CEMI
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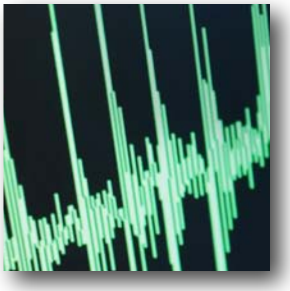
in Mining Innovation

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



Microseismicity

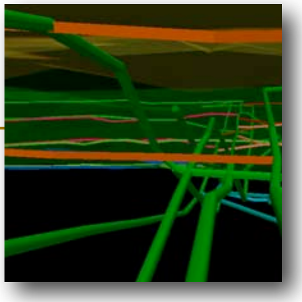
Geophysics

Summary of Feedback

Structural Geology

Modeling, Data Integration & Mine Design

Kingston, Ontario, Canada
Four Points Sheraton
April 23, 2010



Modeling & Mine Design

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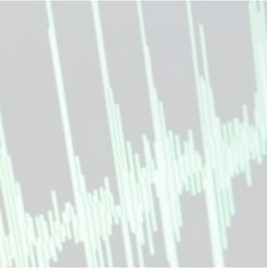
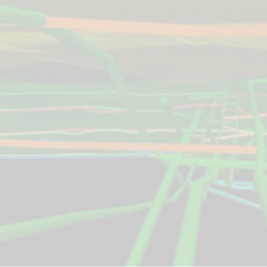


Introduction

Key Points



Detailed Discussion

Workshop Participants

Alex Henderson
Vale Inco

Benoît Valley
CEMI

Bernd Milkereit
University of Toronto

Brad Simser
Xstrata Nickel

Branko Damjanac
Itasca

Brian Buss
Vale Inco

Bryan Tatone
University of Toronto

Charles Lilley
Beck & Arndt Engineering

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Scott Carlisle
SRK Consulting

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Queen's University

Tatyana Katsaga
Itasca

Trevor Carter
Golder Associates

Will Bawden
University of Toronto

Wilson Blake
Consultant

Introduction

Preamble

On Friday, April 23, 2010, an Experimental Design Workshop in Modeling, Data Integration & Mine Design for the proposed International Fault Slip Control Research Initiative (IFSCRI) was held. This workshop was the final of four field-specific workshops, 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 following the workshop. Please feel free to contact Damien Duff at dduff@miningexcellence.ca should you have additional information to add to this feedback document.

(From left to right) | Top row: Denis Thibodeau, Javier Vallejos, Glenn Lyle, Doug Stead, Rob Bewick, Bryan Tatone, Graham Swan, Charles Lilly, Wilson Bake, Erik Eberhardt, Jessa Vatcher, Benoit Valley, Mark Diederichs, Peter Kaiser, Brian Buss, Fidelis Suorineni, Steve McKinnon, John Curran, John McGaughey, Tatyana Katsaga | Middle row: Will Bawden, Trevor Carter, Alex Henderson.
Bottom row: Giovanni Grasselli, Keith Bullock, Damien Duff, Scott Carlisle, Brad Simser, Doug Goldsack, George McIsaac, Bernd Milkereit, Ming Cai

Missing from photo: Branko Damjanac, Mark Board, Richard Brummer

Agenda

Workshop Leaders: Damien Duff (CEMI), Steve McKinnon (Queen's University)

07h30 - 08h00 **BREAKFAST (Provided)**

Introduction
08h00 - 08h30 Workshop objectives | **P. Kaiser, D. Duff**
08h30 - 08h45 Background: High level summary of workshops to date | **D. Duff**

PART I
08h45 - 10h15 **The biggest challenges we face in controlling fault-slip in underground high stress ore bodies**

- Challenges faced in controlling fault slip rock bursting at Xstrata Nickel's Craig Mine- A review | **B. Simser**
- Do we know how to assess the amount of stored energy in faults and fault systems? | **R. Brummer**
  - Coming to terms with the problem of energy release associated with fault slip
- How do we currently identify or characterize relevant structures or systems?
- How do we determine the potential for fault propagation, fault re-mobilization, fault system disturbance or "failure", and rock mass failure? | **M. Diederichs**
- How do we determine our "position" on the full stress-strain (or stress-displacement) curve? |**W. Bawden**

10h15 - 10h30 **COFFEE BREAK**

PART II
10h30 - 12h30 **Mine design and planning optimization when dealing with fault slip energy release issues in underground mines**

- What are the current approaches to mine design and planning issues when dealing with fault slip problems or fault-slip prone ground? | **S. Carlisle**
- How do we engineer to control energy build up on faults or within fault systems? | **W. Blake**
- How do we engineer or control energy release on faults? | **W. Blake**
- Are the current rules of thumb sophisticated enough?
- What numerical tools help us today? | **M. Cai**
- What opportunities are there to create greater flexibility from a mine design and then mine planning standpoint when addressing fault slip energy release issues (if improved analysis allows for option analysis)? | **B. Buss**
- What if our design fails and we still have unreasonable energy release during mining? | **A. Henderson**

PART III
12h30 - 13h00 **LUNCH (Provided)**

13h00 - 1500 **Our current modeling deficiencies**
Review of the character and nature of what we are trying to achieve in mines with a fault slip problem and of the capability (or lack thereof) of our current modeling approaches to dealing with it

- How do we currently model for expected behaviour? | **M. Board**
- How to translate fault characterization (measurements) and properties data info fault behavior models **R. Bewick**
- How do we recreate more complex fault systems or realistic fault geometry | **S. McKinnon**
- How can non-conventional use of numerical models help to derive realistic (potentially heterogeneous) initial conditions? | **S. McKinnon**
- Do we adequately consider mine stiffness issues? | **P. Kaiser**
- Are new approaches needed? | **G. Swan**

15h00 - 15h15 **COFFEE BREAK**

15h15 - 16h00 **Where are the research gaps and opportunities in what we've heard today?**

16h00 - 16h30 **Wrap Up and Next steps** | **S. McKinnon, M. Diederichs**

16h30 - 16h45 **Concluding remarks** | **P. Kaiser**

Key Points |Summary

Where are the gaps and opportunities in what we heard today? (Steve McKinnon)

1. **We are working with a data poor problem**

- Where are the faults?
- How do we define what is enough data?
- Geostatistical basis for geotechnical data collection - standards?
- Fault behaviour:
- Many faults that slip are not identified as critical before an event
- Need a screening process for selecting and evaluating faults to include
- Some faults that slip a small amount create a lot of damage, some that slip a lot cause little damage
- – how do we characterize potential behaviour?
- – how do we identify the important faults?

2. **Energy release**

- What is reservoir of energy available to be released?
- Locally stored – displacement to release it is good?
- Globally through fault network – tap into much larger pool of available energy
- Passive block vs tectonically pre-loaded model of mine environment?
- Energy release in one region may not always increase stability by removing energy – it can re-arrange the entire system and destabilize other portions of the system
- "butterfly effect"

3. **Geotechnical Characterization**

- Defining a good structural model is a challenge
- "Out of the blue" behaviour – what do we need to do to change this?
- Re-activation changes slip direction, may change behaviour from brittle to ductile – how do (can) we account for this?
- Are our frequency band-limited seismic sensors missing a significant portion of fault system deformation?
- Seismic monitoring does not always delineate burst-prone faults, what should we measure?
- Are we measuring the right things (energy transfers, tilt, time ….)?
- Global vs local measurements (we focus on local)?
- Scale effects – on fault geometry & properties,
- Different instruments to measure on different spatial & temporal scales
- Vast amounts of seismic data available – waiting to be analyzed
- Characterization of fault morphology
- Fault classification
- Key to creating models (then design) is adequate characterization

Key Points | Summary

Where are the gaps and opportunities in what we heard today? (summary by Steve McKinnon)

4. Modeling

- Model must be capable of incorporating kinematics of fault system in order to allow energy release to occur, and be calculated
- Do we even need to model bridges, fault propagation?
- Aseismic deformation not monitored – a critical portion of system behaviour
- Failure processes may affect each other over many scales – how can we accommodate this in models (size limits)
- From rupture process to mine scale
- Numerical laboratory – role of modeling in experimental design
- Are we at a point where we can use the models available?

5. Management

- Solution to fault slip not clear, so put effort into reactive side
- Lots of reactive measures, but few control measures
- Mine planning toolbox to manage fault slip – what toolbox?
- Migrate from empirical tools to more quantitative - need good data and to make better use of data

Detailed Discussion | Part I

The biggest challenges we face in controlling fault-slip in underground high stress ore bodies

The following is a collection of feedback received during the workshop, and includes key points made by each presenter as well as the discussion which ensued.

A context-setting presentation by Brad Simser on the challenges faced by Xstrata Nickel in controlling fault-slip rock bursting at its Craig Mine in Sudbury

Brad's main points were:

- We are relying a lot on luck in many instances of ground falls & rock bursts
- Trying to find pre-cursory events is very difficult
- Burst-prone support doesn't always work – have relied on luck
- Most bursts at Craig attributed to fault slip
- Usually less emphasis on faults than ore block models – faults difficult to see
- Faults that are difficult to see, tight, often related to most violent bursts
- Development of good structural model in advance very difficult, especially in advance as opposed to back analysis after a large problem
- Seismic monitoring systems not very sensitive/accurate for events outside of the array – hampers collecting seismic characteristics of new mining blocks
- High material stiffness contrasts can cause ground control problems similar to faults (very weak, soft materials) – focus stress, ability to deform (a stiffness issue)
- Exploration drilling for ore body orientation may not be adequate to pick up structures

Comments:

1. Is difficult to convince drillers at early stage to drill for things other than ore. -all about quality of data (e.g. triple tool drilling, appropriate geophysical tools etc.) (W. Blake)
2. Is not difficult to get infill drilling to help with stope sizing etc and is not a hard sell with many companies. (G. McIsaac)
3. How much data is enough data? When finished mining it's too late! We need guidelines for geotechnical drilling. (D. Thibodeau)
4. Need for geotechnical drilling for major infrastructure is becoming more common- things are evolving for the better but proper geotechnical drilling sometimes requires new development and a case needs to be made for it (A. Henderson)
5. There are large variations in industry practice in standards of geotechnical data acquisition. We need to log RQD (not always happening - missed opportunities). Important structures can sometimes be oriented within the plane of our drilling and thus are missed (T. Carter)

Detailed Discussion | Part I

The biggest challenges we face in controlling fault-slip in underground high stress ore bodies

Richard Brummer: Assessment of stored energy in fault systems:

Richard's main points were:

- ERR (energy release rate) concept of South African gold mines is related to stiffness, and energy release potential
- It depends on span opened, which governs convergence during mining. The broader "outside world stiffness" is important to consider
- DD formulation of element in shear is controlled by stiffness (shear)
- ESS (excess shear stress) - for slip need to know change, i.e. state of shear stress prior to slip, plus after, because during convergence there are both the straight convergence as well as shear displacement effects.
- 27 faults incorporated into Kidd mine, faults of different types (presumably strength)
- Predictions of slip locations and magnitude at Kidd mine appeared reasonable
  - o What characteristics of this situation enables this to be successful?
- Moment – magnitude relations from earthquakes do not work for mining
  - o Difference in kinematic constraints – mine has volume into which displacement can occur
- Difficult to choose slip candidates
- Many faults that slip are not identified as critical before an event
- Need a screening process for selecting and evaluating faults to include
- Some faults that slip a small amount create a lot of damage, some that slip a lot cause little damage

Comments:

6. At Kidd Creek, we found that time dependency was also an issue (W. Blake)
7. Identify faults – Can we classify them by what they are capable of doing? In particular, faults that will be intersected by an excavation and may be impacted by, say, the extraction ratio
   - This is a stiffness issue (D. Thibodeau)
8. Where is reservoir of energy coming from that gets released? (M. Diederichs)

a. What is a fault? Do faults change stress or vice versa?

9. Release of energy in one place may be causing loading in another (S. Carlisle)
10. Energy release in one region may not always increase stability by removing energy – it can re-arrange the entire system and destabilize other portions of the system (S. McKinnon)
11. Agreed, a small trigger area can lead to a big release area (W. Blake)
12. Models need to represent system kinematics not just stress (M. Board)
    a. This is hard to do (except by modeling) and we have a tendency to over predict the results
13. Isn't stick slip behaviour what this is about? (C. Lilley)
14. We need to understand peripheral deformation (G. Swan)

Mark Diederichs- How do we determine the potential for fault propagation, fault re-mobilization, fault system disturbance or "failure", and rock mass failure?

Mark's main points were:

- Large event is small zone of failure tapping into large reservoir of energy
- Fault system disturbance vs rock mass failure
- What codes can be used to represent fault systems correctly?
  - Challenge is validation & verification
- Do we even need to model bridges, fault propagation?
- Why are we always just considering shear as mode of slip?
- Re-activation changes slip direction, may change ductile fault into brittle one
- Is movement on faults helpful or dangerous?
- Verification of the validity of numerical modeling codes is problematic and challenging

Comments:

Discussion of burst fracturing here…

15. Ortlepp-like burst fractures are a stretch- don't think they exist (W. Blake)
16. At a mine scale, it's not critical to understand every rock bridge (B. Damjanac)
    a. But it's important to understand how the process of fracture failure occurs
17. Models must be capable of incorporating kinematics of fault system in order to allow energy release to occur (M. Board)
    a. earthquake faults are boundary displacement driven, which is different from mining
18. At Kidd Creek, 20 minutes prior to the June 2009 3.1 event, interviewed miners reported that the steel door to the refuge station they were in rattled for 20 seconds.
    a. This was 24 hours after the last major production blast- what can we deduce from this? (G. Swan)
        i. No one was monitoring deformation occurring on aseismic structures
        ii. We need to understand this as a much as we do the seismic stuff.
        iii. Understand the peripheral deformation driven by convergence
19. There was a paper by Healy in Nature in 2006 which looks at determining fault system interactions and predicts the sequence of energy release (M. Diederichs)

Detailed Discussion | Part I

The biggest challenges we face in controlling fault-slip in underground high stress ore bodies

Will Bawden - How do we determine our "position" on the full stress-strain (or stress-displacement) curve?

Will's main points were:

- Need to monitor and back-analyze to determine where one is on the stress-strain curve
- Fault slip damages rock and leads to degradation, but tensile opening would not
- Pre-peak: does field behave same as lab models (mobilization of cohesion, friction)
- Generic post peak parameters are not necessarily related to the problem of fault slip
- Mine designers don't understand the concept of post-peak behaviour

Comments:

20. The issue isn't just about "post-peak" in mine design, it's about the history of an opening (D. Thibodeau)
    a. It's about how to cover going from pre-peak to post-peak that's important
21. Telling how close we are to the peak is important- that's critical (W. Blake)
22. More sophisticated modeling is needed to understand what's going on post-peak (M. Diederichs)
23. Beck Arndt Engineering is focused on the strain-softening (down slope) part of the curve. That's the critical place. It governs the entire stress path for the whole mine (C. Lilley)
24. Can only get there if consider static stiff conditions-Have just said the mines is not stiff so don't know how to relate those data to a process that's unstable. That's not realistic (G. Swan)
25. Very little testing has been done in the field (J. Curran)
26. Need to monitor and back-analyze to determine where one is on the stress-strain curve
27. Fault slip damages rock and leads to degradation, but tensile opening would not
28. Pre-peak: does field behave same as lab models (mobilization of cohesion, friction)
    Note: all of the discussion of deformation path, lab-based parameters, considers single load path. This may be changed in field, i.e. re-activation along a direction in which strength is different
29. Post-peak curve is a function of mine geometry as well
30. Failure processes over many scales affect each other
31. Should we not be focused on the point between pre- and post peak? (D. Duff)
32. Agreed, are we interested I the failure process or the criteria that lead up to the failure process? (M. Diederichs)
33. Caving systems are perhaps the best place to approach this. Databases exist which cover the entire process of caving- including surrounding the caves themselves- reported in the International Caving Study? Useful as rock goes through entire stress-strain curve from intact to rubble (M. Board)
    a. Start with intact rock mass and go through process of "rubbelizing" it.
    b. Has been a lot of work in this area
34. 2 separate discussions here (P. Kaiser)-
    a. rock mass post peak behaviour analysis.
    b. Has the same rationale been used in trying to figure out how fault systems have been "globalized"
    c. Whatever experiment is- needs to focus/measure how faults are behaving when they go over peak

Detailed Discussion | Part II

Mine design and planning optimization when dealing with fault slip energy release issues in underground mines

Scott Carlisle- What are the current approaches to mine design and planning issues when dealing with fault slip problems or fault-slip prone ground?

Scott's main points were:

- In strategic planning would we do anything different with knowledge of faults?
    - Probably not – data & predictions of what will happen are not reliable
    - We may oversimplify things
- Structural interpretation is poor
- Knowledge of stresses is poor
- Avoid areas with core disking – they observe indicators of stress but do not measure
- Stress shedding strategy – don't really know where peak stresses are.
    - Use big blast
- Improvement in fault response prediction is high priority
- Early information valuable
- Where will we be after a $20M project?

Comments:

35. If the focus of our dealing with fault slip presently is an appropriate re-entry protocol, is that sufficient? (G. Swan)
36. We can't change mining methods. We need to find ways to minimize the risk to workers (D. Thibodeau)
    a. If we were to design a new mine, would we know how to do it in a way that minimizes the risk to workers?
    b. Is there a new mining method entirely which we should be considering?
37. Fluid injection has been tried and doesn't work (W. Blake)
38. Control is too much to ask for (G. Swan)
39. We need to look into energy release credit - manage energy reuse/distribution (e.g. install permanent energy sills, get a credit) (B. Buss)
40. In his experience, changing mining method resulted in changing rock burst mechanism and a re-distribution of energy release away from more nearby stopes to fewer larger events but further away from stopes –thereby overall safer. Was a result of long planning and experimentation process (W. Blake)
41. Agreed, things can be different in different places (R. Bewick)
42. It's the mine sequencing issue that needs to be addressed- the control of energy build up and release (M. Diederichs)
    a. It's how the energy is released, we do have options.
43. Lucky Friday mine was a planned mining method change after years of testing (M. Board)
    a. Over 4 years, the idea was to change the bursting type/style

Detailed Discussion | Part II

Mine design and planning optimization when dealing with fault slip energy release issues in underground mines

Wilson Blake- How do we engineer to control energy build up on faults or within fault systems and how do we engineer or control energy release on faults?-
(Presentation focused on observations made in the case of several rock bursts)

Wilson's main points were:

- Various cases reviewed – modeling results usually inconclusive or could not reproduce the events
- One case showed that mechanism was foundation failure – so not all large events are shear slip
- Microseismic systems do not always delineate candidate fault structures
- Modeling back analysis not always successful
    - o Lack of real input data
    - o Mechanism not confirmed?
- Overall mine closure may be driving force
- Rock burst characteristics can be very mine specific – important for planning experiment at a mine

Comments:

44. These cases clearly demonstrate that movement on some structures stimulates movement on others (M. Board)- referring to case review of Falconbridge #5 shaft rock burst event
45. How much do we look at rotation? (T. Carter)
    a. This changes the behaviour of the whole system!
46. Microseismic networks use high frequency sensors, we are missing a lot of slow low frequency deformation effects (B. Milkereit)
    a. Currently used instruments can't pick this up
    b. Strain and tiltmeters could be used to capture this
47. Agreed (W. Bawden)
48. Bursting from mine to mine is different- we need more burst research (W. Blake)

Mine design and planning optimization when dealing with fault slip energy release issues in underground mines

Ming Cai- What numerical tools help us today?

Ming's main points were:

- Benefits of outside vs inside modeling help
- Models are sophisticated enough- what is most important is the level of geological understanding

Comments:

49. Simple quick elastic tools very good at mine site (D. Thibodeau)
    a. More complex tools cannot be used at mine sites – domain of consultants
    b. No longer do mines have in-house expertise, one reason is that it can be bought externally. Issue is with continuity of information, and ability of external consultant to really understand the problem.
    c. Where does research fit into this? How do mines identify the longer-term research deficiencies in a cost-driven environment? Need to always show value of activities.
50. At the risk of losing focus, let's agree that the level of geological understanding is important but what have we done as a geomechanics community to convey that importance outside of just talking among ourselves? (D. Duff)
    a. How have we tried to demonstrate its value?
    b. If we don't try to do that and act upon it, we'll be "whining" about this very issue every time we meet
51. Do people do variogram analysis on geotechnical drilling? (G. McIsaac)
52. Yes, that is the current practice at VI (D. Thibodeau)
53. We still don't do enough with the data we collect now (G. Swan)
54. We need better geological understanding so that we can feed the right data into the models!!!
55. What is going in rock mass - we need to find a way to validate and calibrate our model (D. Thibodeau)
56. We still do not know how to make the most of data we do collect now - running theme!! (S. Carlisle)
57. We do not know what we absolutely need to address the issue. Needs to be determined (S. Carlisle)
58. Need to prove out the data. Any data that is collected needs to go into a digital medium otherwise the data is wasted (M. Diederichs)
59. We need to learn from caving operations. they have constant monitoring (M. Board)
60. Geotech data increasingly collected during exploration due to requirements of NI 43-101 with a need for geotech analysis to show an orebody can be mined (R. Bewick)
    a. 4301 reports – create the right level of motivation when estimating mineral resources - we need to create incentives like this within geomechanics

Detailed Discussion | Part II

Mine design and planning optimization when dealing with fault slip energy release issues in underground mines

Brian Buss- What opportunities are there to create greater flexibility from a mine design and then mine planning standpoint when addressing fault slip energy release issues (if improved analysis allows for option analysis)?

Brian's main points were:

- Lots of empirical mining strategies
- Microseismic data is a lagging indicator (is this always true)
- Can't predict singular fault slip events
- Global distressing – no good if don't know where the problem is
- Understand the "butterfly effect"
- No toolbox in mine planning for fault slip
- We heard earlier about how we struggle to recognize the important structures and of the energy storage and release issue.
- Is there a way to manage energy build up/storage/release?

Comments:

61. What's the feasibility of trying to simulate this for an operational situation? (M. Diederichs)
    a. If we can see build up on faults, at what resolution do we need to see it in order for it to make a difference- that is, change our decisions?
62. If someone can come to me and say that this fault is going to create problems- where the "out of the blues" are going to occur, then we would take mitigating measures- some of the known techniques (B. Buss)
63. If could see that certain extraction ratio triggers something and can evaluate Mn and where trigger has happened. Trace PPV circle based on that and then establish what's higher risk and move a drift away- if necessary. Or do we have to increase the ground support for that kind of sequence- leads to flexibility in schedule (D. Thibodeau)
64. Where we have experience we do modify our sequencing- once we have demonstrated evidence of value in doing that but need to know where and when ideally. Can't cone bolt from day 1- not feasible (B. Buss)
65. Controlling measures are lacking, we have lots of reactive measures (A. Henderson)
66. How can the likelihood aspect of the risk be reduced?- we're not good a modeling for this (P. Kaiser)
    a. How can we reduce the risk [of major failure due to fault slip] ever happening?
    b. Can't do it before or during mining
    c. What do we have to do to get better at defining that the likelihood is acceptably low?
    d. To design our mines to reduce the likelihood of reducing the risk of failure due to fault-slip?
    e. We know the likelihood is not the same at the beginning of mining as at the end

   f. If we could get into a test site, what is it we need to investigate to answer that question, reducing the likelihood of these things happening? How can we give management the confidence it needs? Data and modeling are nice but we're maybe not taking the right measurements- looking at the right things?
   g. What kind of geophysical monitoring is needed?
   h. Can we measure energy flow/transfer?

67. We often miss the time component? (B. Simser)
   a. Look at example of core disking- at exploration stage. When put a drill hole in an abutment when mining is actually in progress. Need monitoring capacity during mining.
   b. We have to be proactive
68. 3D sensor arrays are needed- for stress: there are tools like this(tomographic) in use in coal mines right now- they measure stress change, not stress directly (T. Carter)
69. We do know which rock properties are stress sensitive- but we don't monitor them! (B. Milkereit)
70. From an energy viewpoint, we need to measure the displacement- the rock mass as it moves- as it generates energy release (D. Thibodeau)

Alex Henderson- What if our design fails and we still have unreasonable energy release during mining?

Alex's main points were:

- Control measures are lacking – we have lots of reactive measures
- Work we`re doing has to help make people safer
- We don`t put too much reliance on modeling
- Systems development is needed to make systems improvement

Comments:

71. We need to study mines that are doing well- we haven't talked about those (R. Bewick)
72. But at what point are we in overkill mode. How do we measure how safe we are (S. Carlisle)

Detailed Discussion | Part III

Our current modeling deficiencies

Mark Board- How do we currently model for expected behaviour?

Mark`s main points were:

- Implicit vs explicit representation of structures
- Kinematics is important
- Need to design a seismic system from which advanced analyses of data can be done
- Discontinuum representation can enable quantitative calculation of seismic parameters
- Limitations of implicit models in terms of no ability to determine energy release
- With explicit models, what constitutive model should be used, and how to calibrate?
- Go back to the earthquake community - much experience with modeling energy release; earthquake community follows evolution of fault rupture process from seismic data - explicit models are better than implicit for providing understanding of process
- Research required in following areas:
    - understanding morphology and classification of faultsWe need models that can translate physical characteristics into constitutive behaviour --> we require a catalogue of discontinuum models, use morphology info to model (deriving displacement weakening of fault)
    - We need a separate understanding of fault from understanding of rock mass
    - Determine which mining sequences are related to higher levels of energy release - models are meant to aid in thinking process only!!
    - Need `what if` scenario analysis capability

Comments:

73. We need to determine stiffness on a fault- what is its apparent stiffness (G. Grasselli)
74. Can model global changes in stress using tilt meters etc (M. Board)

Rob Bewick- How to translate fault characterization (measurements) and properties data info fault behavior models?

Rob`s main points were:

- Treat discrete faults differently from fault networks – different scaling?
- Drained or undrained faults is likely important
- Kinematic freedom of faults during mining process – daylighting critical
- Different instruments to measure different spatial & temporal timescales
- Older faults can me more burst prone; what data do we therefore need to collect and what to leave out
- It`s not just characterization, it`s necessary to have an understanding of the entire rock mass system

Comments:

75. The foundation of modeling is based upon what is collected by a structural geologist - we need to know the fault system' in order to better model (T. Carter)
76. We need to report and deal with fault fracture networks separately from discrete fracture networks (D. Stead)
77. Synthetic rock mass model advantage –being validated by the bulk and mass mining folks (B. Damjanac)
    a. Can put actual geometry in DFM
78. How many boreholes with information are needed to build a DFN cube (referring to zones shown in slides) (B. Milkereit)
79. Data is only as good as the core logs; calibration of DFNs - look to the nuclear industry in Sweden (transport of fluids) (T. Carter)
80. There`s broad acceptance of the DFN kind of approach in Australia- with wide usage, in particular, in open pit mines (C. Lilley)
81. The nuclear waste world use DFN models for modeling fluid movement
82. Should have had someone from the nuclear waste discipline at workshop (P. Kaiser)

Charles Lilley- the experience at beck Arndt Engineering

Charles`s main points were:

- Modeling of fault slip seismicity seems to be working
    - o Experimenting in caving systems
- If we model damage correctly we can validate the other values

Detailed Discussion | Part III

Our current modeling deficiencies

Steve McKinnon- How do we recreate more complex fault systems or realistic fault geometry and how can non-conventional use of numerical models help to derive realistic (potentially heterogeneous) initial conditions?

Steve`s main points were:

- We need to decide how big and how small to go with our model scales
- We need to decide what really needs to be worked into our models
- How do we make stress and displacement compatible?
- Our models need to be on average one scale larger than our problem area
    - Need to know what`s going on outside to understand the inside. Just how large is individual situation-specific
- Scale is critical from an experimental design standpoint

Comments:

83. What`s the starting point in re-creating initial conditions? (M. Diederichs)
    a. On top of this problem, a heterogeneous system changes everything
    b. (discussion here around Phases 2 modeling capability)
84. There is some simple but effective capability in Phases 2- can start to vary stress mode. Is not perfect but a start (R. Bewick)
85. Is not clear what the required level of information is needed in specific situations from a fault slip standpoint (P. Kaiser)
    a. From an experimental design point of view how much effort is required to resolve stress variability for fault-slip?
86. That’s because we don’t understand the fault slip mechanism yet (E. Eberhardt)
87. It comes down to understanding which faults are critically aligned relative to the stresses we`re creating (E. Eberhardt)
    a. Also, what are the fault characteristics- this is where the test site may provide an advantage. Is it young faults or mature faults?
    b. We haven`t talked about water- drained and undrained faults and the interaction with pore pressures
    c. What are the characteristics which are most critical from an operational standpoint? Until we know that it’s hard to know what we can be doing operationally.
    d. We should be looking at seismicity and what attenuation is doing and how the interactions combine to make faults go critical.
88. Kinematics and changing geometries during mining are important (D. Stead)
89. Our models are sophisticated enough to solve brittle mechanistic-type problems (E. Eberhardt)
    a. Can solve mechanistic problems in mines- at a simple scale anyhow.
90. Are we sophisticated enough to use the models though? (M. Diederichs)

Our current modeling deficiencies

91. We can put pieces together and make progress. Our simple models are strength models- based on Mohr-Coulomb and Hoek-Brown criteria (E. Eberhardt). If we find that dilation is important, for example, we need to research it. To develop an experiment need to focus on key things.
    a. When modeling, is important to know whether more attenuation should be used or whether mine noise is detrimental. These factors are important for our experimental design.
92. We need to distinguish between stochastic and probabilistic joint models

Peter Kaiser- Do we adequately consider mine stiffness issues?
(Peter did not present at this time, his presentation on mine stiffness was made as part of his introductory remarks earlier in the workshop)

Peter`s main points were:

- Dealing with the problem of fault-slip in fault-slip prone mines is about engineering risk so as to either lower the chances of serious/costly damage, diminish the severity (consequence) or both.
- Where risk mitigation measures are not completely capable of eliminating risk, that is, overlap of demand and capacity distributions still occurs, uncertainty still needs to be reduced through proper management techniques.
    - Mining reality is comprised of data-rich and behaviour-rich cases
- Mine stiffness issues need to be considered more often than they are presently when determining a system’s stability and its capability to deal with energy release.
    - Can impact on faults- their behaviour and their propagation.
    - Can even cause faults to behave differently along their lengths and over time, as the system stiffness around them is altered.

Detailed Discussion | Part III

Our current modeling deficiencies

Graham Swan-Are new approaches needed?

Graham's main points were:

- Spend too much time on precision, not enough on accuracy

93. Better to be almost right than precisely wrong – (G. McIsaac)

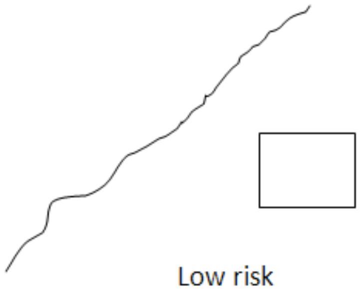
- We have lost the adventure of experimental research
- Experimental people are trying to control something which is uncontrollable
- We must live with uncertainty
- Strain rate influences failure
- Support may improve strength and lead to more violent ultimate failure
- Novel (fully yielding) support systems should be considered?

Comments:

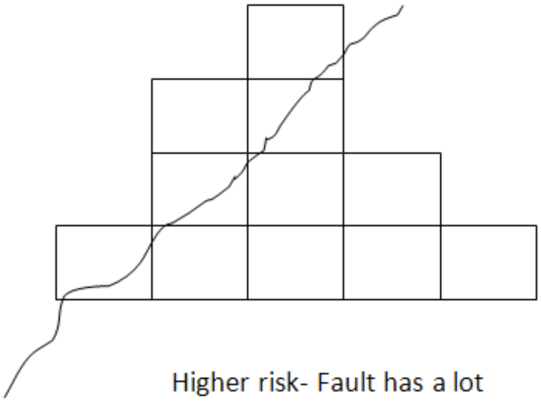
94. Fibre-glass reinforced shotcrete works. Mesh reinforced is the best (C. Lilley)
95. No it doesn't work- maybe we need a material scientist at this workshop? (G. Swan)
96. May need to pay more attention to models (C. Lilley)
97. Maybe we're not looking at probabilistic modeling with the right parameters? (M. Diederichs)
    a. Or enough at the variable stresses in our models?
    b. Maybe we're not using common sense.
98. We should be talking more about stochastic modeling (G. Swan)
99. The "weights of evidence approach" incorporated into the Mira geosciences hazmap tool seems promising (S. Carlisle)
    a. Put DFN models into that- incorporate them
    b. Use proxies for stress like extraction ratio
100. We often misunderstand the meaning of stochastic and probabilistic modeling (M. Diederichs)
    a. Probabilistic modeling is when one takes a deterministic model and puts distributions on parameters.
    b. Stochastic models, on the other hand, imply that the location of the next joint (say) depends on where the previous one was placed.
101. Do we know which we are doing with the models we have? Not sure where stochastic models are going to get us (M. Diederichs)
102. Agreed, this is in issue (W. Blake)
103. We're doing well at indicating what the issues are that were' having but not the solutions (P. Kaiser)
    a. We need to establish task-forces to discuss details of issues brought up at this workshop (energy flow, mine stiffness...
    b. What else in addition to fault slip should be included in the IFSCRI experiment?
    c. Next-generation monitoring technology (energy flow...)
104. Trevor Carter offers to work on Rock characteristic team; PKK offers to lead the energy flow and mine stiffness team.
105. Teams are needed to deal with stochastic modeling and support requirements and a group is needed to look at the next generation monitoring technology.

Post-Workshop Comments

106. What’s missing in these workshops is what controls or mitigating measures should be investigated as part of the IFSCRI planned experiment? (D. Thibodeau)
    a. We should talk about an integrated model, that is, geological, geotechnical, numerical and financial for the entire mine that can be used for simulation purposes to improve design taking into account the fault system.
    b. This model should be interactive as new data or information comes available.
107. Please share the list of workshop attendees with email addresses (C. Lilley)
108. Test the “waterless mine” concept, perhaps by comparing hydraulic vs paste fill techniques (D. Goldsack)
    a. Could test “stiffening” of mine at the same time
    b. Earth tide effects on rock bursts and seismic events should be investigated- particularly for events which are in the Mn1.0 range
    c. The perturbation effect of earth tides (if proven to exist) could be added to our static- simplest- models in order to help make them dynamic
109. In terms of re-entry protocols there are two key issues (J. Vallejos)
    a. Background levels and
    b. How the data is returning (decaying) to those levels
    c. I would suggest correlating the decay of aftershock sequences after blasts and large events with mining information
    d. This will provide a better understanding of the factors affecting/controlling the decay of mining-induced aftershock sequences and [thus] a better understanding of [appropriate] re-entry procedures
110. We need to capture creeping risk (B. Simser)
    a. Make sure there’s enough time in the IFSCRI experiment to do that



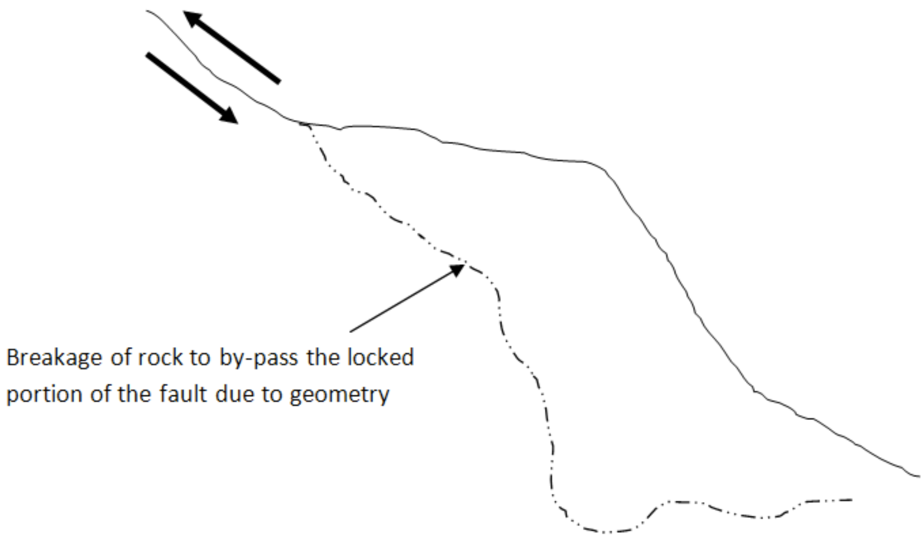
Low risk



Higher risk- Fault has a lot more room to move!

Post-Workshop Comments

111. What really is fault slip? (Rob Bewick)
    a. In an asperity example, we break the asperity by “shearing” around it and therefore we, in essence, cause the failure of intact rock



    b. There are typically (commonly) good ore zone block models created for a mining block. It’s rare to find an existing host rock mass model of the host rocks to the ore- even though the data may exist. RQD data, for example, is routinely collected as is core disking data. These parameters, if modeled would improve our understanding of the rock mass variability and should be created to assist in numerical stress model creation.

112. I like Peter Kaiser's "mine stiffness" concept and Richard Brummer's "outside world stiffness matters" as stiffness could be one of the parameters suitable for 24/7geophysical monitoring. (B. Milkereit)

113. I expect the discussion of the complete stress-strain curve (Will Bawden) - including pre-peak and post-peak behaviour to become the centerpiece of IFSCRI: how can we get from well understood lab data to field observations?

114. Related to 104, I found the discussion on the total energy release rate (Brian Buss) extremely interesting: we need tools to capture total energy release in a 3d rock volume:
    a. seismicity + deformation + heat + ...? (clearly, we will need broadband sensor arrays to capture all these effects).

115. Modeling (Mark Board's presentation) can provide the necessary platform for linking up with geophysics & microseismicity (4D stress and displacement models should be translated into temporal variations of 3D rock physics models).

116. What is the problem that we are trying to solve? (Alex Henderson)

Is it:

a. Energy released in a controlled manner that does not put employees or operations at risk?

b. Stochastic modeling of mining options that will minimize energy release exposure?

c. Can we monitor in-situ energy changes (other than seismicity) that will assist us in understanding drifts at risk?

d. Energy Release rate - How do we measure it?

e. Is there something that we are not monitoring that could be used as a precursor to a slip fault event? (for example the doors rattling 20 minutes before the event at Kidd or how do some animals know that an event will occur)?

If we can't find a proactive solution:

f. How can we improve dynamic ground support to protect/mitigate the consequences of an event?

Somehow the problem that we align with must be one that the earth quake people would align with as well so that it is not just a mining problem that we are trying to solve.

117. Composition of participants (Fidelis Suorineni)

- Experienced mine planning engineers were not well represented. These are keys to mitigation/controlling of fault slip problems from planning and design stages

118. Unidentified structures – Faults

- This was seen as the most serious problem in active mines. Participants concluded microseismicity or seismic events cannot be used to identify faults. In our experience microseismic events can be used to identify faults that are not identified in routine geological mapping (seismically active planes). There are case histories from Creighton and North Mines to support this.

  Earthquake seismology models can assist in using rockbursts data to locate sources that might not have been previously observed. However, one needs the right seismologist to achieve this. During the North Mine rockbursts review of the September 11th events we unofficially used the expertise of Dr. Robert Herrmann of St Louis University. This is some one to consider in future workshops.

119. Control Measures

- I was surprised to hear that change in mining method cannot mitigate fault slip rockbursts. There is overwhelming evidence to the contrary. The evolution of mining methods in Creighton Mine over its 100 years of operation has always been to mitigate rockbursts!! In 1984, mechanized cut and fill mining was changed to VRM after a MN 4 event.

120. Microseismic and seismic data processing

- This was another surprise. Workshop participants seemed to agree that data should not be filtered?!

- Most data from seismic monitoring systems are erratic, if the data is not managed daily by a competent seismic monitoring technologist. Our experience shows that most events claimed as events are not events because reliance is placed on automatic processing routines that are erratic. Wave arrival times are rarely correctly picked by auto routines.

  Research should be expanded to include fault detection and not only characterization.

121. Mine stiffness
    - The importance of mine stiffness was emphasized. No attempt was made as to how to determine it!
    - In situ stress orientation relative to orebody is shown to have significant impact on mine structures behaviour – pillars / bridges, excavations etc. This will have even more significant impact on whether a fault is active or not.
    - Experience has shown that stress orientations in which the major farfield stress is oblique to the orebody considered normal to the orebody. Example is the Campbell Red Lake Mine F-Zone. In situ stress measurements often give very variable stress orientations. Also, most mines consist of multiple orebodies and are influenced by regional faulting and shearing. Thus, orebodies with major principal stresses oblique to them are more common than often assumed.
    - Fault slip cannot be studied independently from mine operation activities. Mine activities often cause a structure that was previously inactive to be active. Active stoping near a previously inactive fault can activate the fault.
    - It may be important to review and validate stress measurement databases for mines that behave abnormally seismically.
122. Mine water can trigger fault slip events – not discussed at workshop
    - Water from hydraulic backfill that infiltrates a fault zone can trigger fault slip. A case example is the MN 4.0 event of 1984 at Creighton Mine. Should mines with significant structures use pastefill instead (pay attention to drainage paths)?
123. Insufficient collaboration among mine staff
    - There is often insufficient collaboration between planners, ground control engineers and geologists in mines! Mine planners and ground control engineers need to be encouraged to recognize the importance of geology in order to operate a mine safely! Tonnage should not be the bottom line.
124. Surprise that some people found microseismic data not helpful (Tatyana Katsaga)
    - I had a number of very good discussions with people. One thing that surprises me that some people indicated that microseismic data was not helpful (or was not helpful enough) in understanding/studying/predicting slip events. What we know is that the active seismic monitoring technique was very successful during URL experiments. Moreover some people were not very acceptable to the idea of seismic tomography which is supposed to be a very effective tool to study any fracture processes.

125. Risk assessment stream (Erik Eberhardt)

- Based on the different discussions during the workshop, I see the problem as involving two streams. On the risk assessment side, much of the discussion seemed to steer towards stochastic treatments of the problem, pointing out that it would be impossible to deterministically identify beforehand specific faults that may slip. There is too much geological uncertainty, and too much is hidden behind the excavation boundary. As such, I would carry out a 3-D modeling study to understand the stress interactions between an advancing drift and faults of varying orientations relative to different principal stress directions. Stress heterogeneity and the influence of mine sequencing should also be considered. By understanding these interactions, critical fault orientations can be determined and then related to the mapped/stochastic population of faults to statistically assess the level of hazard for a given mine as a function of different mining depths, mine sequencing, etc.

126. The second stream of study is to better understand the fault slip mechanism relative to the fault characteristics.

- Are slip bursts developing along faults that are not fully developed, perhaps involving shear through intact rock bridges, or do they occur along well developed faults with a thick gouge where asperities may be locked up (or maybe both)? My feeling is that it is the first scenario. Perhaps a first step would be to collect data on the characteristics of faults involved in slip burst events (if any exists), or maybe this has already been done. Simply studying/reviewing the architecture of the faults encountered at the mines would be a good first step in any case. Any input of this kind would help focus the direction of investigation as the scope of study would otherwise be quite broad. Once some initial understanding is gained, the behaviour of these faults under a changing stress field could be studied through numerical modeling (using a FEM-DEM approach) together with specialized laboratory experiments. There may be some synergy to tap into by bringing some earthquake people into the fold (which I guess has been done through Chris Scholz); I have several colleagues here at UBC who are looking at the same problem but from a strike-slip earthquake perspective (San Andreas).

127. Excellent overview (John McGaughey)

- The workshop was an excellent learning experience as an overview of state-of-the-art in fault modeling and numerical stress modeling as they relate to fault-slip instability. Data integration in the broad “data fusion” sense of combining many disparate streams of evidence towards the IFSCRI objective of “minimizing the risk to the safety of miners and the economic future of deep mines” was not directly addressed in the workshop.

128. Many fundamental questions regarding fault behaviour

- It was evident from the workshop that there are many fundamental questions regarding fault behaviour whose answers would have a positive impact on the IFSCRI objective. Examples include assessing the amount of energy stored in fault systems, or triggers and mechanisms for energy release in a dynamically-changing mine environment. Many of these questions are related to those addressed by earthquake seismologists in which there is a rich legacy of previous work. These appear to be fertile and important research questions, to which IFSCRI could make an important contribution (breakthrough perhaps?) but, due to their fundamental or theoretical nature, present relatively high-risk R&D avenues when set against the need of delivering practical tools to operators over a research program spanning a few years. In these areas perhaps the more practical research questions would concern how best to utilize existing theoretical understanding of fault-slip behaviour and the existing, highly advanced 3D numerical modelling such as discussed at the workshop, in the development of practical tools that planners and operators can use to manage and mitigate fault-slip risk.

129. Even as the theoretical fault-slip issues discussed at the workshop become better understood, practical application of that theoretical knowledge will always be limited by observational constraints. Knowledge of conditions in the mine will always be incomplete, and always a combination of observation and assumption. It was stated several times in the workshop that the faults that cause the most damage may not be directly observable, and that there is a history of damage caused by slip on faults that were never identified as critical before the event. So even if we were to understand fault behaviour theoretically, the existence of hazardous fault-slip conditions may in general only be inferred through combining a number of data streams: rock mass characterization, statistical fault models, microseismicity, geophysical surveys, deformation monitoring, geometry, etc. Development of methods for inference of risk through a holistic interpretation of large data sets, guided by experience and theoretical knowledge, presents relatively low-risk R&D opportunity to IFSCRI.

130. There are a couple of research areas related to data integration which, based on both this workshop discussion and the feedback documents from the other workshops, provide achievable objectives. The first is site characterization. Creation of rock mass models integrating both standard rock quality measures and statistical fault models, constrained by direct observation in boreholes or openings, should not be too great a challenge. It was underlined at the workshop however, by Trevor Carter and others, that this is not systematically done. From our own CEMI project work at Craig we know that there are knowledge gaps regarding both treatment of the basic observational geotechnical data (i.e. how to convert those data into useful 3D models) and how the resulting models, probably best expressed stochastically, should ultimately be applied to the estimation of fault-slip rockburst hazard risk. Such methods should be capable of readily assimilating new data as mining proceeds—from boreholes, underground mapping, interpretation of microseismic data (in terms of both host medium and source characteristics), and radar or other more novel investigations. The CEMI Craig Mine hazard project, which demonstrated that 3D fault model geometry was an important factor correlating to fault-slip rockburst, also showed that understanding of the fault model geometry evolved greatly from 2004 to 2009, and this evolution of knowledge had a quantifiable impact on risk estimation. For the field research contemplated by IFSCRI a number of useful experiments could be performed to produce and then validate site characterization models as knowledge of the site increases with time and the volume of data collected.

131. The second area where achievable, low-risk gains seem obviously to be had is the data integration itself, which I call “data fusion” here to indicate the specific task of quantitatively combining all relevant streams of data into a derived quantity such as spatial and time-dependent hazard or risk. (“Data integration” is a vague term.) Since fault behaviour in mine environments is incompletely understood theoretically, and because the mine environment can ever only partially be known, the data integration approach will ultimately be empirical and statistical. It is an important step to bring all site knowledge and expertise to bear on the IFSCRI

problem of “minimizing the risk”. The objective of minimizing the risk would be best served by development of a framework for quantitative evaluation of that risk. This was underlined by Peter Kaiser, who stated that “the real question is how can we estimate the probability of a fault slip event happening?”. Without knowing the best answer before doing the research, one can almost certainly state at the outset that the most useful fault-slip probability estimation method will be quantitative, empirical, statistical, 4D, and use all all relevant data on hand. In other words, a data fusion framework is required.

132. Aspects of the data integration issue came up in passing at both this workshop and others: for example the need to integrate geology with microseismic data or the need to integrate novel geophysical methods into interpretation of fracture or stress models. These are important components of what should be a larger and ultimately more important data integration vision. There is a rich legacy of research in this area from other fields of application. The Craig Mine hazard project showed the potential of this approach, adapting to the 4D mine environment statistical methods developed for 2D spatial expert-systems, based in turn on work done in medical diagnostics. This was one of many possible approaches, and merely the one most conveniently at hand. Research into these methods for the IFSCRI objective could easily be accommodated within the framework of the proposed mine experiment. We have collaborated extensively with scientists at the GSC in spatial expert systems (and also, relevantly, construction of 3D structural models from sparse observational data). It may benefit the IFSCRI working group to solicit input from these or other scientists working in similar fields.

133. Contribution by Dr. T.G. Carter and Mr. R. Bewick

During the discussions relating to application of distinct element and other fracture capable numerical modeling codes (ELFIN, FEMDEM, PFC, 3DEC, etc.) and discrete fracture network (DFN) assessment methods it became apparent that scales of faulting and associated fracturing is an important issue and furthermore that across the group, clarity of what might be envisaged as a fault differed between practitioners. To provide some clarity and understanding of natural faults at various scales we have therefore included below a suite of diagrams at various scales – from continent wide down to mine scale that will hopefully allow better appreciation of the fact that natural interference geometries although similar at the various scales, do in fact vary markedly from the very simplistic understanding of faults most prevalent perhaps in the discussions (a la the Anderson model - Figure 1).

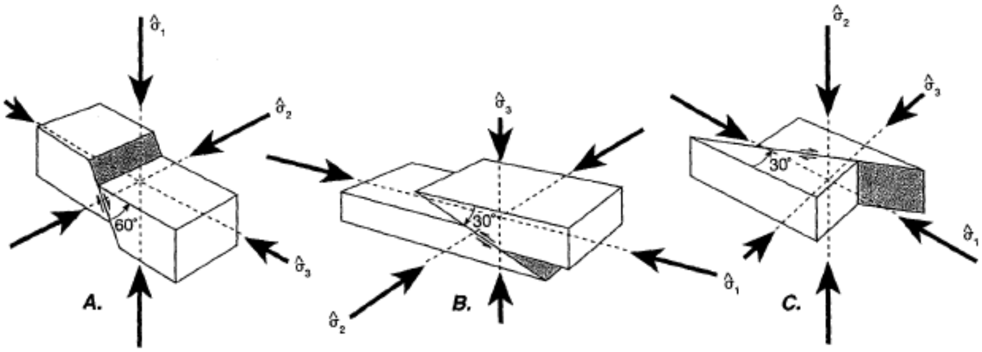


Figure 1 – Simple Anderson Model of Principal Fault Types – normal, thrust and wrench

Real faults almost never occur as single planar features, and nearly always occur as suites of anastomosing structures. The map below (Figure 2) shows quite a simple natural fault system – note the quite complex pattern of fracturing associated with extensional faulting. Note also the numerous embryonic cross shears.

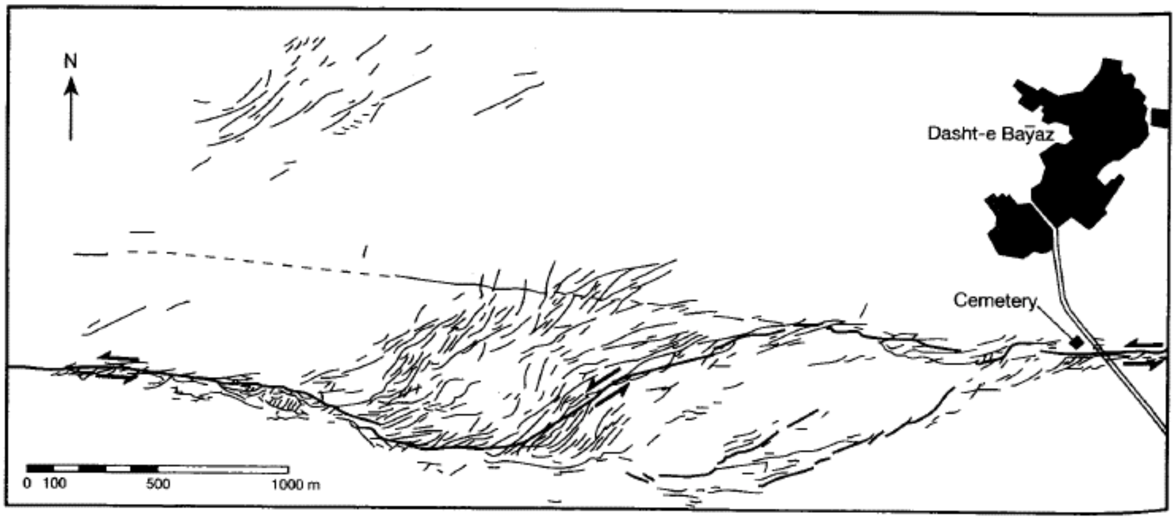


Figure 2 – 4km section of Dasht-e-Bayaz Fault showing classic cross-shear development at various scales

This mapping is from North Eastern Iran – where the geology can be clearly defined because there is little or no vegetation cover obscuring rock exposure. This clarity of observable geology where every level of fracture association can be seen – for example on aerial photographs, is rare worldwide in the natural world. In the mining environment we get a chance underground to also see this detail, but rarely can we, or do we put together the big picture view – we tend to look only at the micro features that we map at drift or stope scale. At the other end of the scale – we commonly see simplifications of plate margins in text books, yet the real fault patterns and interaction splays of associated features at plate scale or even mining camp scale, let alone mine scale, are typically much more complex and interaction development much more difficult to unravel than at first glance. Take for instance a simple faulted anticline with tear faults – such as shown in Figure 3.

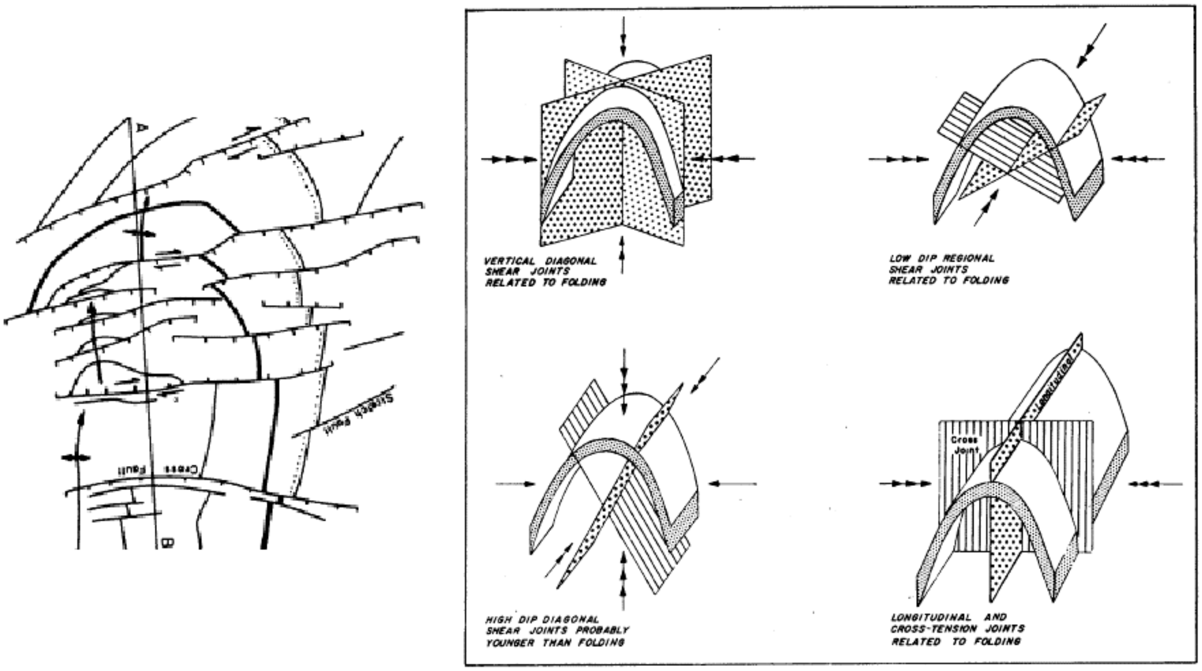


Figure 3 – Realistic complexity of quite simple faulted anticline structure (left diagram) versus conceptual fracture patterns expected within anticlinal fold fabrics

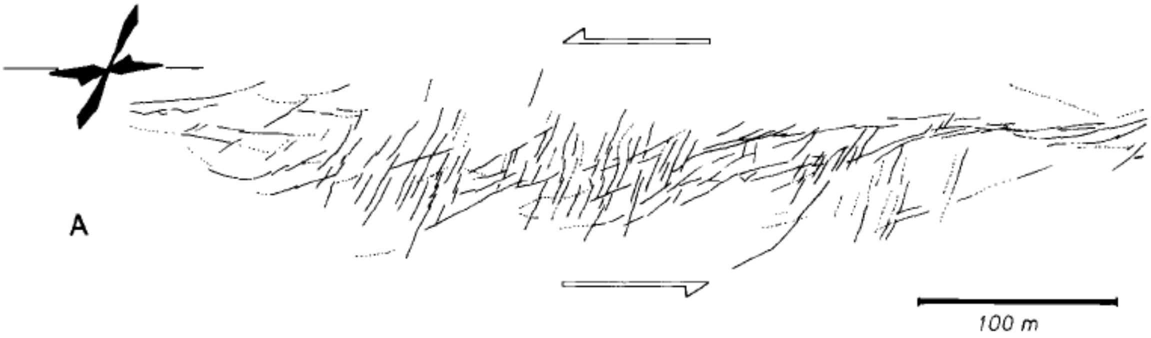


Figure 4 – Part of the Dasht-e-Bayaz Fault shown in Figure 1 – at a few hundred metres scale

The degree to which, for modeling, we simplify fault geometry at mine-wide scale and even down to stope scale, and in particular the degree to which we linearize fault traces, will to large extent control the behaviour we replicate in our models. We have to get to grips with the degree to which we can simplify and characterize faults such that their behaviour under induced mining changes is realistically replicated. In this regard, natural plate behaviour shows that unless we can properly represent the interlock and interaction mechanisms in our modeling, we probably will never be able to replicate anything close to realistic behaviour.

This interlock problem also appears scale dependent as can be appreciated by comparison of Figure 1 – which shows the Dasht-e-Bayaz Fault – over a 4km stretch versus Figure 4 which shows a 500m stretch of the same fault. As can be seen, the morphology is different at the various scales, but with some overriding similarities, and this scale difference in fact is quite apparent continent wide, as can be appreciated by comparing Figure 5, which shows the main fabric of the foliation and faulting controlling the geology of Eastern Canada at both continent and province-wide scale, versus Figure 6, which shows the detailed fault fabric of the Porcupine camp. As is very evident, different structural elements dominate at each scale, so to what extent do we need to consider the stress state prevalent in the higher and higher scales as boundary conditions perhaps in our mine scale or stope scale models is another question that needs clarification.

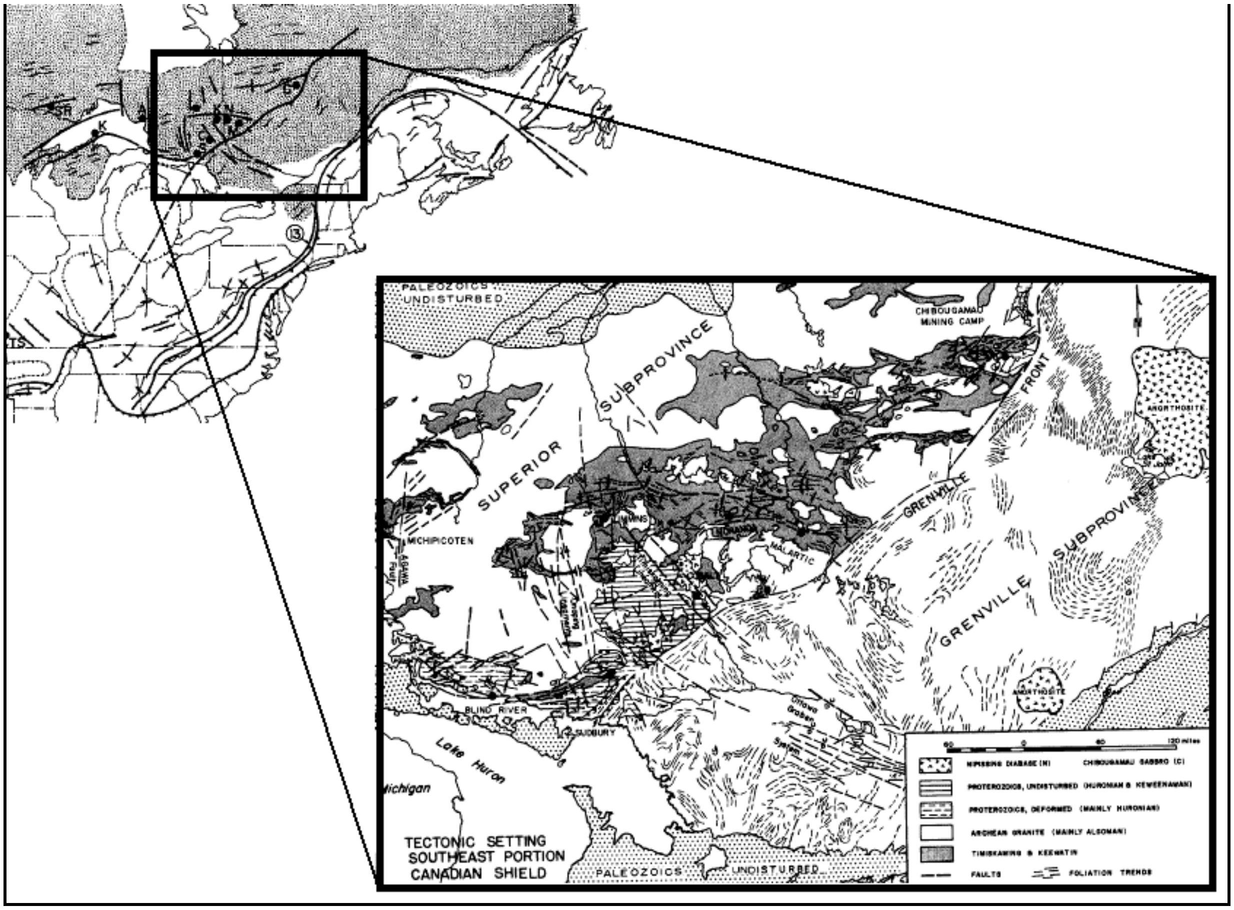


Figure 5 – Generalized Structure of Eastern Canada – at 3000 and 1000km scales

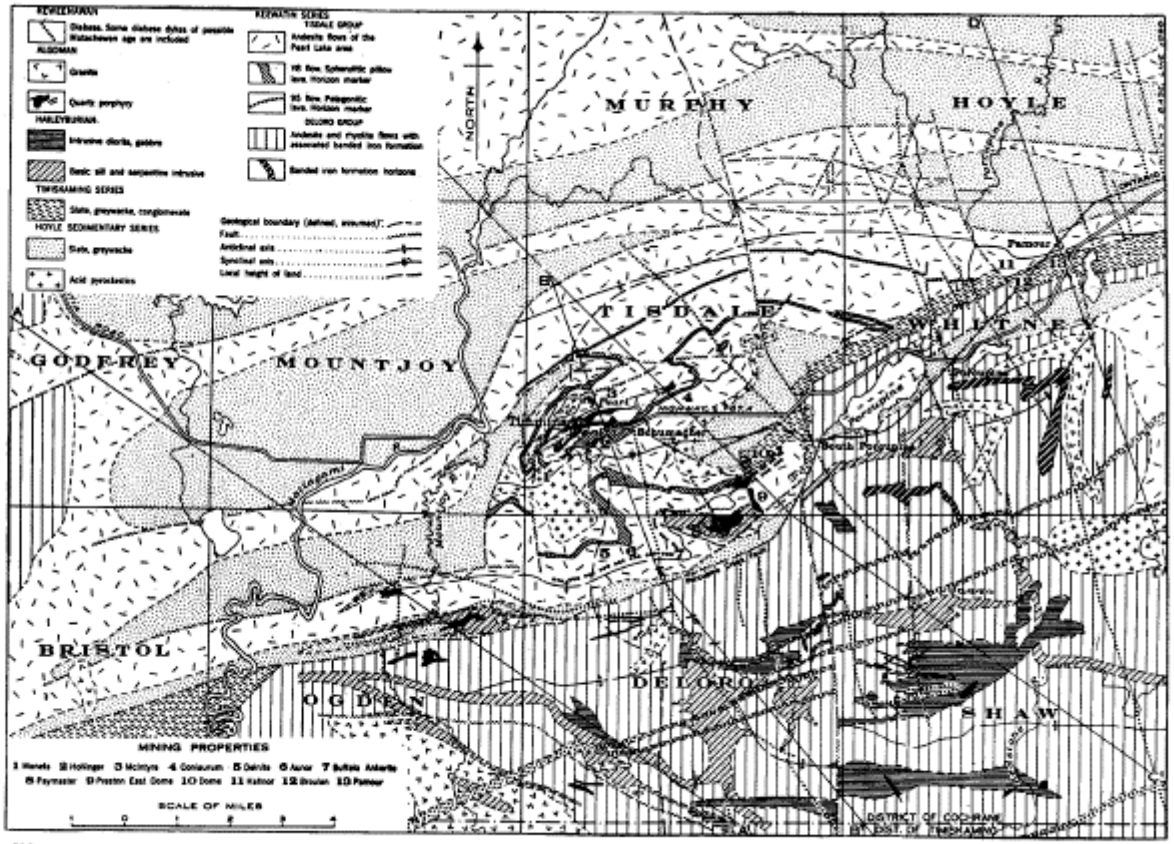


FIGURE 323. Geological map of the Porcupine mining camp, Timmins, Ontario. The Matachewan dikes are of Huronian age, the Haileyburian rocks are of Pre-Algoman age, and the Hoyle sediments are of Pre-Laurentian age. (From W. R. Dunbar [1948], *Structural Geology of Canadian Ore Deposits*, Can. Inst. Min. Met.)

Figure 6 – Porcupine Mine Camp Structure – at 50km scale

Note: criss-cross pattern of faulting hardly visible in regional or continent wide scale maps in Figure 5

The map above of the Porcupine camp reflects the same structural domain in which Kidd Creek Mine is situated and yet its relation up to plate scale (shown in Figure 5) contrasts markedly with the relatively complex, but still significantly linearized pattern of fault structures that have been brought into the Kidd 3DEC model, which perhaps reflects our current state-of-practise in mining rock engineering, but perhaps is different in direction than where perhaps we need to be going in the future. In this regard, the ensuing discussion with respect to the added complications that introduction of such faulting creates in extending the run times and complexity of behaviour of our already complex 3D models in some ways perhaps needs re-channelling as it detracts from the need to get better replication of realistic faults. Modelling of the various criteria to assess energy release or fault instability such as the Energy Release Rate (ERR) and Excess Shear Stress (ESS) have shown promise, but prediction based on computed patterns based on too linearized a fault fabric may be grossly misleading, and we need to be able to refine to what extent we need to model the interaction/intersection effects in order to get proper replication of real behaviour. The fact that the majority of the modelling images of faulting presented during the workshop showed fairly planar fault surfaces (some of which cross cut each other in perhaps not the way reality might show at a detailed drift mapping scale, and thus perhaps their interaction might not truly be representative of natural behaviour) is a problem that we need to get to grips with, perhaps by better fault characterization scale-wise and behaviour-wise. It is clearly apparent that many limitations exist with respect to how to adequately incorporate fault geometries and properties into these complex 3D numerical stress models. Again, unless proper replication of the differences in character at different scales can be represented, model behaviour will certainly not replicate reality.

The example below shows a relatively simple fault geometry model as actually mapped and interpreted from Mine drift plans that has been zoned into three segments; as shown in Figure 7 - (1) a thick gouge zone; (2) a relatively thin planar connected fault segment; and (3) a yet to be linked fault zone, comprising a zone of en-echelon joint elements.

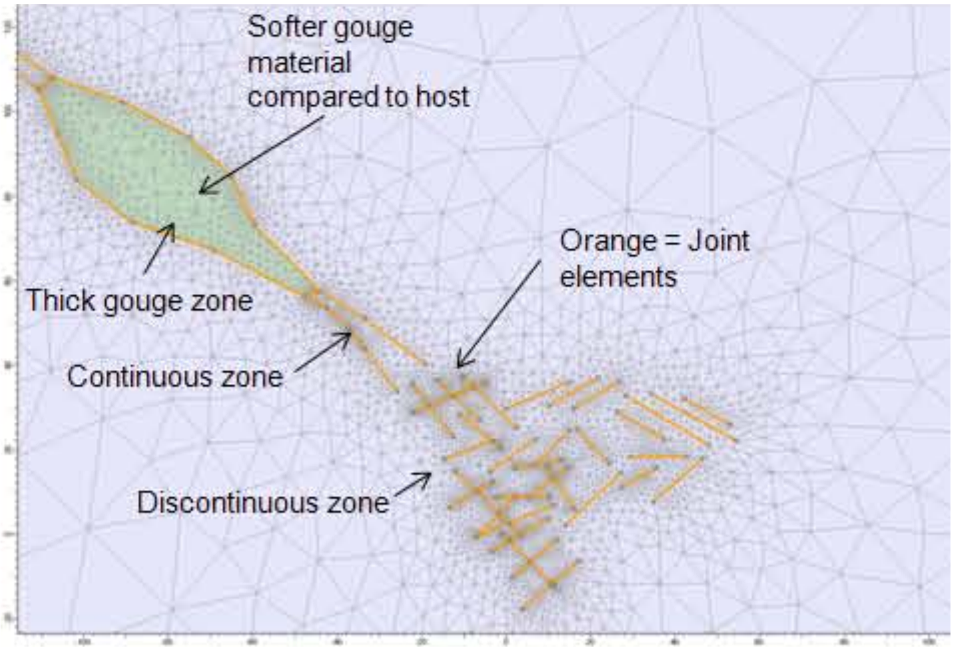


Figure 7: Fault model geometry, materials, and mesh.

Using displacement loaded boundary conditions to obtain a far field stress ko ratio of 3 considering a major principal stress of ~70MPa and a minor principal stress of ~23MPa, typical of many mine camps in Canada, it can be seen from the two diagrams in Figure 8 that above average stresses concentrate in discrete zones, and as well lower and higher than average far field confinement levels also occur. If a single linear fault plane had been included into the model as opposed to the segmented model geometry shown in Figure 7, these stress variabilities would not have migrated into the rock mass surrounding the fault in quite the same way. These minor, but fundamental changes to geometry and material characteristics clearly have major implications for the correct assessment of rock mass failure mechanisms and also for any determination of the amount of energy locked into a rock mass or along such a fault structure. While implementing faults into numerical stress models as planar surfaces rather than more realistic fabric complexes is current practice, research is needed to determine what parameters and geometric complexity is actually required in order to allow adequate assessment of potential fault-slip or other rockburst/seismic events. Back-analysis of real events hold the most promise potentially to be able to make some advances in this arena.

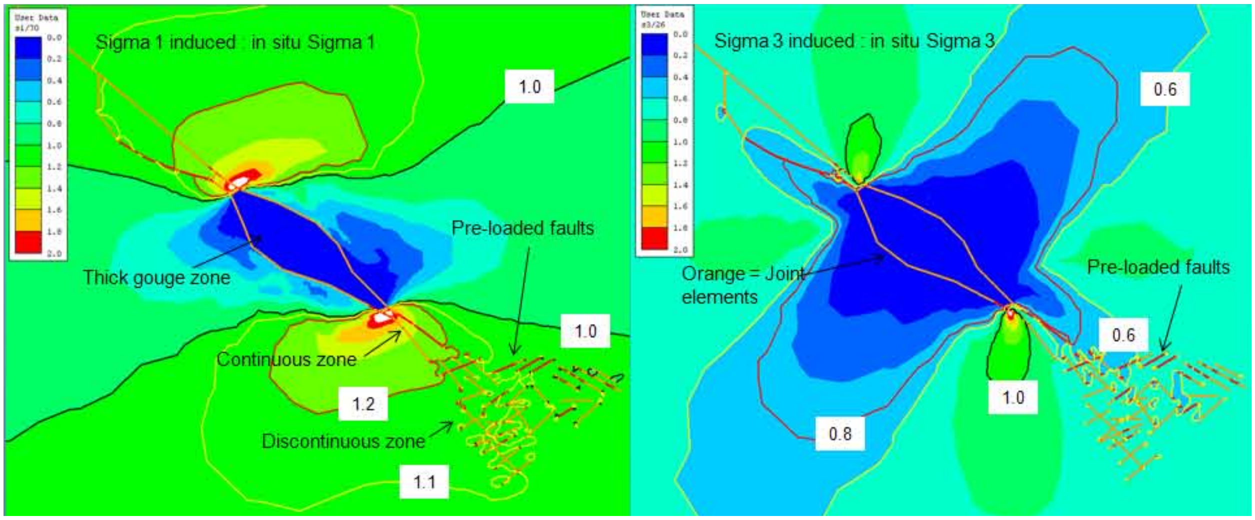


Figure 8: Major (left) and minor (right) principal stresses normalized to far field stress conditions. (Stresses in MPa)

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