping 45° structural zone was the cause of the simultaneous events on 4470L, 4600L, and 4700L. It is interesting to note that when the stiffness of the north dyke limb was reduced in the models, there was limited shear displacement along the 45° structural zone. This again shows, as outlined in Section 2.2, that it is not one structure at Garson that is generating the seismicity, it is the interaction of the major structures.

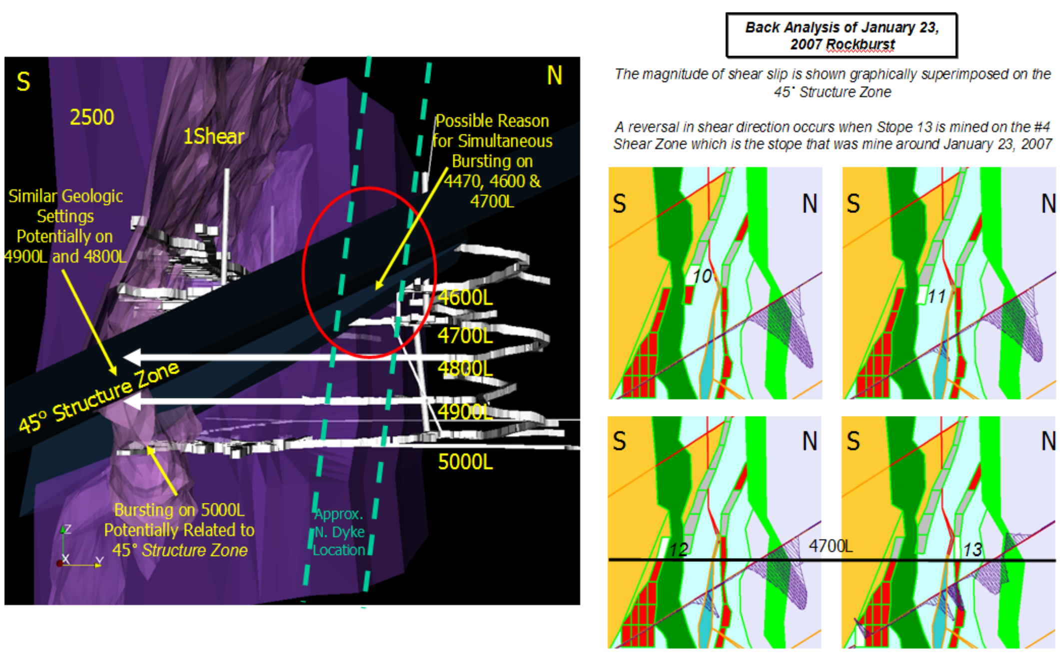

Figure 7: Left: Problem geometry showing interactions between the 45° structure and the dyke possibly explaining the simultaneous bursting on 4470, 4600, & 4700L. Right: Phase^2 analysis showing 4 mining stages leading to a change in shear slip direction and magnitude as a result of mining stopes in the #4 shear on 4700L.

3.3 *Displacement Boundary Conditions*

It is common with 2D large scale, mine wide numerical modelling to apply fixed boundaries at a large distance from the area of interest and specify a constant stress field of a given magnitude and orientation throughout the mesh. This approach ensures that the model is at, or is close to, equilibrium when the simulation begins before any mining excavations are removed. This is normally quite acceptable if the rock mass in the model is homogeneous with little or no variability in the stiffness of the materials. This is not a good representation when the area to be modeled is composed of materials with significantly differing stiffness. Such is the case with the dykes, faults, and the host rock masses at Garson.

In reality, regions of a rock mass that are stiffer will tend to attract higher stresses than the surrounding rock even in the absence of mining and more importantly, when flat lying structures are present, high horizontal stresses lead to near equilibrium states of stability and thus are very sensitive to mobilization. As stress differentials appear to have a significant effect on seismicity patterns, it was decided that it would be better if the model could represent this initial uneven and more realistic distribution of the stress field. This would result in the dykes being more highly stressed than the surrounding rock mass and the geologic structures being preloaded because of the stiffness contrasts. In such a situation it was found that modelling the initial stress field using fixed boundaries and an applied constant stress field were inappropriate.

To achieve a more realistic and uneven initial state of stress, in which features such as the dykes would be more highly stressed, displacement boundaries were applied to the model, compressing the model inwards and generating the desired internal stresses as a function of this displacement. Not only did this transfer more stress to the stiffer materials, but it also loaded the geological discontinuities unevenly as a consequence of the resultant variable stress field. The model was compressed in this way until it had been strained sufficiently to produce a global stress field with magnitudes similar to those anticipated in the area being modelled. When the stress state within the model sufficiently matched the measured stress state in the field, the boundaries of the model were fixed prior to continuing with the rest of the simulation in the normal manner.

The results of applying a displacement boundary condition criteria to the Phase^2 models are interesting in showing that the geometry, or shape, of the dyke causes certain parts of it to act as even higher stress concentrators; as can clearly be seen in the plot of the major principal stress shown on Figure 8a & b. The modelled offsets of the dyke (which may be fault offset controlled) appear to act as stress intensifiers, resulting in local stress concentrations at these points. Even with smoothed corners, significant stress concentrations still exist in the dyke. Such stress concentrations are of concern, as they could potentially become overstressed or ‘unconfined’ with ongoing mining-induced stress transfer, thus potentially causing difficulty when crossing the dyke with development drifts.

The displacement boundary conditions were compared to the created RQD block model (ref. Figure 4 for dyke lithology and RQD models) with focus on the dyke. In review of the core logged in the dyke, it was found that the areas of low RQD were attributed to core disking (high stress concentrations) as shown on Figure 8c, as opposed to low rock mass quality due to broken core or gouge filled discontinuities. Plotting the RQD in the dyke as shown on Figure 8d, it can be seen that the core disking areas (low RQD areas) appear to be consistently located in the areas where the high stress concentrations are predicted in the dyke.

This analysis is not unduly complex and even simple modelling can be completed during the planning stages of a mine to identify areas of highly stressed ground and thus help define areas to avoid if possible.

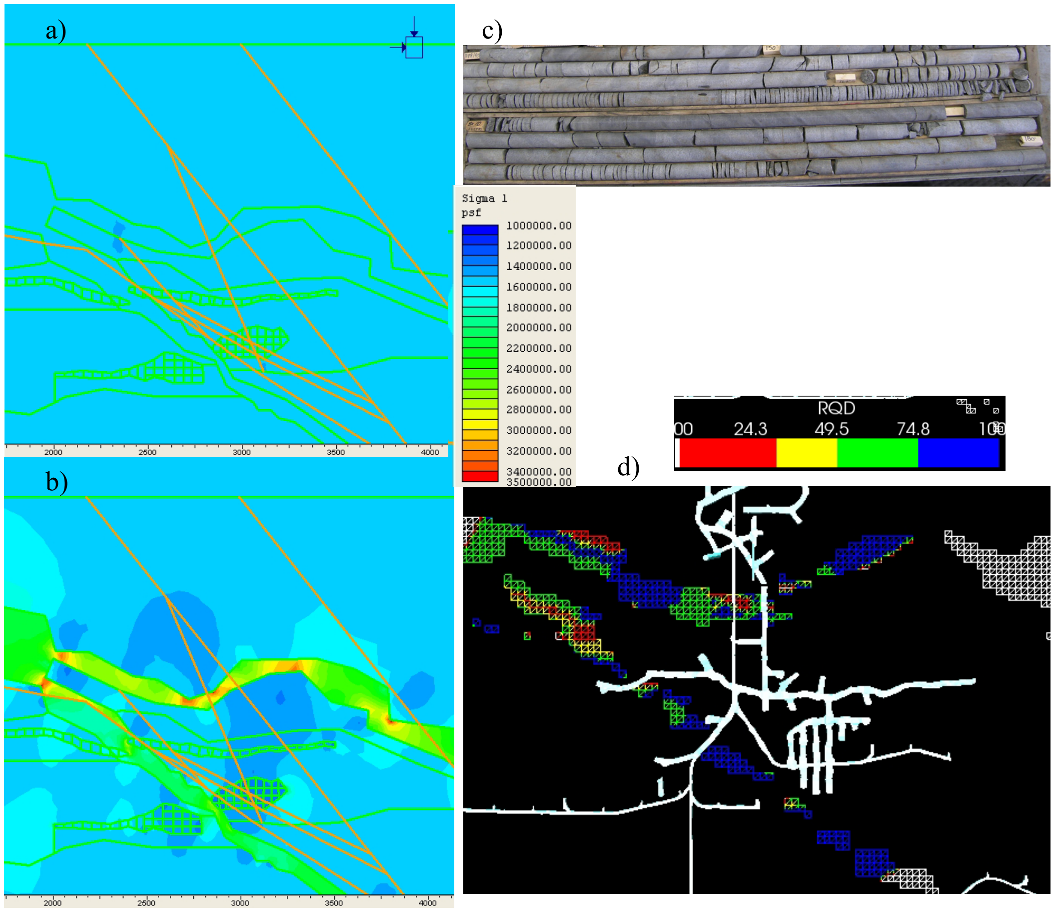

Figure 8: a: Constant stress field (1 MPa is ~20885 psf). b: Displacement loaded model showing stress variability (joint yield not displayed). c: Disking in north dyke that was logged as 0 RQD. d: RQD block model for dyke showing low RQD (core disking) in areas similar to the stress concentrations in (b).

4 DISCUSSION & CONCLUSIONS

A series of rockburst events at Garson mine which occurred over several years could not be explained using a direct relationship with stope extraction activity, as the events occurred relatively far from the active mining front or during periods without stope extraction in the project area. In order to better understand the involved mechanism in the rockburst activities, a global approach to address the risks associated with mining in such environments was developed. Such a global approach was proven to be necessary, as it appears that the seismic activity at Garson mine was controlled by larger scale interactions between identified geological structures and thus can be captured only by a methodology considering interactions controlled by structures. The integration and analysis of all available data supplemented by numerical analysis of the problem areas determined that:

- The built EGM proved to be a reasonable model. Rockbursting experienced after the creation of the EGM has occurred in excavations projected to intercept the active structures (Figure 9).
- The analysis of the fracturing at Garson mine could be used for the extraction of the dominant structural trends.
- The trends corresponded to some major structures with various characteristics such as; the 2500 structure system which is comprised of faults with anastomosed internal architecture and lenses of gouge with varying width; the 45° structure system which is made of not fully formed reverse faults occurring as bands of en-echelon tension gashes; and the non-continuous and offsetting OLDI dyke geometry.

- The micro-seismicty was not seen in direct geometrical relation with active mining but was strongly controlled by the identified structures. Moreover, interactions between the structures played a dominant role in the concentration of the observed seismic activity.
- Modelling of the mining sequence and its impact on the stress and strain condition on the main identified structures confirms the importance of structure-structure interaction with respect to the slip pattern of a fault system and its related seismic activity.
- Displacement boundary numerical modelling of the area of interest including the main identified structures highlights the impact of the geological characteristics of the structures (dyke ‘undulations’ and holes, rock bridges between en-echelon fault systems or stiffness contrast between gouge filled rock and more brittle fault sections) on the possible initial stress state conditions. These conditions tend to induce heterogeneous stress fields.

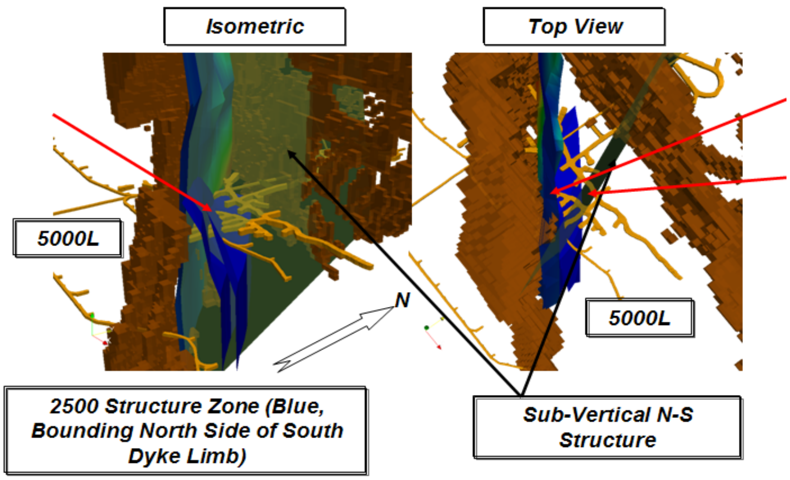

Figure 9: Red arrows point to location of some rockburst events in relation to major structures.

5 ACKNOWLEDGMENTS

The authors would like to thank Garson mine personnel for their help in the successful completion of this study and the project team that was composed of colleagues from various Golder offices; Luiz Castro, Trevor Carter, Joe Carvalho, & Nic Lightfoot (Mississauga); Veronique Falmagne (Montreal); & Kevin Beauchamp (Sudbury); MIRARCO; Sean Maloney & Pavel Vasak; CEMI; Peter Kaiser; and Vale Inco; Steve Runnalls, Jeff Whitney, Yurek Krynicki, Darren Hodder, Darrell Butt, Denis O’Donnell (Golder Sudbury), Denis Thibodeau, & Dave Duncan.

REFERENCES

Beach, A. 1975. The Geometry of en-echelon vein arrays. *Tectonophysics,* v.28, p. 245–263.

Castro, L. A. M, Carter, T. G., and Lightfoot, N. (2009). Investigating Factors Influencing Fault-Slip in Seismically Active Structures. Proc. of the 3rd Canada-US & 20th Can. Rock Mech. Symp.

Cochrane, L.B. 1991. Analysis of the structural and tectonic environments associated with rock-mass failures in the mines of the Sudbury district. Ph.D. Thesis. Queen’s University, Kingston, Canada.

Kaiser, P.K., Vasak, P., Suorineni, F.T., & Thibodeau, D. 2005. New dimensions in seismic data interpretation with 3-D virtual reality visualization in burst-prone grounds. Keynote Address to 6th RaSiM6, Perth, Australia, 33-47.

Maloney, S. & Cai, M. 2006. In situ stress determination at Garson mine. Report n°06-015. MIRARCO. Sudbury. Canada.

Riedel, W. 1929, Zur Mechanik geologischer Brucherscheinungen: ein Betrag zum Problem der Fiederspattern. *Zentblatt Mineral Geol. Paläont B:*354–368.

Roussel, D.H. 1984. Structural geology of the Sudbury Basin. In E.G. Pye, A.J. Naldrett & P.E. Giblin (eds), *The Geology and Ore Deposits of the Sudbury Structure:* 83–95. Ontario Geological Survey Special Volume 1. ISBN 0-7743-9423-4. Canada.

Vasak, P., Suorineni, F.T., Kaiser, P.K. & Thibodeau, D. 2004. Hazard Map Approach Using space-time clustering analysis of Mine-induced Microseismicity. CIM conference 2004. Edmonton. Canada.