GeoRisk Workshop

Summary of Feedback

May 14-15, 2009 | Toronto, Ontario, Canada | Royal York Hotel

Photo courtesy of Brad Simser

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Geo Risk Workshop | Feedback Summary

Introduction

On May 14-15, 2010 in Toronto, Ontario, a multidisciplinary group of mining experts in their respective fields joined together to brainstorm the fault slip needs of the mining industry. The need for such a workshop materialized when in a recent bow-tie risk analysis, Vale Inco concluded that while significant advances have been made in seismic monitoring, data interpretation, hazard mapping, reentry protocols and support design, there were still insufficient controls to mitigate risk associated with fault slip events. Through this workshop, the foundation for identifying potential areas for innovation in the field of fault slip controls was established. Following this workshop would be the establishment of the International Fault Sip Control Research Initiative (IFSCRI), a pilot project with the goal to determine the technology and tools required by industry to better manage the risks associated with fault slip rock bursting in underground mines.

Break-out Session Questions

In this workshop, participants were asked to address the following questions:

1. What are the R&D opportunities?
2. Outline the key immediate ones (list them)
3. Who are the researchers or consultants that are not at this meeting who should be part of the research solution team?

Workshop Groups Composition

Participants were set into one of five domain-specific groups. The composition of the groups was as follows:

Group 1	Group 2	Group 3	Group 4	Group 5
Modeling	***Geophysical Tools***	***Seismicity***	***Structural Geology/RMC***	***Mine Design***
Steve McKinnon	Claire Samson	Gerrie van Aswegen	Wouter Bleeker	Brad Simser
David Beck	Kevin Fenlon	Cezar Trifu	John Fedorowich	Jerry Ran
Richard Lynch	Erik Westman	Matt Purvance	Trevor Carter	John Hadjigeorgiuo
John Henning	Richard Smith	Dave Counter	Mark Board	Veronique Falmagne
Scott Carilsle	Vladimir Shumila	Pavel Vasak	John McGaughey	
David Collins		Denis Thibodeau	Steve Falconer	

Agenda

CEMI FAULT SLIP WORKSHOP- ROYAL YORK HOTEL, MAY 14-15TH, 2009
Salon 1 (19th Floor)
Preliminary Agenda

SESSION	TOPIC	TIME	PRESENTER	COMMENTS
THURSDAY, MAY 14TH				
BREAKFAST (PROVIDED) 0800-0830				
SESSION	**TOPIC**	**TIME**	**PRESENTER**	**COMMENTS**
INTRODUCTION AND OVERVIEW	1. Welcome and purpose of workshop/Intro. of Co-facilitator	0830-0850	Damien Duff	Each participant will briefly introduce him/herself
CASE HISTORIES AND PROBLEM DEFINITION	1. Definition of Problem 2. Kidd Creek 3. Xstrata Sudbury 4. VI Sudbury	0850-0900 0900-0920 0920-0940 0940-1000	Denis Thibodeau Dave Counter Brad Simser Denis Thibodeau	Present examples that demonstrate success/failures in how we have dealt with controlling geological structures (Don't limit to Sudbury)
COFFEE BREAK				
STRUCTURAL GEOLOGY/ROCK MASS CHARACTERIZATION	1. The structural geology and tectonic environment associated with rock mass failures in Sudbury mines and implications for the assessment of fault slip events 2. What are the important characteristics of faults and how do we identify them? How can we anticipate the unexpected?	1020-1040 1040-1120	Larry Cochrane Mark Board John Fedorowich	In areas where too little geological information exists is it possible to scenarioize the potential structure so as to optimize the chances of managing energy release more effectively during mine design and operation? Can the possible geological architecture of an area be postulated so as to potentially anticipate a chain link reaction of ground failure?
WHAT WE'VE HEARD - DISCUSSION		1120-1200	All	
LUNCH (PROVIDED) 1200-1300				
SEISMOLOGY AND MINE SEISMICITY	1. Large Scale Fault Slippage- what we know and can learn from large systems? 2. Instability Indicators and detection of faults using microseismic data 3. Assessing Seismic Hazard in Mines 4. Lessons learned about fault stability assessment in S.A. mines	1300-1320 1320-1340 1340-1400 1400-1420	Matt Purvance Richard Lynch Cezar Trifu Gerrie van Aswegen	What are the fundamental mechanisms of fault slip?
ENERGY RELEASE CONTROL	1. The state of the art in energy release control 2. Can we define if and when a fault becomes critical?	1420-1440 1440-1500	Mark Board Steve McKinnon	"We don't know how to manage the energy release associated with Fault Slip"
COFFEE BREAK				
GEOPHYSICS & OTHER POTENTIAL TOOLS	1. Probabilistic Estimates of excavation performance in mines with fault slip 2. The state of the art in geophysical instrumentation as a means to map structural and other rock mass characteristics 3. Use of Seismic Tomography for inference of stress redistribution in rock 4. Data Integration as a tool to identify risk associated with fault slip	1520-1540 1540-1600 1600-1620 1620-1640	Dave Beck Claire Samson Erik Westman John McGaughey	- The need for better instrumentation and monitoring In conjunction with Richard Smith and Steve McKinnon
FRIDAY, MAY 15TH				
BREAKFAST (PROVIDED) 0800-0830				
SESSION	**TOPIC**	**TIME**	**PRESENTER**	**COMMENTS**
FRIDAY MORNING KEYNOTE ADDRESS	1. Rock Mechanics Challenges in mining	0830-0910	Peter Kaiser	
RE-CAP OF THURSDAY'S PROCEEDINGS	1. What we heard you tell us yesterday-	0910-0930	Cochrane/Duff	the takeaways from our presentations and discussions
BREAK-OUT SESSIONS	1. Selection of Break Out Topics and group assignments 2. Break Out Sessions	0910-0920 0920-1015	Facilitated by Duff & Cochrane	Identify what research gaps exist and what opportunities there are for CEMI to support research excellence
	COFFEE BREAK			
	3. Presentation of results from Break Out Sessions	1030-1115	To be assigned from within groups	
NEXT STEPS AND THANK YOU	1. List of action items	1120-1200	Cochrane/Duff	

Workshop Feedback

Group 1 - Modeling

(1) What are the R&D opportunities?
(2) Outline the key immediate ones?

1. *We need to:*
    i. Build a set of Guidelines for use by Modelers when dealing with Fault Slip Modeling Problem
    ii. Ensure it has a user-perspective

2. *Initial Appreciation of problem- what should go into the geotechnical block model?*
    i. Regional tectonics (Regional stress considerations)
    ii. Regional geology/structures
    iii. Local known structure/anticipated structure
        - How large/how strong are the structures?
        - Are any structural orientations potentially more sensitive than others
        - What about possible and anticipated structures?

3. *Tool Selection Process:*
    i. Recommendations for model-type selection (2D, 3D, elastic, non-elastic etc
    ii. Also impacted by need to deal with:
        - mine geometry
        - Sequencing
        - Sensitivity analysis
        - Fault orientation control on mining
        - Mining stress re-distribution

3. *Analysis and Implementation of results/findings:*
    i. What criteria are being analyzed? E.g. Stress increase or decrease?
    ii. What analysis criteria should be considered?
        - Should new criteria can be established?

4. *Back analysis/forward analysis*
    i. Managing Uncertainty

5. *Appendix:*
    i. Fault characteristics?
    ii. Physics of models
        - Non linear versus elastic, 2D vs 3D etc.

(3) Who are the researchers or consultants that are not at this meeting who should be part of the research solution team?

The research team could consist of experienced mine personnel/consultants/University types. Team members would be 'drafted' to contribute specified material (Chapters) for an SME-style document/workbook. Perhaps the compiled material would provide content for a Short Course targeted at industry users.

Workshop Feedback

Group 2 - Geophysical Tools

(1) What are the R&D opportunities?
(2) Outline the key immediate ones

1. Time Lapse Monitoring:
    i. Seismic Velocity from tomography
    ii. Seismic attenuation
    iii. Using active systems
    iv. Using blasts as seismic sources

2. Borehole:
    i. Acoustic/optical televiewer
    ii. Sonic
    iii. XRay
    iv. Gamma/density
    v. Integration multi-tools
    vi. Resistivity logs
    vii. Radar

3. Data Integration:
    i. Auto interpretation?
    ii. Data access issues?

4. 3D Seismic for large structures

5. Looking at smaller microseismic events below normal trigger level? There's a lot of events which we don't use.

6. Full waveform interpretation- there's a lot of data associated with each specific event which we don't use either

SHORT TERM BENEFITS

1. Time Lapse Velocity/Stress
    i. Monitoring existing systems and historical data (Erik Westman, MIRARCO, POLARIS/ESG

2. Re-analysis of seismic/microseismic data to quantify the value of small events, full waveform data
    i. Re-looking at 2D/3D seismic results for large structures (Sudbury, Voisey's?)
    - Validation/comparison with more recent drillhole logs (Claire Samson, Don White)

3. Project to highlight value of borehole integration and interpretation
    i. Importance of combining all geotechnical data- geophysical/geological etc. (Mark Moner Williams)

Workshop Feedback

Group 3 - Seismicity

(1) What are the R&D opportunities?
(2) Outline the key immediate ones

1. Risk Assessment or Forecasting Technology
   i. Probabilistic risk assessment?
   - In space
   - In time

   ii. Impact on building codes and design guidelines (create a building code for fault slip event e.g. what should be the support design and workings design subject to fault slip events.)
   iii. Similar to large earthquake systems

2. Identification of structures – or structural trends/patterns
   i. In Greenfields/brownfields environments?
   ii. Would back analysis of existing datasets help? At least could be used to refine/tweak existing tools…

3. Asperity Models
   i. To identify discontinuity patterns
   ii. Share data with earthquake seismologists

4. Tomography (Active/Passive)
   i. Velocity models
   ii. Accuracy of source locations
   iii. Identification of failure zones

5. Standardized Seismic Hazard Analysis Code (SSHAC)
   iv. Standardized analysis process/methodology for the mining industry

The following were identified as potential people to do research on seismicity for the mining industry:
Dan Heal (ACG); Marty Hudyma, Rich Brummer, Pacific Gas and Electric (San Francisco), ISS &ESG, GRC at MIRARCO, GSC, Earthquake Engineering folks)

Workshop Feedback

Group 4 - Structural Geology/RMC

(1) What are the R&D opportunities?
(2) Outline the key immediate ones

A: Structural Geology Issues

THE MAIN QUESTION IS:

1. What Faults are Critical and how do we characterize them?
   - i. Stress rotation
   - ii. Offsets
   - iii. Interaction
   - iv. Gouge Criteria
   - v. Disking
   - vi. Location
   - vii. Continuity
   - viii. Topography of fault
   - ix. Release mechanisms

2. Deficiencies seen in addressing this goal:
   - i. High level structural input missing in exploration
   - ‣ Data only interpreted from ore perspective and not "operational behaviour"
   - ‣ Not enough training of people in structural geology techniques
   - ‣ Too much data is collected but not analyzed- drift maps, other structural stuff etc.
   - ‣ Early interaction of structural geologist with exploration team needed
   - - Set up "structural geology team"
   - - Define structures of significance to mining early
   - ii. Need to educate folks about the need to collect appropriate structural data (Can be done through university teaching or through championing of the cause by an appropriate mine executive
   - ‣ There are issues with the loss of information as people move on and retire
   - - Maybe use GoCAD-type approach to capture data rather than leaving it in people's heads

B: Structural Opportunities

1. Develop 43-101-style standard methodology for what data needs recording at the exploration stage:
   - i. Reliably identifying important structures (list in order of type)
   - ii. Descriptions not enough. Need area and volume quantification etc.
   - iii. Hierarchical classification of structures is important
   - iv. Need to develop case histories of "problem structures" which try to understand why they were problems.
   - v. Develop set of simple criteria for early detection of problem structures, based upon early "cartoon models and concepts".

2. Make use of FRACMAN-type DFN models of structures and domains
   - i. Develop standard methods/DFN styles
   - ii. Consider typical structural domain categorization – war zone models etc
   - iii. Clarify scale dependency early on.
   - iv. Look at ways to present big picture vs drift scale, mine vs regional etc information for improving mine management's understanding.

3. Develop interfaces to new geophysics tools
   - i. ATV/OTV, tomography, and available downhole gear
   - ii. Make use of deep seismic tomography
   - iii. Integrate mine-style structural analysis with airborne exploration geophysics programs etc (meaning???)

Workshop Feedback

Group 4 - Structural Geology/RMC, cont.

(1) What are the R&D opportunities?
(2) Outline the key immediate ones

4. We need both cartoons and details (there's not enough overlap of these in going from an exploration project to an operating mine)
   i. Data collection must not be "in a vacuum" but we need to avoid black box solutions
   ii. Cartoons and detail are both needed at all stages to test hypotheses
   iii. New data must be integrated and used to refine and re-interpret. Does is still fit with the original exploration ideas/concepts/

5. More emphasis needs to be placed back on staffing
   i. In the 1960's-1980's- 12-15 people in geotechnical and structural geology role were not uncommon in most major mines.
   ii. Now there are too few- especially at a senior level
   iii. Almost no one form the original exploration team is involved in the day to day mine geology

6. Structural attribute data are often on drift maps (and buried within core logs- DD comment) and need to be collected, extracted and turned into something useful (stereonets etc)

7. Structural geology audits are needed

(3) Who are the researchers or consultants that are not at this meeting who should be part of the research solution team?

1. Old mature discipline, that has got lost in the new wave of computational exploration driven by geophysics and "definition drilling" (viz .. visualization and krigging/stochastic methodologies have rather supplanted conceptual structural thinking)

2. Need seen to get back to basics and rekindle interest in structural geology as a necessary tool for mine design this will in turn spin off R&D into interface areas - eg., using new geophysics tools but applied to structural analysis

3. Deficiency of good APPLIED MINING structural geology departments in Canadian Mining Companies or in Universities.

4. Worldwide there are some places that have historically had good reputation for structural geology teaching, but few students in mining

5. Many good Structural Geology University Departments and Consulting Firms still exist, eg. in California - but they tend to be earthquake or plate-tectonics driven, not mining specific;

6. No-one could think of anywhere with a high profile - that was specifically training MINING structural geologists

7. Major geotechnical/rock mechanics consultancies have some staff with the right technical background, but few of those staff are actually involved in application of their skills to mining

8. Mining Companies also need their own "beat geologists" to be more structurally aware and lead from within

9. Considered worthwhile to do a little searching on the web etc and via the grapevine to identify specific possible other firms or individuals

Workshop Feedback

Group 5 - Mine Design

(1) What are the R&D opportunities?
(2) Outline the key immediate ones?

1. Develop convincing economic argument for good geotechnical design through example of:
   i. Sterilized reserves
   ii. Safety issues etc
   - Will require a critical re-assessment of safety and geotechnical designs

   This would be a specific project that could be proposed by CEMI . A potential leader of such a s project might be Larry Smith or Bruno Lemelin of Xstrata. Potential researchers: Brian McKenzie (may be retired. He is- DD comment. His successor at QU is Michael Doggett, also very good but now in Vancouver but remains as an adjunct at QU), Charlie Pelley (retired), George McIsaac (now in Chile). These people might be able to identify their successors if they are not able to do the work themselves.

2. Integrate tools/disciplines for mine design

   Separate issues and level of investigations/tools required depending on the stage of the project. The project would be to outline the specific potential risks and identification methodologies
   i. Greenfield (early stages)
   - Identify high level risks at the scoping and feasibility study stages (or when developing a new zone in an operating mine) leading to :
     - Appropriate mining method selection
     - Position of infrastructure
     - Identification of potentially fatal flaws, such as fault slip
     -

   ii. In Operating Mines (later on). Here, each item below would be a separate project.
   - Create feedback loops enabling a re-evaluation of the effectiveness/appropriateness of the selected mine design based upon:
     - Seismicity (e.g. MIRARCO, Hudyma, ISS)
     - Observations (e.g. MIRA)
     - Instrumentation
     - Ground support performance
   - Use all available information to challenge/adjust the selected mine design

   iii. Ensure knowledge transfer from exploration phase to the mining phase.
   - Structural model should be dynamic and will evolve over time
   - Stress modeling is important and appropriate mechanisms should be in place at the design stage to collect and model and monitor rock mass behaviour (Itasca, Beck, Golder)
   - At the mining stage, appropriate feedback loops are important to monitor performance against design

   iv. Make televiewer logging of every borehole cost effective

   v. Assess usefulness of new “toys” for practical purposes, e.g. LIDAR, laser mapping etc.

(3) Who are the researchers or consultants that are not at this meeting who should be part of the research solution team?

Some are identified for specific projects but they were already at the table except on the economics aspects

Post-workshop Comments

Larry Cocharane

Workshop Summary

Importance

- Fault slip events primarily occurred at Creighton; however, these events are now occurring more frequently at other mines (Garson, Stobie and CCN).
- The magnitude of the events is increasing and the impact on operations is becoming more of a concern in terms of risk, lost production and operational cost.

Status

- Sufficient pre-event controls are in place to manage strain and pillar bursts.
- For fault slip events, sufficient post-event controls have been established to mitigate the consequences to personnel and the operation.
- Focused research is required to develop and implement pre-event controls for fault slip bursts.

Objective of Research

- How do we effectively characterize the structural geology of a mining block and identify the faults or fractures that produce fault slip events?
- How do we manage the energy release associated with fault slip events?

Comments on Workshop Presentations and Proposed Research Requirements

Comments and Some Key Conclusions

- A primary conclusion from the workshop was that there is not an adequate structural characterization process in place for mine planning, specifically to identify fault systems, fracture systems or zones that are susceptible to failure by fault slip as a result of mining.
- My research on Sudbury suggests that the faults and fractures that are activated by the mining are the system that is already active under the current stress field. One of the workshop attendees in a question session indicated that the primary cause of fault slip events is the mining activity. He indicated that any major structure can be "activated" by the mining stress regardless of current tectonics. A component of the research required to develop effective methods to characterize the structural and tectonic environment should include determination of the chronology of the regional structural events (structural episodes or orogenies).
- An important aspect is to be able to identify the zones or areas within the deposit that are most at risk. A large step in that direction would be to identify the susceptible structures and their projections and the rock mass quality within the immediate area of these structures.
- Matt Purveyance's presentation suggests that mining-induced shear events are similar to earthquakes, which implies that previous and ongoing earthquake research can be applied to mining-induced fault slip. This conclusion suggests that the underlying mechanisms causing the events are similar and emphasizes the application of applying earthquake research techniques to fault slip events induced by mining. The similarity of mining-induced fault slip events to natural earthquakes is consistent with a recent study on the characterization of mining-induced seismicity in the Witwatersrand Basin by Jordan and Richardson from the University of Witwatersrand and MIT.
- The workshop participants agreed that a key area of research is the analysis of the source mechanisms of the events from the waveform records using the techniques traditionally employed in earthquake studies to determine the failure mechanism, possible stress orientations, source characteristics, energy release and stress drop. The research investigations being carried out by ISS, as described by Richard Lynch and the investigations by Steve McKinnon are very beneficial, particularly when integrated with structural investigations.
- The concept of having the seismic events for several mines also being recorded at Laurentian, with a team of people examining and analyzing the data to develop interpretive tools and a longer-term understanding of the mechanism seems to make sense. My impression was that ISS was delivering this service to the South African mines.
- The suggestion that the cost of not managing these events in terms of sterilized reserves and production loss should be quantified is important. The importance of the research needs to be emphasized in an appropriate manner.

Post-workshop Comments

Larry Cocharane, cont.

Comments and Some Key Conclusions

- Mark Board's list of "Practical Guidelines" is very useful. Although he indicated that these observations were "obvious", they are not always followed. Certainly, the suggestion to install a seismic monitoring system prior to mining is not a common practice. It would be useful to put these guidelines together in a more formal deliverable as an early initiative and deliverable.
- Longer term, however, for the effective control of the energy release, it is important to understand the fundamental process causing these fault slip events. A key issue is the understanding of the triggering mechanism whereby stress changes associated with mining or a fault slip event can induce seismic activity along other associated structures either immediately or subsequently (ranging from minutes to months). It is this time-delay failure that is difficult to manage.

Current Research at Memorial and Possible Synergies

Passive Seismic Monitoring Project

We have installed an array of three-component geophones and a seismic monitoring / telemetry system along the line of known deposits at Voisey's Bay. In addition to assisting in identifying the presence of any active geological structures, the data will be used to develop an understanding of the local stress field for mine planning. This presents an excellent opportunity to monitor the seismic activity in the region of the underground working prior to the beginning of mining. The results of this research will becompared to the traditional methods used to estimate the in situ stress field for mine planning. Once mining begins, it will act as a baseline to determine the increase in seismic activity resulting from the mining excavation. In conjunction with the structural assessments and borehole caliper studies, this research will allow the development of methods to establish tectonic models of the underground for mine planning purposes.

This project is being led by Chuck Hurich, a seismologist and Steve Butt, a mining engineer. We have applied for an NSERC grant to support the research. We are bringing in a research associate (seismologist) in June to interpret the seismic events.

The structural component of this project needs strengthening. There is a significant amount of geophysical data available. In addition to the core logging and the point load testing data, Vale Inco have conducted televiewer surveys in most of the holes, sonic logging in many of the holes, and borehole to borehole cross-hole tomography in both the Eastern Deeps and Reid Brook deposits.

The access to these data, coupled with the seismic monitoring data provides an opportunity to establish methodologies to collect and evaluate structural and seismic data for geotechnical planning. A regional structural component would need to be added.

This is an area where we may be able to collaborate. We are investing a considerable amount of time and money on the seismic monitoring and a stronger structural component leading to the development of a characterization methodology could provide a much stronger deliverable.

Seismic Detection Project

We are developing a low-cost seismic system that can be applied to mineral exploration. This program has involved the development of a new portable seismic source and interpretive techniques. We have purchased a recording system and trained the technicians to operate the system. The seismic source has been tested and a full-scale production survey is proceeding next month in Western Newfoundland over a line previously surveyed using the vibreosis method. We then plan to carry out a survey at the Voisey's Bay site in September. Although the program is aimed at seismic detection of the massive sulphide and host troctolite dykes, it is also ideally suited to test the effectiveness of the seismic method to identify and map steeply dipping faults or fractures. (The general description of the seismic detection project is outlined below).

Post-workshop Comments

Larry Cocharane, cont.

The overall objective of this research project is the detection and imaging of massive sulphide ore deposits at depths > 500 m. The research focuses on the use of a variety of active seismic methods to achieve this objective. While other geophysical (remote sensing) methods inherently have the capability to probe to depths comparable to that above, the resolution of those methods decreases with increasing depth of investigation making them, for all practical purposes, of very limited value to search for ore deposits beyond 500 m in depth. The promise that active seismic methods holds is that the resolving power of the methods is primarily controlled by the frequency of the seismic waves and the acoustic properties of the earth. Hence, it is possible to control the resolving power by controlling the frequency of the source for the seismic waves. Much of the cost (40-70%) of both 2-D and 3-D seismic acquisition is associated with the seismic source. We will address the source cost issue by development of an efficient, environmentally sound and portable seismic source and by developing techniques that minimize the source effort required.

The specific activities are as follows:

Property Scale – Surface-to-Surface

This component of the research will involve collecting high-resolution, multichannel seismic data in both 2-D and 3-D formats with the goal of structural delineation and to test the potential to map the troctolite intrusions that host the sulfide mineralization. The data will be acquired with the ARAM Aries recording system (capable to 1000 channels) that is able to operate in conventional 2-D and 3-D modes as well as accommodate unconventional recording setups. The seismic source for this will be a purpose-developed small pneumatic hammer (rock breaker) that is portable and environmentally sound and that generates the necessary energy levels of signal at high frequencies. The source is based on the swept impact seismic technique that involves stacking of a large number of individual hammer impacts to generate the required depth penetration. The field research will take place in two field seasons – The first season will include tests run locally focused on optimizing the operation and processing technique for the swept impact source and initial tests of several different 2-D and 3-D recording geometries in the Eastern Deeps area of the Voisey's Bay mine site. The initial tests at the mine site will focus on P-wave recording and evaluation of several approaches to economical 3-D seismic acquisition and imaging. The Eastern Deeps area is appropriate for these initial tests as the area is well-characterized through drilling. The second field season will build on the results of the first season and will also include 3-component recording to take advantage of S-waves and full wave field information.

The group has many software algorithms to process the seismic data from the vertical geophones – both near normal incidence and wide-angle. It is expected that new algorithms will be developed to use the horizontal geophone data and the different azimuth data (3D). The project will also investigate the concept of beam forming and steering to achieve improved imaging qualities of the sub-surface.

Mine Scale – Surface-to-surface and surface-to-borehole

This research has the primary goal of increasing the seismic recording aperture by recording surface and borehole geophone (3 component) data concurrently. The objective of increasing the aperture is to gain access to elements of the seismic wave field that cannot be recorded at the surface but carry information that aids in imaging of steeply dipping geology. The experiment will employ a large number of receivers (surface and borehole strings) and a limited number of source locations. The data will be initially processed with beam-forming techniques on both the surface and borehole data to identify and locate (in 3-D) consistent sources of seismic scattering that might be associated with ore zones or geologic structures of interest. The potential value of this beam forming approach, as opposed to traditional seismic imaging, is that it is likely that the technique could be developed for application near real time in the field. The initial imaging could then be used to guide placement of additional source locations to build up an image of a particular zone of interest. If the beam-forming is successful, full imaging of the zone of interest through pre-stack depth migration with an appropriate but limited number of source positions will be possible. Migration that takes advantage of the information from the down-hole receivers has been demonstrated to provide superior imaging of steeply-dipping bodies.

Post-workshop Comments

Peter Kaiser

Opportunities to recognize the right interdisciplinary linkages (such as at this workshop)

- Better Structural geology models
  i. Improved orebody (and general environs) architecture/fabric characterization models needed. In the absence of potentially sufficient/desirable data/information (boreholes etc) we need to be able to postulate possible structural frameworks
  - Develop conceptual models for possible pre-mining geological structural picture for use during mine design process
  - Put in the context of an understanding of the:
    - Tectonic history
    - Regional stress and structure
    - Effects on structures of changes in stress direction and magnitude
    - Of the fault episodes recognized, which are the really important ones for mine designers to consider, i.e. which ones are likely to react most to stress variations imposed by mining?
    - Adopting the approach which Larry Cochrane took for his Ph.D in Sudbury is recommended

- More development of appropriate geophysical tools or, alternatively, better use of existing ones
  i. Integrate with ATV data
  ii. Virtual core logging
  iii. Focus not only on structures themselves but also on damage zones associated with them
  iv. Lithology changes

- Classification of critical/active fault structures
  i. Systematic back analysis of FS classes (they may change over time- DD comment)

- Do a better job at integrating exploration data into appropriate hazard assessment tools, into mine design framework, into appropriate modeling software

- Better use of microseismic datasets- including arrival times and location
  i. Stress orientation and strength/stress ratio from seismic data
  ii. Fault (structure) properties
  iii. Recognition of "critical" faults within the geological architecture of a pre-mining block

- (Use)probabilistic earth modeling
  i. Focus on uncertainty assessment technique

- Re-evaluate chosen mining methods within the context of uncertainty leading to:
  i. Flexibility to permit risk management

- Develop more sophisticated modeling techniques
  i. Fracture growth simulation
  ii. Integrated models with dynamic updating capability

- Develop a handbook/set of guidelines on current best practices e.g. logging etc

Post-workshop Comments

Peter Kaiser, cont.

- ISSI Piezoelectric methodology
  i. Test in different rock types
  ii. And for soft versus brittle faults

- Mines as a real lab for seismology and seismologists

- Seismic data- stress inversion
  i. Use microseismic data for pre-mining stress field determination

- Ore body architecture modeling for pre-mining state definition (at all scales)

- Focus on integration of interdisciplinary R&D
  ii. GeoRisk is an example

- Improve utilization of drilling programs
  i. Think of boreholes as research platforms from which more than just ore-waste information can be derived
  ii. Add further instrumentation
  iii. Can we log damage zones/properties geophysically/physically?

Mark Board

Issues

As I see it, to develop an effective modeling tool for assessing fault slip potential, there are a few questions/issues that need to addressed:

- We need to understand how these characteristics impact the constitutive behavior of faults – ie, what type of model and physical properties do we need to use as input to faults
- We need to determine how accurately we need to represent the geometry of the fault systems in simulation models – is it necessary to define the fault topology carefully, do we need to model individual structures explicitly, can we represent major structures stochastically using a DFN-type approximation
- Does the model need to represent the non-linear yielding response of the rock mass in a reasonably accurate way to get the proper stress distributions or kinematics of loading of faults
- How does one calibrate or validate these models
- Can we develop general mining guidelines from these models that can be used as a guide for planning purposes, or must one run complex models for every situation

Fault Characterization

I feel that characterization of faults is an essential, yet largely undefined area. I have been on a review panel for Yucca Mt called the "Extreme Ground Motion" panel for the past 5 years. This group has been tasked with defining how big an earthquake can possibly be, and determining how to adjust standard seismic risk assessment models that are "capped" at long time periods for maximum ground motions. This has been a real privilege since the group consists of some of the top seismologists in the country, including Tom Hanks – chief of the seismological branch of the USGS in Menlo Park, CA, Jim Brune, U of Nevada, Reno (he of the Brune model), Norm Abrahamson (Pacific Gas and Electric, San Francisco), Dave Bohr (a source mechanism/ground motion expert from the USGS) and Allin Cornell of Stanford (recently deceased), a ground motion, structural dynamics and probabilistic risk assessment expert.

Post-workshop Comments

Mark Board, cont.

Fault Characterization, cont

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We need to develop methodologies for describing some fundamental characteristics of faults that relate to their properties, much in the same way that Nick Barton has done. This would include: a) the macroscopic roughness (amplitude) via a standard sort of amplitude scale such that the ratio of amplitude to surface area or length can be defined, b) continuous length/area, c) termination, d) surface and infilling (type, strength, thickness), planarity (wavelength of undulations, offsets, etc), and general thickness of the shear zone accompanying the fault. In much the same way that Barton has developed quick look-up methods for describing joints, we could do the same for faults. Maybe we could even use s similar methodology.

One place to start would be to go to existing mines (eg, Kidd and selected Vale mines) and use existing exposure and drilling information to develop the characterization system. At the same time, we know from case histories which faults have created problems – we could use this information to begin to associate fault characteristics with seismicity. Perhaps some geophysical methods could be tested here to attempt to understand fault morphology using reflection methods or something like that.

Fault Constitutive Behavior

A good place to start here is to do a literature review of constitutive behavior understanding of faults from the seismic community as well as perhaps apply some of Barton's methodologies and length scaling relations (I'm not sure if these are correct).

I then feel that much could be learned from doing some fundamental "synthetic" analyses with a code like PFC2D or 3D. One could develop a series of large scale "laboratory" simulations of idealized fault surfaces that include realistic topography, thickness of shear zones, infilling materials, etc. The PFC intact material could be calibrated to produce a reasonable fit to the brittle rock (S-shaped) failure response to ensure that both shear and brittle failure modes are modeled. Then, direct shear tests on these samples could be conducted for varying normal stresses to generate a family of shear stress-shear displacement curves and failure envelopes. From these, constitutive models can be developed and a range of expected material properties. These analyses could also answer over what range of fault geometries that representation by planar surfaces in more simple models makes sense. We could also perhaps identify what types of geometries create "lock-ups" that effectively prevent shearing in the regimes we are dealing with in mining. These properties and constitutive models can be tested in back-analyses.

Post-workshop Comments

Mark Board, cont.

Fault Constitutive Behavior, cont.

Peter Cundall did a series of analyses like this for the Mandel workshops on fault behavior a number of years back (I'm not sure if this is where Peter got the slides from for his presentation). Matt Purvance and Peter have recently done another series of PFC models of rupture nucleation for the earthquake community (funded by the Extreme Ground Motion project). In these analyses, the generated synthetic seismograms as well and calibrated the model against the foam fault slip model of Jim Brune at the Univ of Nevada, Reno.

Need for Non-Linear Modeling of Rock Mass Behavior

Researchers have used several basic approaches to modeling of fault slip seismicity, including:

- Elastic models with assumed (but not modeled explicitly) fault locations with stresses projected on the fault planes, estimate shear stresses and rides, moment magnitudes
- Non-linear models with faults assumed as above. Like above, but impact of yielding around the mining geometry is estimated
- Non-linear models in which the faults are represented by anisotropy in the plasticity, or "weak" zones in the model – ie, faults and their interconnections are not represented explicitly, but a series of elements are placed along the fault trace. I'm pretty sure this is what David Beck was doing in his presentation. This may be ok for representing the general weakening effect of structures (as in a caving simulations), but I think it presents issues when estimating slip and energy release.
- Non-linear models for the rock mass and explicit modeling of faults as discontinuities – this approach essentially states that it is important to represent specific structures as accurately as possible, which including the effect of the rock mass yielding on load distribution or kinematic forcing of movement on the faults. Explicit determination of partitioned energy – stored strain energy, energy dissipated in plastic work, kinetic energy release.

In general, I feel that the first or second methods can be used for quick studies to guide mine planning, but not for detailed understanding of mechanisms of slip. To truly attempt to understand how a critical-state structure can have a small perturbation of stress or deformation and show effects propagating over large distances and multiple structures, I believe the final approach is necessary. Regarding the type of material model and properties of the rock mass, I believe a form of softening model based on brittle and shear behavior is reasonable. It is always possible to confirm assumptions for specific rock masses using a form of SRM analysis, but I'm not sure that is, in general, necessary.

Calibration or Validation of Models

I believe some form of demonstration of the models on numerous, well-documented case histories is necessary. These case histories would start with simple demonstrations of the basic material assumptions – ie, one would need to show that the component "parts" work. This includes showing the representation of fault constitutive and rock mass constitutive behavior works for simple cases of direct shear and triaxial compression. I would suggest that at least 5 well-understood case histories be run. This would include:

a) Description of the event history, observations, deformation measurements, seismic data, in situ state of stress.
b) Structural model of the rock mass using the fault characterization method developed as well as rock mass material model assessment using GSI, laboratory testing, and brittle/shear constitutive model. All of this needs to be based on field observation, if possible.
c) Estimate of fault and rock mass properties
d) Model analysis of sequence of extraction and energy release estimate. One or more of the modeling types could be used to identify level of detail necessary in the model to reproduce the observations.
e) Assessment
f) Lessons Learned

Post-workshop Comments

Mark Board, cont.

Calibration or Validation of Models, cont.

From my own knowledge, I think some of the Kidd examples and Vale examples are excellent because they are relatively fresh in memory and access to underground locations are still available in some cases. Additionally, the mine has likely developed at least a reasonable structural/lithologic model of the site.
It may be that our S. African friends could supply a well-documented case example. Typically, the SA gold geometries are simpler and the fault geometries known reasonably well where they offset the orebody.

Practical Guidelines for Mining Methods/Sequences, etc in Faulted Ground

One of the outcomes, I believe, is a set of practical guidelines that can be used by engineers on the mines. It might be that we take what we learned from above, and use the modeling to run a series of scenarios to examine impact of stope sizing, placement of pillars, sequencing, etc, to define flexible mining systems that minimize fault slip impacts. We could also develop guidelines for infrastructure location, ground support for fault slip events, etc as part of this task.

Wouter Bleeker

Role of Structural Geology

An in-depth structural geology study, from the regional or even subprovince scale, down to the property scale, and finally to the mine and outcrop scale, should be able to define most of the major (paleo)structures. Even lineaments and joint patterns that could be easily defined at surface could prove to be the key structures. Many structural elements, but not all (!), are self-similar in nature, repeating the same structural motif across various orders of scale. Thus observations at one level feed back into another level, all contributing to an understanding of what structures might be or might become important as mine development progresses.\

It is important to understand that some structures, particularly brittle structures relevant to the fault-slip and mine stability problem, are not exactly self-similar, but change orientation as one goes down in scale. For instance, second- or third-order fault splays (and their joint patterns) are not parallel to first-order fault structures. Hence, from a regional perspective, one may be aware of the nature and attitude of a first-order structures but it may be third-order structures and associated joints that are going to be important, due to their particular orientation in the ambient stress field around deep mine development. With changing and increasing stress levels, an existing en échelon joint pattern, related to some paleo-fault or some higher order splay thereof, may progressively connect up into a fracture network that may slip once the shear stresses reach a critical level.

Nevertheless, a structural geology specialist with the right kind of background (fault systems and brittle fracturing) should be able to systematically assess all these structures and characterize their macroscopic and microscopic properties and, in conjunction with rock mechanics and geotechnical specialists, their possible dynamic properties in terms of possible future behaviour in a changing stress regime. What is their age and how would they re-activate in the present day stress field. There is generally a lot of information available at various scales, including the largest scale, that needs to be evaluated and integrated into a systematic and coherent description of a developing mine. Clearly, some apparently major strucutres (early largely annealed an possibly folded faults) may have no importance for mine stability whereas some late cryptic joint patterns may turn out to be critical. Therefore, early integration and sharing of such data with rock mechanics and geotechnical specialists would assure the information is relevant to stability and stress issues, and where possible focused on those structural elements that may become problematic.

Post-workshop Comments

Wouter Bleeker, cont.

Too often, structural geology information only plays a role in the exploration (geology) phase of a project, and the expertise has moved on by the time the rock mechanics people start to ask questions. So, closer integration and team-work, with above objectives in mind, are essential but this rarely happens. Even if the structural geology expertise is still available at a more advanced mine stage, it tends to be more focused on the overall geometry of ore lenses and how faults may offset such lenses then on ground stability, fault slip and stress problems. But there is no fundamental reason why this more integrated teamwork could not become a standard practice. A more enlightened and forward looking team approach is need. This is the "culture change" issue that came up many times during the workshop.

Capturing and Analysis of Routine Structural Data from Underground Mapping

In many mines, numerous structures, including potentially fatal joint sets get routinely mapped, as part of standard drift and stope mapping in support of grade and ground control. Rarely does this information receive any systematic analysis and synthesis. This could be easily implemented, e.g. to summarize, characterize (what type of surface, cohesion, slip, continuity, etc.) and statistically analyze all joints and faults for every 100 m of developments. After some time, a pattern will emerge that will feed back into the potential ground stability questions.

Of course, some of this gets done in Canadian mines, but typically only after a problem has emerged. If such information would have been summarized and analyzed as development progressed, it is likely that many problems could have been anticipated prior to becoming critical. Again, this may require "culture change" and probably training of beat geologists in better structural geology skills. Although beyond my expertise, I imagine that properly summarized structural data could probably be fed, semi-automated, into geotechnical and stress models and software for a developing mine.

Case Studies

As identified at the workshop, detailed case studies seem an easy and obvious way forward. Similar to the goals of the workshop, they will help to define the problems better. If one could get the various expertise present at the workshop to integrate their research on some high-profile case studies, a lot of progress would be made. Availability of targetted research funding would do wonders to bring this expertise together. As was evident at the workshop, there is a lot of high-level expertise out there but it appears very scattered, across the world, across somewhat different disciplines with different cultures, and across different organizations. Bringing much of this expertise together on a routine basis would catalyze major steps forward.

Closer Integration and Culture Change

Clearly integration and culture change seem two key issues, featuring front and center in each of the above sections. Much relevant expertise may be readily available, but it seems to revolve in separate universes, even within one company, and to operate at different time scales and time lines (exploration vs. mine planners vs. rock mechanics). There is a major role here for better and ongoing education at all levels, a need to demonstrate the longer term benefits to corporations, and probably for regulation. Subtle changes in regulation could encourage the needed integration of expertise over the life time of a mine.

How to Measure Success

As briefly discussed at the meeting, an important issue in this whole business, is how to measure and demonstrate success. If by spending X dollars on research and mitigation of these problems one can save a corportion 1000X dollars, by not having any major incidient or fatality, how does one demonstrate to management that it was due to the initial investment. Failure is easily demonstrated, but success much less so. This relates back to how one can achieve the needed culture change. So, this whole issue needs some careful thinking.

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