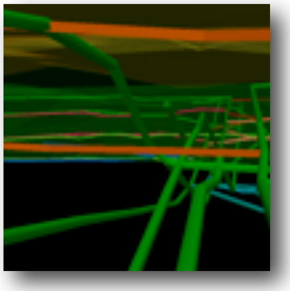
CEMI
Centre for Excellence
in Mining Innovation

One of a series of workshops in support of the development of the International Fault Slip Control Research Initiative (IFSCRI)


Geophysics


Modeling & mine design


Structural Geology


Microseismicity

Summary of Feedback

Geophysical Technology & Tools Experimental Design Workshop

Toronto, Ontario, Canada
Holiday Inn on Bloor Yorkville
December 4, 2009

To provide comments and suggestions, please email info@miningexcellence.ca.

Revision 14.12.09

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Introduction

Preamble

On Friday, December 4th, 2009, an Experimental Design Workshop in Geophysical Tools and Technology for the proposed International Fault Slip Control Research Initiative (IFSCRI) was held. This workshop was one of five field-specific workshops which are to be held over the next 6-8 months, each one with the purpose of brainstorming exciting and relevant research and technology projects needed to better understand the fault slip problem in underground mines within the context of a ~$20-50 million, multi-year research program.

The following document contains a summary of the feedback received during the workshop, as well as detailed feedback received from both workshop groups and individual participants. Please feel free to contact Bernd Milkereit at bm@physics.utoronto.ca or Damien Duff at dduff@miningexcellence.ca should you have additional information to add to this collection of feedback.

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Introduction

About the International Fault Slip Initiative (IFSCRI)

Of the most common types of rockbursts in underground mines (fault slip, pillar burst and strain burst), fault slip (FS) is often the most disruptive. Despite an increasing number of incidents worldwide and the consequent huge economic impact on mines as well as the health & safety risk to workers- and despite significant advances in seismic data interpretation- relatively little focused research has been undertaken to address the problem of controlling FS-events in mining.

Fault slip incidents are thought to occur in part due to stress variations induced by mining activities. However, there are many unknowns, such as why some faults are more fault-slip prone than others and how the potential energy release associated with them can be controlled. It is thus imperative for the mining industry to adequately understand the cause(s) of fault slip and develop the tools to deal with and control them.

Vision

To execute an internationally-recognized underground research initiative to improve fault slip management techniques.

Other groups are working on related issues to IFSCRI including:

- Red Waste Storage Research
- Tunneling & Computational Seismology
- Exploration & Reservoir Geophysics
- Scientific Drilling: Sampling & Monitoring

Lessons learned from these groups include:

- +/- Repeatability of geophysical "sources“
- - Longevity of sensors/monitoring equipment
- + performance of strain meters
- Some unusual parameters evaluated (temperature etc.)
- Limited number of physical parameters tested for 3D rock mass characterization & 4D longterm monitoring

The goal of IFSCRI therefore, and for participants in this workshop in specific is:

To determine what role geophysics and geophysical tools can play in optimizing the chances of CEMI’s 5-year major global research initiative focused on Fault Slip.

Workshop Agenda

4 December 2009

Bernd Milkereit, facilitator (University of Toronto)

	Introduction
7h30	BREAKFAST (provided)
8h00	Welcome and Workshop Objectives - *P. Kaiser, D. Duff (CEMI)*
8h15	Global Perspective on Current Fault Slip Research Initiatives and Challenges Ahead - *B. Milkereit*
8h25	Background: Summary of CEMI Microseismicity Workshop - *D. Duff*
	Part I. 3D Rock Volume Characterization
8h40	The Role of Rock Physics
9h10	3D Rock Volume Characterization: Geophysical Imaging Tools
10h00	BREAK
	Part II. 3D Rock Volume Monitoring
10h15	From Lab to Mine Scale
10h35	Geophysical Imaging
11h00	Review of Borehole Instrumentation - *B. Prevedel (ICDP OSG, GFZ-Potsdam)*
11h30	Integration of Geophysical Imaging with Microseismicity, Geology, Numerical Modeling and Mining Engineering Research
12h00	LUNCH (provided)
12h45	Geophysical Imaging Revisited - R&D needs
	Part III. Next Steps
13h15	Building a Better Mousetrap or Designing a New Mousetrap? A Preliminary Risk and Cost-Benefit Analysis
13h45	What May be the Showstoppers?
14h00	R&D Funding & Project Timelines
14h30	BREAK
14h45	International Collaborations & Partnerships
15h00	Summary, Outlook & To-Do-Lists
15h45	Closing Remarks - *P. Kaiser*

Workshop Feedback Summary

Compilation of Identified Opportunities (Presented in no particular order)

1. **We need to identify/quantify initial stress conditions.** Differential stress conditions produced during/by mining presents an opportunity for research. Heterogeneity of rocks and rock structures also has an impact on stresses and also represents an opportunity for research. Microseismicity is a proxy for stress but there are a number of petrophysicial parameters (such as resistivity, dielectric constant) that go with that which can and should be measured and looked at more closely.

2. **We need for active/repeatable sources within modern seismic arrays.** We need a repeatability index for a seismic source. There has been some work of this kind done ahead of TBM's operated by Herrenknecht by the folks at GFZ- Potsdam (get specs). Broader arrays of borehole sensors are also suggested.

3. **We can use existing geophysical parameters/tools more effectively.** May be more can be gotten out of magnetic susceptibility measurements- especially if looked at over time. Traditional seismology tools are being used in the oil sector in Saskatchewan right now to assess the integrity of cap rocks. Optical and acoustic televiewer- types of surveys should be run and re-run because there's lots of information in that. South African radar imaging experience suggests that faults may be mappable up to 235m away. Is this scalable? Is it possible to develop radio imaging technologies for both exploration and rock-mass characterization? Accelerometer/strain meter developments for boreholes are needed. Fluid injection and the use of tracer brines (because conductive) may be a possibility.

4. **We need to connect with existing/planned related projects.** The SAFOD/US array folks will run a survey looking at Inter-plate seismicity south of the 47th parallel in the Sudbury area in 2012. 70 stations are to be in Canada. Find out how to engage the petroleum sector. Not much work was done with the pre-event data as part of 2008 Lively event analysis. This work was done as part of Polaris Group research.

5. **We need to incorporate passive monitoring.** Suggest passive monitoring of seismic noise (interferometry) to map shear wave velocity variation in time (proxy of stress variation). Passive monitoring of seismo-electric radiation (proxy for stress?)

6. **We need to develop dynamic models.** Establish linkage with dynamic geophysical model of rock mass. Establish detailed baseline data for monitoring changes with time (for all techniques)

Detailed Group Feedback

Part I: 3D Rock Volume Characterization

The role of rock physics

1. A recent EOS article names the "Fault Slip Problem" as the # 1 Challenge for Seismology: How do faults slip and specifically on what the requirements are to meet 3D/4D challenges at multiple scales and multiple parameters.

2. General agreement around in situ stress levels indicated for Sudbury, as shown in Benoît Valley's slide.
   a. Differential stress conditions produced during/by mining presents an opportunity for research
   b. Heterogeneity of rocks and rock structures also has an impact on stresses and represents an opportunity as well for research.
   c. Is difficult to get a good handle on the in situ stress field (P. Young)
      i. must define initial conditions, need to understand heterogeneity. Initial conditions in stress field can affect microseismicity - we do not know how much stress changes after microseismicity
   d. Is generally expensive and difficult to do and not enough measurements are available (SMcK)
   e. We change the stress ratio all the time during mining to the extent that some structures which were otherwise stable (in equilibrium) now are activated (P. Kaiser)
      i. Failure is not always on known structures but on unknown ones, including newly created ones.
      ii. We need initial stress and ongoing stress change measurements separately

3. Early 3D volume characterization is critical (S. Carlisle)

4. We need to get back to the basics of monitoring/measuring rock properties (C. Farrow). Perhaps geotechnical rock properties can be measured, starting at the exploration phase.

5. Currently microseismicity is the only proxy for stress (B. Milkereit) but there are a number of petro physical parameters that could be used to measure and monitor stress in rock volumes including:
   - ΔVp : P-wave velocity
   - ΔVs : S-wave velocity
   - Δd : Density
   - ΔQp : P-wave Intrinsic Attenuation
   - ΔQs :P-wave Intrinsic Attenuation
   - Δm :Magnetic Susceptibility
   - Δe : Dielectric constant
   - ΔR : Resistivity
   - ΔM : Chargeability
   - More…

Detailed Group Feedback

The role of rock physics, cont.

6. This may represent an opportunity- however, it must be noticed the effect of pressure on low parameter physical rock properties did not receive much attention over the past 30 years.

7. There may be more in the density measurement than previously thought (B. Morris)

8. We have a need for active/repeatable sources within modern seismic arrays (P. Young) Opportunity
   a. Could be followed up on simply and easily right now.
   b. AECL has done something like this and can create signals and measure them in existing arrays.
   c. There has been some work of this kind done ahead of TBM's operated by Herrenknecht by the folks at GFZ- Potsdam (opportunity- get specs) (Bernhard Prevedel)

9. Resistivity variations were last looked at in 1965- is anyone doing any work now? (B. Milkereit)
   a. Are there any implications associated with wet-dry effects?

10. Likewise with the dielectric constant- not looked at since 1965 (D. Schmitt). What about conductivity?

11. May be more can be gotten out of magnetic susceptibility measurements (B. Morris)
    a. MagSusc measurements over time may be valuable to look at. Opportunity

Geophysical Imaging Tools: - What can we do with existing data?

1. Considering the Lively 2008 event (published in Seismology Letters) by OWO group- D. Eaton, Atkinson et al- not much work was done with the pre-event data. Future work as part of Polaris Group/ US Array- Opportunity to connect?
   a. Pre-event data could and should be looked at.
   b. These data (among others looked at by the Polaris group) indicate that thrust-type rupture is more common at depth in the earth's crust with strike slip rupture prevalent at shallower depths.
   c. The petroleum sector is ahead of the mining sector in respect of the dynamic range of their seismic systems (B. Prevedel). Models are only being fed pressure, temperature and production data though- not sophisticated. They don't have the people…!
   d. Microseismic systems in mines need to be operating at an order of magnitude higher frequency (D. Eaton)
      i. Similar questions being asked in the oil patch right now about the importance of rock mass characterization

2. Traditional seismology tools are being used in the oil sector in Saskatchewan right now to assess the integrity of cap rocks. Possible Opportunity.

Detailed Group Feedback

Borehole Instrumentation

1. The more we work with microseismic data the more we realize that geology matters.

2. Large sensor arrays in boreholes are critical and far surpass the effectiveness of single sensors.

3. Doug Schmitt's work in Antarctica demonstrates that several useful measurements can be made in slim boreholes (fractures etc) relatively cheaply and quickly using wireline systems.
   a. Is this the system with which to take initial stress measurements? (B. Milkereit).
   b. The equipment used in Antarctica is available (1 unit only) from a small company operating out of New York (D. Schmitt)
   c. Optical, acoustic and EM televiewers can all be used and should be.
   d. These types of surveys should be run and re-run because there's lots of information in that (B. Morris).Opportunity

4. Radar Imaging represents a possible technology development opportunity (R. Smith).
   a. Rock and water permittivities are different.
   b. Can use single or multiple boreholes
   c. Up to 500m reach between boreholes.
   d. But systems still need development work
   e. ETH have good systems which operate at ranges of 10's to 100m
   f. Radar instrumentation prefers dry holes
   g. South African experience suggests that faults may be mappable up to 235m away. Is this scalable? Opportunity?

5. Radio Imaging (RIM) operates at 0.3 to 5 MHz range – lower frequency than radar/
   a. Looks at conductivity
   b. A fault zone might be conductive (or not be) and thus might be amenable to imaging?
   c. We need to focus on dynamic changes (B. Milkereit)
   d. Note: perhaps an under excavation-type technique (UET) such as tried at Vale Inco- Creighton a couple of years ago?
   e. Is there a smaller scale experiment like this (far-field stress but stress increase and decrease in radial direction - every borehole causes a stress change) - therefore we do not need instrumentation that can measure over large distances. Could address some of our questions in a more controlled way. Could do this in various places to get far-field stresses multiple times.
      i. This approach could be effective at the feasibility study stage?

6. Large scale structures often don't pose the problem but smaller secondary and even tertiary ones do. This is the case in exploration models too and perhaps there's an opportunity to develop radio imaging technologies for both exploration and rock-mass characterization? (C. Farrow)

Detailed Group Feedback

Borehole Instrumentation, cont.

7. The ability to operate at multiple scales is important (S. McKinnon)
    a. The ability to operate multi-temporally is also important (B. Morris)

8. Can co-seismic deformational effects be measured? (S. McKinnon)
    a. Can we map changes within a bore-hole-hosted array?
    b. Could use optical strain meters (B. Prevedel, D. Schmitt)
    c. Seismic Interferometry (D. Eaton)

9. Laser technology base has been developed with NASA to measure minute changes in crack size and geometry.

Part II: 3D Rock Volume Monitoring

From Lab to Mine

1. This is about looking at borehole fracturing as a way to say something about stress

2. Coda wave Seismic Interferometry? (Kaiwen Xia)

3. Lab earthquake to field monitoring capability?
    a. High frequency receivers needed

4. Accelerometer/strain meter developments for boreholes needed (B. Milkereit) Opportunity

5.

Geophysical Imaging

1. Controlled source cross-well seismic systems exist but are expensive (B. Milkereit)

2. Possible opportunities on the electrical resistivity side of things

3. Fluid injection and the use of tracer brines (because conductive) a possibility. Opportunity

4. DC/IP system- developed as a CAMIRO project- (the Titan 24 system?)

5. Gap on the physics side with dielectric methods. (resistivity as a proxy for stress)

6. Surface or vertical (in-mine) EM loops could almost be available for free (used by exploration folks). Can that data- which is presently only used for ore-body exploration purposes- be looked at as a means to perhaps better determine rock-mass quality?
    a. An injected brine may be required to render fractures/faults conductive and thus visible?

Detailed Group Feedback

Geophysical Imaging. cont.

7. ICDP supports monitoring in wells.
    a. But there are very few imaging tools available for use in boreholes of less than 2¼inches outside diameter
    b. There are both inside and outside casing applications and some/or all permit some degree of permanent monitoring- 7 years now in case of SAFOD
    c. Permanent installations(cemented in boreholes) are best
    d. The Corinth (CRL) instrument package cost 800K Euro

Emerging Technologies:

1. Some are readily available whereas others need fine tuning

2. The SAFOD/US array folks will run a survey looking at Inter-plate seismicity south of the 47th parallel in the Sudbury area in 2012. 70 stations are to be in Canada (D. Eaton). Opportunity

Part III: Next Steps

1. Are tools needed which look at stress variations that influence physical properties which cause ground failure? (P. Kaiser)

2. Perhaps an intermediate Underhand Excavation Technique-type experiment/step is needed?

3. Controlled source seismic "pinging" approach has merit and could be implemented almost right away.

4. Measuring resistivity as a proxy for stress.

5. RIM and Radar imaging technologies have merit- explore further.

Post-Workshop Comments

Comments

1. Briefly, I felt I saw more potential in this area than the previous Microseismic workshop. It could just be I have more familiarity with microseismics, and feel we have been quite stagnant for years, even with excellent vendors and researchers such as ISS, ESG, and the SA research council.
   Geophysics I believe can benefit us 2 fold,
   - 1 - as a preliminary 3D rock mass characterization tool and,
   - 2 – as a time based/ monitoring system for tracking changes.

   3D characterization by geophysics has its challenges but any information can only help to accentuate the drilling and structural interpretation we get from geology. It appears that only significant structure can be identified by many of the methods but this will still complement classic structural interpretation. To me it's a solid step in the right direction. Peter mentioned and I agree, that larger structures are often not the big issues, but I feel building on McKinnon's area that they affect stress magnitudes and orientations, as such can give us a better insight for modeling, and basic understanding of ground response. It may be just a case of miniaturization of some of the instruments to better collect the data during drilling?

   Note this would build on the work flows Mira has developed for the Craig Mine review.

   Time based monitoring, which microseismics as actually a subset, seemed to be universally accepted as feasible and useful, and I concur. However I feel microseismics has led us a bit astray with too many black box "source parameter" investigations. I generally like a simple grass roots approach, such as the old velocity versus density relationship, or discontinuity reflection/ refraction concept. There were some compelling graphs showing stress versus velocity, with the underlying basis being density increases due to crack and porosity closure. Supporting these types of technologies is probably quite simple using existing microseismic systems with "controlled sources", or taking a statistical approach. Feel free to call me to discuss further, I have some back ground and experience in this area from a past life.
   ~ Scott Carlisle, Xstrata Nickel (now at SRK)

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2. One area that I'd like to reiterate – is mapping of structures. I don't believe mines do a good enough job early on getting structures identified. By the time drift mapping, diamond drilling, and the ensuing fault models get mature enough to have confidence in, the mine plan, and overall strategy gets locked in. With less and less flexibility I know back in one of the earlier Onaping Depth studies, some 3D seismic surveys were completed in an attempt to identify structures I suspect if we were to use some of the geophysical techniques to help extrapolate existing diamond drill and mapping information we could develop Better fault models, earlier on. Also a better fault model would lead to better numerical simulations – we often make gross simplifications with existing information and then miss some critical Asperities (e.g. a roll in the fault).
   Anyway – just getting more accurate geometries on these structures will be a big help, so some of the 3D type techniques like seismic imaging, coupled with Diamond drill and other info would in itself be a good goal.
   I was pleased to hear the recurring theme of doing repeated surveys, whether its' just something simple like a repeat televiewer survey to look for more borehole breakouts as the mining progresses Or something more sophisticated like tomography surveys, early on in the mining sequence, and then again later – this type of approach will pay dividends. Mines get in the short term thinking mode – very quickly – so simple use of existing technology – but in a more thorough manner will be a big help.
   ~ Brad Simser, Xstrata Nickel

Post-Workshop Comments

Comments cont.

3. It may be interesting to include in the proposal an array of electrodes permanently fixed around the perimeter of the test cube. The orientation of the array isn't critical, as long as it is representative of what you are trying to measure. These electrodes could be used to permanently measure small resistivity changes during the course of the program. Such an array could be established in existing drill holes vertically from surface or horizontally from existing underground drifts. To maintain stable conditions, it would probably be best to cement the electrodes in place. There may be issues around shielding the cables connecting the electrodes. Once established, the equipment required to monitor and record the data should be relatively inexpensive. The array could be calibrated by applying a fixed current at a specific time interval to monitor changes in the array due to things such a corrosion.

   There are some studies (http://jphyscol.journaldephysique.org/index.php?option=article&access=doi&doi=10.1051/jphyscol:1984871) that document the change in resistance as a function of pressure. Intuitively, if you squeeze something hard enough, its electrical characteristics will change. I don't know if the changes in pressure that are envisioned in this experiment can be measured through changes in resistivity. That being said however, if you are able to indirectly measure these subtle changes in pressure, the results derived from these measurements would be interesting to look at in conjunction with the micro-seismic data. Will the data show gradual changes in resistivity (pressure) prior to a seismic event? If major seismic events trigger a piezo electric effect, the array may be able to detect these subtle changes during the event itself. If this sort of concept could be validated by this experiment, the installation of such a system in a mine environment would be relatively inexpensive to set up and monitor.

   Such an array of electrodes could also be used to induce a periodic current from specific electrodes to measure IP effects. I guess that it would also be possible to place some permanent coils to measure some secondary fields (dB/dt). The loop configuration and transmitter could either be placed on surface or underground in close proximity to the cube.

   I'll leave my comments on seismology to the seismologists, but some sort of array based upon current and established techniques would be less problematic than installing a seismic array down a borehole.
   ~ *Daryl Ball, Xstrata Nickel*

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4. The following are some points from Friday's workshop:
   It was enjoyable & insightful to have this mix of geophysicists, geologists & engineers in the same room. I got a lot out of the discussions.

   Rock Properties
   Once again, the collection, compilation, & application of physical rock property data is critical to the assessment of the 'fault-slip' problem as it is in so many other geoscience-related problems. However, this is not sexy, does not attract NSERC or other dollars, is difficult to publish, does not attract students, & there are limited labs currently set up to collect raw, rock property-related data. Aside from that, we're not fully sure which data should be collected. How do we get around this? Private labs may be the answer (we are currently doing this to some extent to solve some geophysical problems at FNX).

Post-Workshop Comments

Comments cont.

4. cont.

The part about integrating geophysical imaging with microseismicity, geology, numerical modeling & mining engineering research was a section in the 11:30 time slot that was skipped over on Friday. To me, this is the story, & the multi-disciplinary approach is what is totally exciting - & I imagine would be of interest to students.

The study of 'relaxation' features is highly important (i.e., discing, etc.) as basically 'fault-slip rupture' is just catastrophic relaxation. I would push this area of study from the geological side.

Although the idea about coming up with 'predictive' capability is regarded by some in Friday's group as impossible, perhaps we should use the term 'forecast'. It is nice to have the microseismic data to interpret as to 'what happened' & 'where', but we don't want people running to the refuge stations with the backs coming down around them either. If we know where we need to apply more stringent ground control measures, then we have forecast that the probability of there being a problem is higher. We have begun the process of 'forecasting' potential events & trying to mitigate\limit the risk associated with them. We need to do more to improve our forecasting, & studying events will help – but the goal is forecasting (improving forecasting capability). I am afraid that the goal will be forgotten.

~ Catharine Farrow, FNX Mining Company

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5. Comments:

- The project should bring excitement and innovation. I suggest the location of the cube be very deep: where rocks are very stressed. This is also the current "frontier" in mining.
- The project should engage several graduate (HQP) students. We could sell it saying that it will provide them to work in close collaboration with industry.
- If the project aims at developing a dynamic model for the cube, there must be a software to integrate the different types of data.
- Deploying mining seismic networks is an old idea and is totally uninspiring. Let's try new technologies!
- To add some science content…could we add the dimension that Sudbury is an impact canter?
- It will take time to make a proposal to major funding agencies (NSERC, CFI). Couldn't some small pilot projects start immediately? It will help our case when writing the proposal.

~ Claire Samson, Carleton University

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6. I would like to take this opportunity for allowing me to participate in a very interesting discussion regarding the application of geophysical methods to studies regarding Fault Slip Research Initiatives.

I brought to this discussion an extensive background in potential field geophysics as applied to mineral exploration. I have been working with borehole geophysical logging tools for over twenty years. Prior to joining McMaster I operated a small consulting company which provided borehole surveys for mineral exploration. I have recently published results on the elimination of magnetic remanence effects on borehole navigation surveys, and on the derivation of magnetostratigraphy from borehole magnetic logs. I have also recently published a paper looking at the spatial distribution of clasts in fall back breccias as defined by a photographic record of bore core.

Post-Workshop Comments

Comments cont.

6. cont.

Background: Prior to our meeting last week I had very limited exposure to the problem of Fault Slip Research. I was aware of previous issues regarding mining of some orebodies in the Sudbury Basin (specifically the Garson Mine). I am cognisant of two possible approaches to this issue: a) embedded continuous recording instrumentation; and b) repeat measurements. Given my background I can only effectively comment on the second option. Further, since from my perspective the outcome of any proposed research on this topic should lead to a protocol which can be applied in a working mine setting I believe that the repeat measurement approach offers an opportunity that could be readily tested.

Proposal: I have taken as my starting point a mining approach based on a series of drifts which would be followed sequentially by the removal of ore by a series of raises. I assume that upon completion of the drifts and prior to the raises that a pattern of boreholes could be drilled between individual drifts. These would form the basis for my proposed experiment. Next I assume that the pressure release imposed by the mining process would lead to the enlargement of any pre-existing fracture patterns. The rate of enlargement of the fracture patterns might be related to their proximity to the free surface of the mine wall.

I propose that the each borehole be logged using a combination of optical and acoustic televiewer, and caliper probes. The televiewers provide detailed images of the walls of the borehole. Most common televiewer systems provide a geotiff image which is referenced to the Earth's magnetic field. On the first pass through a borehole the televiewers provide an image of both lithological and fracture pattern distribution through the rock mass that is being traversed. With any subsequent repeat surveys of the same borehole it would be possible to identify and quantify any changes in the morphology of fractures. An additional approach would be to include a borehole caliper system. Analysis of borehole wall breakout patterns is commonly used in oil exploration as a method for mapping regional scale stress field patterns. There is no reason why a similar type of approach could not be used in a mineral exploration program.

If rock slip events have precursor events which result in minor displacements then it should be possible to detect these events. Having knowledge of the geometry of the possible fracture systems in a number of boreholes could be used to link fracture geometries into a predictive model. Clearly much would need to be done in terms of determining the frequency of repeat survey activity and to find means by which we could optimise the detection of fracture activity. This is an attractive option since it is something that could be implemented using current available instrumentation. Small diameter acoustic and optical televiewer systems are available from a couple of manufacturers. We already have the winches and interface for the Mount Sopris system; we do not have the probes.

~ Dr. W. A. Morris, McMaster University

Post-Workshop Comments

Comments cont.

7. The project objectives are to understand the rock dynamics of ore bodies and eventually be in a position to predict and control fault-slip related events in deep mining operation.

   Therefore, the project could be proposed to be initially divided into two parallel running project phases:

   1. Real-time recording of fault-slip events in operating mines, incl. post-mortem data analysis, locating of the events and interpretation of their geophysical dynamics. A variety of potential permanent measurements in mines can be qualified and ranked according to their relevance for fault-slip characterization.

   2. Building of a geo-mathematical 3D rock mass model with forward simulation capabilities in time (4D). The code must assure a learning model, where its forecast capability improves with time and number of detected events. The results from phase-1 can be used for initial set up of boundary conditions and calibration of the model.

   Phase-1: Real-time recording and data interpretation

   The potential mine candidates in the Sudbury area are apparently deep located, high stressed and in excess populated with existing exploration holes. They were all drilled in the past from underground in typically 2-1/4“ (57,2 mm) bit size. They were either core drilled with diamond crown bits (gauge hole) or percussion drilled with insert bits (rough hole wall), and are water filled and if intact, are likely accessible to final depth of up to 3000m. Hole temperature is uncritical at approx. max. 40°C, dry rock.

   There are only a limited number of monitoring sensors available for such small hole size, but the opportunity for a large amount of borehole installations for 3D coverage does warrant to equip as many of these holes as possible with solid state passive sensors for an immediate start of the data collecting activity, like fiber-optic temperature, pressure and analogue 3c-seismometers parked at bottom hole (see installation in Basel/CH monitoring holes). The instrumentation would be ideally installed with a winch on a wire, with instrument cables strapped to the steel carrying wire. Bottom flushing with hose equipment of some holes might have to be considered prior to sensor installation

   In a next phase, selected boreholes could be considered to be installed with sensors mounted on a reinforced composite hose (coil tubing) or on drill rods. These sensors could then be cemented or grouted-in after having reached their deployment depth. Ideally, these sensors would be 1c-optical or electrical strain meters, directional tilt-meters or electric/magnetic antennas. Such an operation is more expensive/time-consuming and would require a drilling unit of some kind to perform the job.

   Some measurements, like 3c-HiRes-strain, 3c-MultiStage passive seismic monitoring and other advanced electro-magnetic devices will however require the drilling of new boreholes with a bit size of 120 mm or larger. Those installations will have to be limited in number, due to cost and time to drill, but enough to complement the 3D-grid of the small-hole installations.

   Array layouts and sensor combinations will have to be decided at and some sensors may even need to be developed during the course of the project. Mine wall laser scanning, geodetic mine surveys and data from surface strain gauge stations could also represent an additional important contribution to the characterization of fault-slip event build-up.

Post-Workshop Comments

Comments cont.

7. **cont.**

Engineering will have to be devoted to the synchronization and data gathering into a single recording unit. One potential solution could be recoding and local data storage at the borehole head, with WLAN data collection to a surface acquisition unit, similar to the FireFly system of I/O Company. However, for such a variety of available different monitoring data, no automated acquisition unit does probably exist yet today on the market, hence a tailored solution might have to be specially developed during the project.

Phase-2: Rock mass model

A prospective ore body with existing exploration bores, but no mining activity yet, would be an ideal basis for the building of an initially static 3D geologic-mathematical model. The exploration bore-holes could be equipped with instrumentation similar as in phase-1, but ideally they are drilled in a larger OD, so that the optimum instrumentation array can be installed in selected borehole locations, ideally equally distributed over the body. Fault-slip events will probably not occur before mining starts, so the model will have to be calibrated initially with artificial sources.

Research results from phase-1 in respect to the characterization of fault-slip events will play an important input role for the model building in order to set the model's boundary conditions as well as the grid pattern of the cube sufficiently small, so that the model will later be able to dynamically history-match the stress behavior of the ore body with time, as events start to happen when mining progresses.

Unlike the hydro-dynamically driven dynamic reservoir models from the oil & gas industry, this code will represent a structural model, more similar to the finite element models of mechanical engineering, i.e. Ansys, etc. In other words, if the model is sufficiently defined, future mining progress actions could be forward modeled and the reaction of the ore body dynamically predicted, ideally also including every single induced fault-slip occurrence and their magnitudes.

It would certainly be beneficial to the project economics, if the study area of pase-1 and phase-2 could be adjacent to each other., i.e. area of phase-2 would be located in a deeper level to area-phase-1, where some of the boreholes incl. their instrumentation could serve the tasks in both phases, with the same monitoring instrumentation.

A significant show stopper therefore would be, if we were though able to understand the science behind fault-slip dynamics, but for some reason not be able to forecast the events ahead of time with mathematical forward modeling techniques.

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Post-Workshop Comments

Suggested Reading

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