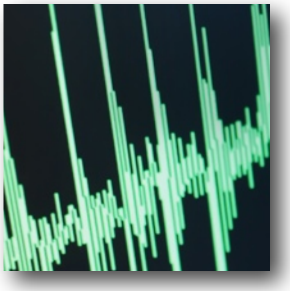
CEMI
Centre for Excellence
in Mining Innovation

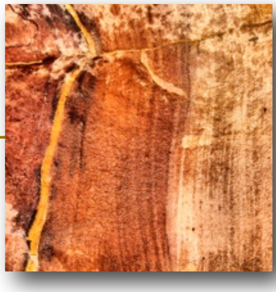
One of a series of workshops in support of the development of the International Fault Slip Control Research Initiative (IFSCRI)



Microseismicity

Geophysics

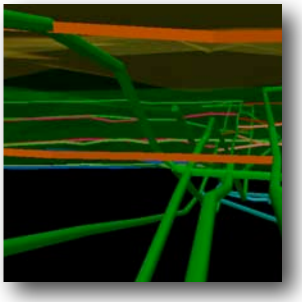
Summary of Feedback



Structural Geology

Structural/Engineering Geology Experimental Design Workshop

Toronto, Ontario, Canada
Ontario Investment and Trade Centre (OITC)
January 21, 2010



Modeling & Mine Design

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Introduction

Preamble

On Thursday, January 21, 2010, an Experimental Design Workshop in Structural/Engineering Geology 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 Damien Duff at dduff@miningexcellence.ca or Trevor Carter at trevor_carter@golder.com should you have additional information to add to this collection of feedback.

Workshop Contributors *Thank you to the following contributors:*

Rob Bewick
Golder Associates Ltd.
rob_bewick@golder.com

Scott Carlisle
SRK Consulting
scarlisle@srk.com

Trevor Carter
Golder Associates Ltd.
Trevor_Carter@golder.com

Luiz Castro
Golder Associates Ltd.
luiz_castro@golder.com

Sandy Cruden
University of Toronto
cruden@geology.utoronto.ca

Chris Davis
Vale Inco, Ontario Operations
Chris.Davis@valeinco.com

Mark Diederichs
Queen's University
mdiederi@geol.queensu.ca

Phil Dight
Australian Centre for Geomechanics (ACG)
pdight@acg.uwa.edu.au

Damien Duff
CEMI
dduff@miningexcellence.ca

Steve Falconer
Xstrata Nickel
sfalconer@xstratanickel.ca

John Fedorowich
ITASCA
Jfedorowich@itasca.ca

Doug Goldsack
CEMI Research Management Committee
degoldsack@hotmail.com

John Henning
Goldcorp
john.henning@goldcorp.com

Jonathan Hordo
Queen's University
jonathan.hordo@mine.queensu.ca

Peter Kaiser
CEMI
pkaiser@miningexcellence.ca

Richard Lisle
Cardiff University
Lisle@cardiff.ac.uk

Jim Martin
Queen's University
jim.martin@mine.queensu.ca

Steve McKinnon
Queen's University
sm@mine.queensu.ca

Bernd Milkereit
University of Toronto
bm@physics.utoronto.ca

Denis O'Donnell
Golder Associates Ltd.
denis_o'donnell@golder.com

Ray Price
Queen's University
price@geol.queensu.ca

Ulrich Riller
McMaster University
rilleru@mcmaster.ca

Brad Simser
Xstrata Nickel
bsimser@xstratanickel.ca

Roger Soliva
Université Montpellier
soliva@gm.univ-montp2.fr

Denis Thibodeau
Vale Inco
denis.thibodeau@valeinco.com

Benoit Valley
CEMI
bvalley@miningexcellence.ca

Gerrie van Aswegen
ISS International
gerrie@issi.co.za

Introduction, cont.

About the International Fault Slip Control Research 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:

- Rad-waste Storage Research
- Earthquake Engineering & Deep Tunneling (ITA working group)
- Computational Seismology
- Exploration & Reservoir Geophysics
    - Scientific Drilling: Sampling & Monitoring

The goal of participants at this IFSCRI workshop is:

To determine what role structural and engineering geology can play in optimizing the chances of CEMI's 5-year major global research initiative focused on Fault Slip.

Workshop Agenda

January 21st, 2010

Co-facilitators: Damien Duff (CEMI), Trevor Carter (Golder Associates Ltd.)

07h30 - 08h00 BREAKFAST (Provided)

Introduction

08h00 - 08h30 Workshop objectives | **P. Kaiser, D. Duff**
08h30 - 08h45 Background: High level summary of Microseismicity and Geophysics Workshops | **D. Duff**
08h45 - 09h00 The Importance of faulting and other structural/engineering geology data/information within mine design | **T. Carter**

09h00 - 10h00 **3D structural characterization of the pre-mining geological environment**

- *The importance of having an understanding of the regional and local tectonic history* | **P. Dight**
- *Assessing the likely structure of a pre-mining block in the absence of sufficient data/information*

10h00 - 10h15 COFFEE BREAK

10h15 - 11h30 **3D structural characterization of the pre-mining geological environment, cont.**

- *Making the proper observations and measurements* | **R. Lisle**
- *The tools currently in use by structural geologists*
- *Rock mass and fault property/behaviour classification; Identifying fault-slip-prone structures* | **R. Bewick**
- *Factors influencing fault behaviour* | **L. Castro**
- *Data interpretation and the importance of paleostress analysis* | **R. Lisle, U. Riller**

11h30 - 12h00 **Fault/fracture growth and propagation within an evolving stress regime induced by mining**

- *Understanding how cracks/fractures/faults are initiated and then propagate* | **S. McKinnon**

12h00 - 12h45 LUNCH (Provided)

12h45 - 13h45 **Fault/fracture growth and propagation within an evolving stress regime, cont.**

- *The connectivity of fault systems and the interactions which can occur* | **P. Kaiser**
- *Slip/rupture tendency analysis* | **B. Valley**
- *Re-activation of old structures* | **R. Soliva**
- *Creation of new structures* | **G. van Aswegen, R. Bewick's seminar**

13h45 - 14h15 **Integration of structural/engineering geology with geophysical imaging/ microseismicity, numerical modeling and mine engineering research** | **B.Milkereit**

14h15 - 15h00 **Structural/engineering geology applications in fault-slip control - R&D needs**

- *Where does the focus need to be?*
- *Who are the researchers we should approach?*
- *What are the potential show stoppers?*

15h00 - 15h15 COFFEE BREAK

15h15 - 15h45 **Next steps** | **T. Carter, D. Duff**

15h45 - 16h00 **Concluding remarks** | **P. Kaiser**

Key Points

Part I: 3D Structural Characterization of the pre-mining geological environment

1. **More rigour is needed at all stages of the geological/geotechnical data collection process** to ensure the right data, at the right level of quality, is obtained.

2. **Guidelines for the proper collection of structural geology data are needed.** This will enhance understanding and ensure codes are adhered to (e.g. 43-101-type reporting protocols, JORC Code (Australian Joint Ore Reserves Committee), SAMREC Code (South African Code for Reporting of Mineral Resources and Mineral Reserves).

3. **The value of structural geology data acquisition needs demonstrating to mine management**, and geologists perhaps need to be empowered to make more educated guesstimates of the likely structure of a pre-mining block. The issue of confidentiality is a constraint.

4. **A rock mass rating system should be developed for faults**- aimed at identifying the dangers of fault-slip.

5. **Understanding the tectonic evolution of an area** is important when trying to understand the likely impact on mine stability of new mining.

6. **There is a terminology disconnect between disciplines** regarding fault system environments-ductile vs. brittle etc. Fix this.

7. **Don't overuse paleostress analysis.** It must be used with caution and may be more of an indication of possible fault patterns in a pre-mining block than an indication of the likelihood of future fault instability. We need to better understand how it can be used effectively- perhaps through case histories and "calibration"?

Key Points

Part II: Fault/Fracture growth and propagation within an evolving stress regime induced by mining

1. **Greater attention is needed to microseismicity event analysis -** it may help to understand fracture initiation/growth more clearly.

2. **Repeatable microseismic behaviour patterns** underground perhaps represent an opportunity to identify new fracture/fault growth at an earlier stage.

3. **There are appropriate tools in existence right now**, but they are not user-friendly nor geared for use at mine sites. Perhaps they should be?

4. **Use of stress and tilt meters in boreholes** may have more merit than currently understood and may help to assess the character of individual discontinuities. Broadband accelerometers might help to solve some of the problems of fault connectivity/ interconnectivity not currently understood from normal microseismicity networks.

5. **Ortlepp-type new faults/shears are suspected as being more common in Canadian mines** than currently appreciated. We don't appear to be able to observe them directly, however many old sill bursts failures may be of this type (Macassa, Lakeshore System). Perhaps we need to conduct research to find them and then go looking for them?

6. **We should perhaps pay more attention to man-made stress-** such as evidenced by disking in some boreholes and other anomalous stress situations; getting a better handle on their distribution with respect to some of the problem faults and understanding the shapes of the stress anomalies and how they shift may be important.

9. **Exiting oil patch tools like Poly 3D, if combined with something like Fracman, Elfin or even Map3D**, could perhaps be more useful in a mining context.

Key Points

Part III: Integration of structural/engineering geology with geophysical imaging

1. **The technology is out there now** to allow exchange of our data/information

2. **The emerging common denominator for bringing the various fields together is "stress".** A good example (at the crustal scale) is the paper by Brenguier et al. (Science, 321, 1478-1481, 2008). In seismogenic zones, technology exists to tie displacements, seismicity and stress induced variations in physical rock properties together.

3. **24/7 monitoring** of boreholes is now possible

Detailed Feedback

Part I: 3D Structural Characterization of the pre-mining geological environment

These comments followed introductory slide presentations by Trevor Carter and by Phil Dight on the Importance of Structural Geology in Mine Design and the field of Tectogenesis, respectively. Comments follow the order in which they were presented.

1. Few mines have structural geologists on staff; this needs to be addressed (C. Davis).

2. Acquisition of structural geological data means acquiring it progressively- from the exploration stage and onwards. Protocols need to be developed to do this and cross-disciplinary communication is needed. No silver bullet possible, however- we haven't figured out how to predict slip for the San Andreas Fault even- despite all the work on it.
   a. We need to establish what tectonic fabric already exists in rock mass that hosts the ore body prior to mining. How and when did it develop? It's a 4D problem.
   b. Skeptical of paleostress analysis- isn't analysis of PS, is the orientation of PS field. Sometimes very informative but can lead astray. Our program going forward needs to consider this and accommodate this basic premise (R. Price).
   c. We maybe can do better than the earthquake seismologists since in mining have the opportunity to get underground and see our fault slip problems in real scale before and after they happen (T. Carter).
   d. JORC code logic/disciplines needs to be translated into a geomechanics setting. We are thinking about that and planning a guidelines document (P. Kaiser).
   e. CEMI is pushing the development of manuals in many areas.

3. There's a cultural problem in mines with more emphasis being put on ore body delineation aspects than on anything else- in part due to cutbacks. We're focused on tons and grade (B. Simser)
   a. Agreed (D. Duff). No value is placed in mines (by mine management) on the kind of benefit this work can have, and thus it is not encouraged. Over time, our geologists lose these skills through lack of use.

4. This is also a problem at the exploration stage (T. Carter).

a. Structural models should start getting built at this time and modified as mining advances.

5. Cultural change has happened on the metallurgical side (geometallurgy) and so it can happen in respect of collecting appropriate rock mass and structural data as well. (C. Davis)
   a. But people don't know what to collect

   SEE ALSO POST WORKSHOP SUBMITTED COMMENTS by Steve Falconer pp 25-26

6. The biggest reason why insufficient attention is paid to collecting enough rock mass and structural geology data in mines is because we have adopted mostly bulk mining methods rather than selective ones in our mines. The latter used to require the detailed collection of such data; the former, because people don't go into the stopes anymore, doesn't (M. Diederichs)

7. We need to prioritize what structural geology information we need to make better estimates/predictions/classifications etc for the fault-slip problem and demonstrate its value to mine management (S. McKinnon).
   a. Jim Martin at QU (project underway for CEMI) is going to show through a piece of work he is currently doing for CEMI the economic value of this sort of thing.

Detailed Feedback, cont.

Part I: 3D Structural Characterization of the pre-mining geological environment

8. The data is often there but no connections or improper connections are made (comment made in respect of the use of Tectogenesis) (P. Dight)
    a. Rarely use what data was collected early by explorationist or geophysicists
        i. We don't make use of it but it's available
    b. Stress at the time of the mineralizing event is important to understand
        i. Fault slip prone structures tend to be the larger ones but may be embryonic (i.e. just en-echelon tension gashes - not a real fault) (T. Carter)
        ii. We can therefore target what size structures we're looking at because a specific size of structure leads to a specific event.
    c. Although we see the same sort of thing at a microscopic scale as well.
        i. Tectogenesis works in brittle systems- not sure about ductile systems.
        ii. The concept comes out of Poland- work of Cloos in the 1920's

9. Need to be careful about drawing broad conclusions based upon limited data, however (R. Lisle)
    a. Need to use some self-similarity assumption perhaps, but is only an approximation, especially where more than one structural event has occurred (as is often the case)
    b. Stereonet approaches can be a bit simplistic (and thus perhaps misleading)
    c. The measurement of paleostress is not a trivial exercise and one needs to be careful how the results are used/interpreted.

10. This can be counter-balanced by linking the structural analysis with all other data- such as geophysics but we haven't trained our people sufficiently well generally. Can't be done with stereonets alone- agreed (P. Dight)

11. Embryonic structure is a problem in mines. One notices it especially when mining starts. Am skeptical also about paleostress analysis insofar as it can be used for direct back-calculation of stress state - see it as a means to gain insight on what has happened in the past (T. Carter)

12. Current stress field is being used in tectogenesis and can be measured from oriented boreholes (P. Dight)

13. Structures measured in this way have nothing to do with the current stress field (M. Diederichs)

14. What mechanical conditions can predict density of structures? (R. Soliva)
    a. Rheology of rock is important

15. Mineralized systems often have a repeatable shape. The big dilation zones are where we get correlation with rock bursting (e.g. Hemlo) and this often also correlates well with the occurrence of re-healed structures (P. Dight)
    a. Embryonic structures have been re-healed sometimes and this often allows building up of strain energy.
    b. Recognizing re-healed structures should work in recognition of new ones.

Detailed Feedback, cont.

Part I: 3D Structural Characterization of the pre-mining geological environment

16. Utilize available geological and geophysical datasets in a commonsense way (R. Price)
    a. Screen for geological structures consistent with the current understanding of tectonic evolution of the area of interest and analyze the probability of those structures in the block to be mined. Uncertainty gets reduced as data quality and quantity is improved and as one gets down to smaller scale.
    b. We need to adopt a probabilistic approach to data acquisition when trying to forecast seismic/microseismic events. Relationships are often deduced from adjacent blocks. People need to be trained to acquire and use the data in this way.

17. Linking structural data to behaviour is important. (S. McKinnon)
    a. With fault-slip, we're trying to understand discrete behaviour and, in this case one could use a statistical approach
        i. Numerical methods can help to look at potential mechanisms- links to Tectogenesis.

18. Probabilistic analysis should be conducted in conjunction with mechanical testing (R. Soliva)

19. We need to accept the fact that mines regularly creep (structures move) for a number of reasons- blasting, near excavations etc (D. O'Donnell)
    a. Fault-slip develops when the creep is being impeded by e.g. by a stiff dyke in area; or as block loads up and stress works on it and embryonic faults get created.
    b. Regarding getting proper data- 43-101-type discipline is needed when drilling for structural information. Is extraction at risk or is infrastructure at risk- particularly in abutments to ore zones. Proper acquisition of data needs to be forced to alleviate investor risk.
        i. There's no anticipated adverse ground conditions where there is no drilling!

20. It's important to identify "structure" and not just faults (D. Thibodeau); Consider fabric - not just structure - a holistic approach is needed in order to understand the domain in which mine is located (T. Carter)

21. Isn't a good structural analysis done at surface before a minesite is developed? (U. Riller). Often not, unfortunately - or not reported for confidentiality reasons (P.Dight, T. Carter). Good structural analysis should commence early (U. Riller)

22. A screening process should be defined in a risk assessment process perhaps-which mines need more data at what level of detail? Because a "cookbook" approach to measuring appropriate structural elements at all mines may not be relevant in all cases (L. Castro)
    a. What kind of fault-slip are we talking about? In an open pit where a fault slides or those high energy ones that create problems in deep mines?
    b. In Sudbury- not a problem near surface but below certain depth we have problems. So data/information needed changes- the needs progress over time

23. How do we address the fact that mine design often happens with insufficient data being available (P. Kaiser)
    a. Early identification of possible "kinematic/structural domain models" is necessary. Where are the R&D gaps to permit this?
    b. Cartoons depicting possible structural scenarios for a pre-mining block may be enough to ensure sufficient flexibility is built into the mine design? Can be modified as more data comes in.
    c. Would be good to know which structures may be the critical ones and how does our understanding improve as more data is collected?

Detailed Feedback, cont.

Part I: 3D Structural Characterization of the pre-mining geological environment

24. Mine (or project) geologists need to be empowered to do this kind of analysis and make inferred decisions, without fear of being shot down and criticized for being too "certain without sufficient data". A probabilistic approach may be helpful (S. Carlisle).
    a. Leads to no "scenarioizing" on their part because of the fear of being wrong.

25. Some of this structural fabric/understanding information is collected and interpreted during exploration but kept under "lock and key" as it has ore zone economic significance (T. Carter).

26. We are already capable of doing this but we often don't do it (C. Davis)
    a. Can we get more from televiewer surveys etc?

27. There are obvious data gaps that need filling- such as stress and stress rotation (B. Milkereit)
    a. But how can we measure stress in real time now! We need this! It's the parameter we need and want to monitor. Who is doing it right now? North Parkes possibly? (T.Carter)

28. All of these measurements are necessary and worthwhile but we need to define what we mean by fault-slip? (M. Diederichs). There are different types.
    a. In Peter's Beaconsfield map we see a Riedel system. Riedel systems have 4 structures. One is always guaranteed to behave the same way as you mine it- these are discrete structures. Others always cut across the geology at the same angle- these are the probabilistic ones (these will be re-activated when you mine past them) (see Diagram A) (M. Diederichs).

       There are also are other regional structures, and their exact location is what matters. These are the ones for which surface mapping etc is critical. The point is that different systems need to be approached differently (see Diagram B) (M. Diederichs).

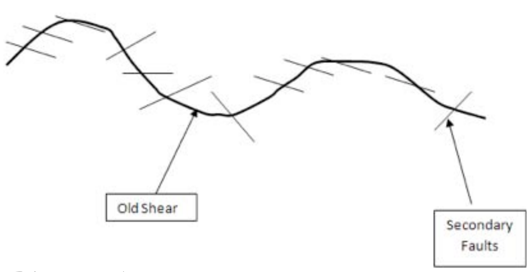


Diagram A
Associative Faults: (parallel to ore) or at a consistent < to ore:
- Paleotectonic?
- Neotectonic?

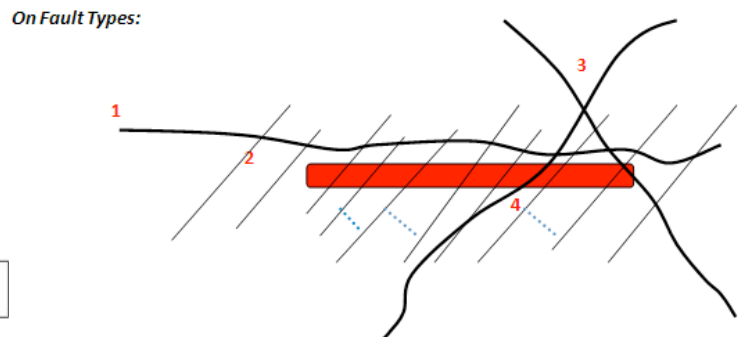


Diagram B

1. Parallel Faults
2. Ubiquitous Faults
3. Discrete X- Faults
4. New Faults

    b. The world needs to be broken into these types of domains (fault slip problem) and see which approach fits:
       On Fault Domains
       - Spatial/ Orientation/Frequency/Persistence
       - Genetic/temporal
       - Constitutive parameters:

Detailed Feedback, cont.

Part I: 3D Structural Characterization of the pre-mining geological environment

28. cont.

    1. Healed
    2. Slickensides
    3. Ductile
    4. Dilative
    5. Cataclastic

    Undulating Fault surfaces:

    - Centimetre-scale
    - Metre-scale
    - Mine scale (M. Diederichs)

    c. In this context maybe location is not critical but structure type is? Mechanistically these things may behave differently. Individual features really matter.

    On Science vs. Engineering Terminology

    More is required…[there's lots of confusion and abuse of the following terms]:

    - Fault
    - Shear
    - Slip
    - Shear zone

    (Fault, Shear, Slip, Shear zone: Scale?)

    - Slickensides
    - Gouge
    - Brittle
    - Ductile

    (Gouge, Brittle, Ductile: Paleo, Now?)

    - Mylonite- was ductile, now brittle
    - Activation/re-activation (M.Diederichs)

    d. These are all things that many geologists measured 50 years ago but in recent years, we seem to have forgotten how to map and interpret (T. Carter).

29. Location is very important and we can't just look at the ore zone itself- we need to look outside the ore zone- within the host geological environment as well (D. Thibodeau).
    a. This would be where the exploration data gets thrown in and considered as well.

30. The risk is important not the probability (R. Price).

COFFEE

What tools are available and in use by structural geologists which we can potentially use?

31. Before the advent of computers in our workplaces, we used to measure the right kinds of things at one time- including structures/fabrics etc. Some of the 1930's to 1960's geological drawings one sees at the old mines in exploration head offices are works of art and reflect a more complete 3D understanding that the geologists had at the time (T. Carter)

Detailed Feedback, cont.

Part I: 3D Structural Characterization of the pre-mining geological environment

32. The quality of data collection is poor now by comparison with previously since we are mostly collecting data onto pen notebooks/tablets with drop-down lists etc, limited graphical capabilities etc (C. Davis)
    a. Not conducive to producing the kind of quality mapping that was common at one time.

33. We used to be forced, through the process of manually making sections and plans, to think about structure etc. We were forced to think in 3D. Computers don't permit us to do that quite so easily (J. Fedorowich).

34. These older approaches are still very much in use in China now and the quality of their structural data is way above ours (P. Dight)

35. We need to use the new systems in a manner that replicates the [collection/use of] important structural detail as in the past (G.van Aswegen).

R. Lisle's Presentation – making the proper observations and measurements

36. What is the data which is ideally needed to collect in order to help with the problem of Fault Slip- that is, aimed at identifying the dangers of fault movement? Perhaps a sort of rock mass rating scheme needs to be developed? Lots of things are considered and points are awarded to generate an overall figure for the risk. Geologists don't like to stick their necks out and to perhaps be wrong (R. Lisle)
    a. Could be aimed toward fault-slip specifically and to providing quantitative measurements to engineering design people.
    b. A list of things to look for could be part of it such as:
        1. Fault characteristics- continuity/geometry/linkages among faults etc. Irregularities on surface are potential source of stress build-up which can provoke slip… and can be diagnostic as a fault slip indicator.
        2. Orientations of faults- many are non-planar and thus multiple orientations are possible. As well as of any linear kinematic indicators on them.
        3. A description of the fault rocks themselves and of their properties
        4. The fault dimensions/size (because faults start small and grow progressively)
        5. Past tectonic history- lots of past displacement and its sense are not a direct measure of future risk but useful to know about.
        6. The age relationships among faults/structures

37. There is nothing like this out there now, and certainly nothing being applied routinely at the mines with direct application to fault-slip problems at the moment (T. Carter)

38. At what scale is it important to apply this in a mining environment? (L. Castro).
    a. Don't know but is important that we understand scale (R. Lisle)

39. Scale is definitely important –e.g. undulations on a fault surface (G. van Aswegen, P. Dight))

40. Not sure that scale of undulations is critical (R. Lisle)

41. Scale is very important since corrugations on a fault surface have an influence on the strength of that surface, but if very small, can ignore (R. Soliva).

Detailed Feedback, cont.

Part I: 3D Structural Characterization of the pre-mining geological environment

42. We also need to be thinking in terms of a high confinement environment (M. Diederichs)

R. Bewick's Presentation - outlining the importance of a combination of properties along faults

43. We may not even know what our problem is. This makes it hard to pick the right approach to investigate it right now (R. Bewick)

44. Why aren't we doing this kind of work? (D. Duff)

45. It takes a lot of time and money and maybe we don't know what we're doing yet? (R. Bewick)

46. We need to re-gain the level of knowledge about faults (and their properties) which we used to have many years ago to have a better sense of how our mines behave (D. O'Donnell)

47. How can we expedite the process of re-building this knowledge? (L. Castro)
    a. Perhaps Garson mine could be used as a test case- a blind test? (P. Dight)

48. Garson was a scale and a confinement question (P. Kaiser)
    a. Unique problem in deep mines- how are faults going to behave as we go deeper because ones that failed above may not fail at depth?
        i. What happens higher up in a mine doesn't necessarily imply the same below
        ii. There is value in having a location to look at differing behaviours of faults (perhaps already well characterized) as we move into high confinement zones (to greater depth).
        iii. We don't know how to characterize the ground for that behaviour.

49. Do we have the tools/techniques we need to do this? It appears so, perhaps we've forgotten a few as we moved into the computer age (T. Carter); it's also a question of available resources at mines. This sort of thing has to demonstrably add value for mines (D. Thibodeau)

SEE ALSO:
POST-WORKSHOP SUBMITTED COMMENTS by Steve Falconer on page 27, John Henning on page 33

L. Castro's Presentation

50. The key research needed into fault system behaviour is on;
    a. System characteristics?
    b. Appropriate scale, system geometry?
    c. Should we be looking at some other parameter than energy release? ER is good but tells fact after burst has occurred. Something prior to this which could help forecast bursting?

51. How do you assess the locked-in energy in a fault that's going to daylight? (R. Bewick)

52. Knowing the characteristics of the fault surface is critical (R. Soliva)

53. Disagree- energy release has less to do with properties of fault at that location. Behaviour has more to do with what's going on around them (M. Diederichs)
    a. The overall geometric system

54. ...and the failure mode of the rock (D. O' Donnell) as well as a more holistic understanding of fabric (T. Carter)

55. But stiffness is mining geometry dependent and varies with time (S. McKinnon)
    a. The loading path is therefore varying and it becomes difficult to measure failure potential. Burst potential therefore varies with time.

56. We normally take a snap shot but it's the stiffness of the loading system that determines the violence of failure (G. van Aswegen)

57. The stress path is difficult to estimate when a series of faults is being affected by incremental stoping in the area (M. Diederichs)

58. This is to be the subject of the next workshop- the stress map, the geometry, the mining, how these influence structures etc (P. Kaiser)

59. This workshop maybe can be thought of as being more directed to getting basic understanding and then also about collecting the right data so we can go to the next step (T. Carter)

60. A key question (we know unclamping and stress rotation occurs during mining but nevertheless we still need to mine) but how can we select the best mining strategy and proper ground support (L. Castro) to deal with this?
    a. There is merit in trying to learn more about the deformation of a damage zone where a fault can then shear through as stress changes. (like with rock mass damage initiation).
    b. How do we create tensile fractures in a confining environment?

61. At seminar yesterday- reference to an example where a fault failed (without being predicted) where no mining occurred (P. Kaiser).
    a. Is preconditioning of a fault- damage initiation, that is- something that may happen early on and be an early indication of structures that later may become critical and lead to failure. "Burst-prone structures".

SEE ALSO POST WORKSHOP SUBMITTED COMMENTS by Luiz Castro on page 31-32

Further Paleostress ("PS") Discussions

62. Words of warning again about the limitations of PS analysis and its use in relation to fault-slip analysis (R. Lisle)
    a. Paleostress produces discontinuities for us which could be influential during mining but we have to bear in mind that deformation conditions originally are very different from environment in mines at present. So, prior instability is not a guarantee of further instability. We need to be careful in making assumption that a fault zone is a weakness we need to be concerned about.

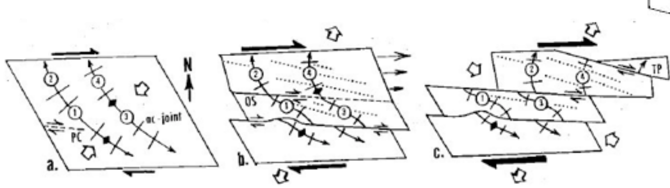
Detailed Feedback, cont.

Part I: 3D Structural Characterization of the pre-mining geological environment

62. cont.
    b. The PS link is indirect therefore but the PS techniques may be getting applied in the wrong place. Can't use in ductile environments. Need to be very strict about where used and, furthermore, any meaningful assessment of stresses will be difficult.

63. Is it not a good approximation? (B. Simser)
    a. Perhaps a good starting point but it can be misleading and will likely change as more data is collected (R. Lisle)

64. Paleostress Analysis can be safely used to indirectly establish/predict patterns of fault/fracture distribution as well as relationships between faults/patters etc. This is what's important (J. Fedorowich)
    a. It's a statistical method to describe relationships among faults?
    b. Agreed, can be used as a better predictor of particular structures and a summarizer of relationships (R. Lisle, G. van Aswegen)
    c. Can also use in mines for back analysis purposes- that is, an awareness of the paleostress conditions at the time of formation of structures can be used as a back analysis-type guide so as to avoid duplicating them during mining? As a risk mitigation technique (D. Thibodeau).
    d. NO! results of paleostress analysis may be miss-interpreted (R. Lisle)
    e. Technique has been around for years and like any good technique can be misused, some good mining examples exist (see Venkatakrishnan and Bennett,1988) (T.Carter)



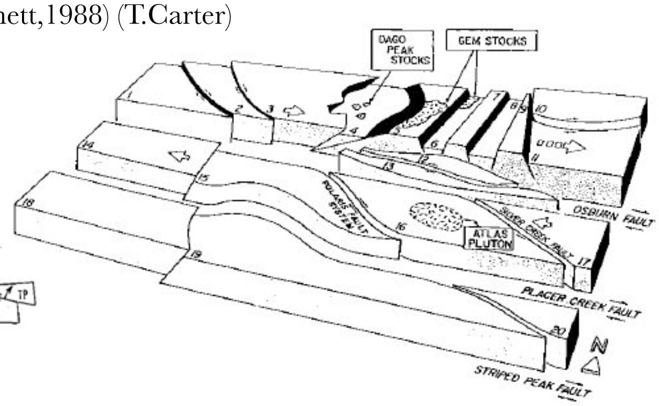


FIG. 4. Block diagram showing the 20 structural blocks and associated fault movements in the district that were used to construct Figure 3.

65. Agreed, we have to be very careful since many fault structures have been rotated through the process of deformation (M. Diedereichs)
    a. We need to tighten up on our use of terminology also.
    b. There's a disconnect between geology and engineering and what's ductile to one may be brittle to another. Mylonites, for example, can be the most brittle structures in mines.
    c. Fixing this terminology issue needs to be a primary objective for this project

66. Paleostress analysis results are very useful for constraining oilfield and mining numerical models with paleostress estimates (R. Soliva)

67. Understanding how faults form will guide in assessment of slip potential in a mine. Paleostress measurements are useful to have in hand as faults are mapped, to assess tendency to form and slip (R. Price)

Detailed Feedback, cont.

Part I: 3D Structural Characterization of the pre-mining geological environment

68. We get hung up on precise #'s. Ranges in paleostress measurements are important nonetheless since we want to stay away from paleostress conditions that create faults. Calibrate to what have seen in the past (D. O'Donnell)

69. Perhaps can be better calibrated if we start back-analyzing known mine failure examples? (T. Carter)

70. The dangers/cautions associated with placing too much emphasis on paleostress measurements is evident from the discussion – THERE IS A RESEARCH GAP HERE- HOW TO PROPERLY USE PALEOSTRESS measurements- CASE HISTORIES? but a topic worth researching nonetheless is how to extract the right indicator of fault kinematics in [and around] an ore body and then assign a value to that for mine design purposes (P. Kaiser)

71. Even if all assumptions are adhered to - what do mining people do once all this stress information is collected, how does PS analysis help assess risk on a fault? (R. Lisle)

72. Gives a sense of the pattern/predictability of faults- frequency etc; (G. van Aswegen)

73. It can tell us how much energy is in the system. Relates back to stiffness of system over mine-life (S. Carlisle)
    a. No, the energy is long gone- faults have sufficiently relaxed (G. van Aswegen)

74. Paleostress analysis is a model to hang observations on and a way of guiding thoughts but there's a risk. DON'T OVERUSE PALEOSTRESS ANALYSIS MEASUREMENTS (R. Lisle)

75. Use it for fault/fracture pattern prediction. A staged process is necessary. (T. Carter)

76. Paleostress analysis may be more useful in mining than it's given credit for because it's likely that some faults are deforming in the current stress field- e.g. Sudbury (where there are also other faults formed in different stress regimes) and these may be the most critical faults/fractures anyway since work shows these are maybe most sensitive to being disturbed by mining activity. They're accommodating the large scale regional deformation (S. McKinnon)
    a. Paleostress inversions may be useful in identifying which of the many fault systems are more important than others. But only one piece of useful info; if viewed with caution?

77. Aren't we just talking about slip tendency? (R. Lisle)

78. Is an indicator of the stability in the current stress field, because prior to mining, the old thinking was to put in the structures, with no attention to stress field variations paid, so therefore with no good idea of stability for different families of faults- the truly ancient ones or the modern ones. Sensitivity to mining therefore wasn't considered. (S. McKinnon)

SEE ALSO POST WORKSHOP SUBMITTED COMMENTS by Brad Simser on page 33

LUNCH

Detailed Feedback

Part II: Fault/Fracture growth and propagation within an evolving stress regime induced by mining

S McKinnon Presentation - Fault/fractures

a. There's a yield zone around excavations and a zone of damage further out- a continuum.
b. There's a poor understanding of this and thus of fracture formation and growth. Fractures are forming in shear and extension. They are hard to link to a physical entity (event) in the mine.
c. There's a lack of detailed microseismic event analysis
   i. Many may be occurring on structures but sometimes they don't appear to. Would help in understanding fracture growth. A reason may be that faults are often projected- they're complex.
   ii. When something triggers a stress re-adjustment (blast), there's a well defined decay process. Important thing is the P value. Main event has a value of about one- similar in large earthquakes. There is repeatable behaviour - even underground; we can learn to recognize patterns therefore. Hope to relate this to different environments/rock types etc. P value is a proxy that something is going to happen or has happened?

79. Observations and analysis of microseismicity data suggests that there is time-dependent behaviour but also spatially-dependent behaviour (S. McKinnon)
    a. How does mining affect future fracturing and growth?
    b. We're missing: what is happening with events – can use existing tools to extract more info from process. Use different types of analysis to do stress inversions. Problem is tools are of research grade- are not commonly available and tricky to use and with no emphasis on what is required in mining environment?

80. But only some rocks "talk"- others don't. Microseismicity monitoring is very lithology dependent. Doesn't mean they don't deform (B. Simser)

81. How do we determine fracture/fault initiation/growth-prone ground? (D. Duff)

82. Answer is in reaction one get when samples are tested. Can define how different rock types fail- violently or softly. If can do in core maybe can outline areas in mine that will deform violently or creep. Back analysis can constrain this (D. O'Donnell)

83. Consider the criteria of failure- the rheology of the fractured media. Porosity issues, the stress state of the rock; energy density (Roger Soliva)

84. No bursts occur in massive sulphides whereas the norite in Sudbury is stiffer, more rigid and brittle and tus strain and pillar busting do occur. Anistropy dictates behaviour (Denis O' Donnell

85. Rheology of fracture pattern and modulus of media is important to constrain (R. Soliva)

86. For clarification, strain burst properties are not applicable in the case of understanding how prone the rock mass is to fault slip rock bursting. A FS event has to do with geometry and other characteristics, not just the host rock (L. Castro)

87. But it's how damage manifests itself in relationship to the excavation vulnerability. So it's not necessarily just because one is in a specific rock type (B.Simser)

Detailed Feedback, cont.

Part II: Fault/Fracture growth and propagation within an evolving stress regime induced by mining

88. The largest variable in mines is the stress concentration around excavation openings (U. Riller)
    a. Look for stress anisotropies and then what stress concentrations are present

89. Need to be very careful where stress measurements are taken (R. Soliva)

90. Put stress and tilt meters into boreholes and assess the character of individual discontinuities (B. Milkereit)
    a. We don't do this now, but should.

R. Soliva Presentation- Fault reactivation

91. The Poly-3D Tool was developed by Dave Pollard and can be used to simulate stresses around faults (R. Soliva)
    a. Fault systems in 3D need to be constrained precisely
    b. Can also model friction load along fault surfaces
    c. The data from 70 boreholes were used in a model of a rad. waste site in Finland and 1300 models were run for 3 key variables, as well as others
    d. There was a 20 minute calculation time and an estimation of what conditions caused slipping and which ones didn't was returned.
    e. Can deal with simultaneous movement on more than one fault.
    f. The displacement is quasi-static and sensitivity analyses were performed.

92. Why aren't we using Poly 3D in our mines?(D. Duff)

93. If tool could be calibrated to a case maybe we could move forward (D. O' Donnell)

94. Because we need to understand faults really well in 3D, and don't, perhaps we should pull the codes from 3D Poly and Fracman (DFN tool) together with Elfin in a discrete model domain or Map3D if we want to stay with BEM solutions (T. Carter)

95. Likes approach but 2 comments: (S. Cruden)
    a. The Poly 3D model may not adequately account for uncertainty associated with cohesion and friction values as well as scale dependencies.
    b. Nor does it capture the likely presence of a network of joints and fractures between faults

SEE ALSO POST WORKSHOP SUBMITTED COMMENTS by Benoit Valley on page 32, Mark Diederichs on page 33

B. Valley Presentation - Slip Tendency Analysis (STA)

96. Putting focus on limitations of the method and what are the needed pieces of research.
    a. STA quite simply measures the ratio between shear and normal stress on a fault surface. The higher the ratio, the greater the slip tendency. Can be confirmed and tested by looking at observed seismicity on faults (or on embryonic, non-connected fault zone places (e.g. Garson) (T.Carter).
    b. Capturing the complexity of pre-mining stress is critical (B. Valley).
    c. May also be important to look at strength anisotropy on fault planes as RL suggested yesterday?
    d. A limitation is the assumption of a homogeneous stress field

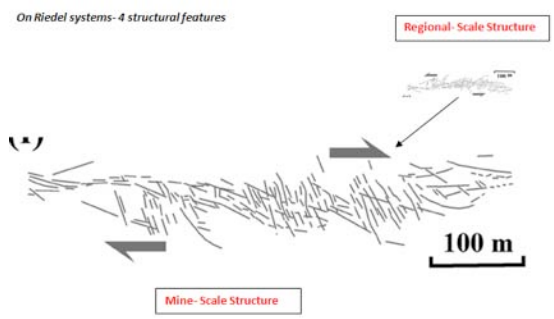
Detailed Feedback, cont.

Part II: Fault/Fracture growth and propagation within an evolving stress regime induced by mining

97. We need to understand the scale of structure we're dealing with and where our mine fits within this (M. Diederichs)- Comments made while looking at fault system slide taken from Kim, 2004 (see Diagram C below).

Diagram C.

- What is fault-slip?
- What scale is important?
- Matching focal planes?



   a. This underscores the challenge of what we're really trying to do. Can get more than one answer from fault plane solutions for example performed on a system of this kind.
   b. How do we assess movement and fault slip? What do we mean by fault slip? Is it the small little elements or something which is more a "system" in complexity and size?
   c. Making mental leap from drift scale to something larger in scale is difficult. There are about 4 scales of structure in the slide. Kim's fault system is not a mess though since the type of system is commonly observed in many different places.

98. Are we chasing our tails since we don't know at what scale we're operating? (D. Duff)
   a. Not necessarily. Can do some statistical analysis at the early mining stage. Gets much more challenging as mine grows and interactions occur. But also have additional data at this point. Probably can solve this general system as a generic system since this system repeats itself. (M. Diederichs)
   b. There are individual subsets within the system which might behave in their own way (perhaps predictably (R. Lisle, S. McKinnon)
   c. Brings us back to need to understand whole fabric, not just individual fault structures (T. Carter).

G. van Aswegen Presentation - New faults creation as we mine

99. We need to know the details of the stress/stiffness model and the conditions in which Ortlepp shears form (G. van Aswegen)

100. We don't know if they form instantaneously or over some longer time. Needs research. Precursor activity has not been clearly observed but there is a suggestion that some ground prep. for the Ortlepp shears happens. So what monitoring resolution is needed and how can we integrate it into our microseismic systems?

101. How much of a problem for us are new faults? (D. Duff)
   a. 2.5Mn events on these sometimes. Tend not to be a problem when mining properly. These things happen in extreme cases.

Detailed Feedback, cont.

Part II: Fault/Fracture growth and propagation within an evolving stress regime induced by mining

102. They may not be common in Canadian mines because our mine layouts tend to be more spread out (B. Simser)

103. Why don't we see these more often in our mines? (Garson being the possible exception) (D. Duff)

104. There's a fair degree of miss-interpretation going on. Far out ruptures (from infrastructure) are produced by Ortlepp shear-like mechanisms (P. Kaiser) Controlling these rupture mechanisms is important.

105. South Africans have made a great contribution to understanding man-made faults. They have good case histories. It's up to us to adapt this to our settings (L. Castro)

106. Are new faults a propagation of an earlier structure; one that existed higher up perhaps?(R. Lisle)

107. Perhaps we should go looking for these things in our mines and broad research should be done? (G. van Aswegen)

108. Faults, because of how they form, don't always connect. Today, we're characterizing faults on their own and that goes into a model of some kind. But we shouldn't just characterize those faults which we think may burst. We may think we have a "new fault" problem but, in reality, the fault is there because of some kind of pre-existing structure(s). In South Africa, the 3km mine above represents a slot (M. Diederichs).

109. Convinced Ortlepp shears exist here- it's just we haven't labelled them as such yet. Some old sill bursts could be on them - Macassa, Lakeshore, and Sigma come to mind (T. Carter)

110. Obliquely loaded sills can form them (M. Diederichs)

111. At Creighton, some of the 3.9Mn events are where we have incompatibility to structures which exist. Has to be new rock mass fracturing which happens (P. Kaiser)
    a. Ortlepp-type fracture mechanisms are an indication of stress change and of the degrading rock mass conditions that can ensue. Are extremely difficult to anticipate. But what is happening in SA now, is starting to happen in our mines. If we can understand the controlling mechanism- stiffness, loading etc, we can start to understand how to control the energy release. Can't only concentrate on existing structures therefore.

112. The mine operator's "generic perspective" is a little biased when investigating bursts because it's assumed the burst has occurred on an existing structure (S. Carlisle)

113. Why don't we see them though? (D. Duff)

114. They happen in the rock mass we don't actually mine in (D. Thibodeau). It's more of an embryonic fault issue perhaps.

SEE ALSO POST WORKSHOP SUBMITTED COMMENTS by Steve Falconer on pp 27-28

Detailed Feedback, cont.

Part II: Fault/Fracture growth and propagation within an evolving stress regime induced by mining

P. Kaiser Presentation- Fault connectivity/interactivity

115. We try to use seismic data to see what's happening.
    a. Intersecting fractures create several degrees of freedom
    b. Looking at microseismicity clusters- the potentially active planes creating the events were determined
    c. Many are on existing structures but others are in degrading rock mass.
    d. They are related to the big stress field we generate around where we're mining. Weaknesses in the rock mass are being mobilized. Underscores why we think that many of the new failures we create pose the most risk for mining.
    e. At Creighton Deep some seismic activity is up to 800m away from where stoping is going on and not related to structures which we know. Has to be connected through geological structures, however. Have to have major structures interconnected and intersecting. This is where we should place our international test site. So we have seismic activity where there's no stress change. Need to be able to explain this. Discontinuum models don't work because we don't know where the discontinuities are and continuum models don't work either.
    f. Since we are activating geological structures therefore we'd like to know where the next burst is going to occur.
    g. This is another issue within the project;. how to use seismic info connected to structural geological information and determine how the greater mine could be affected. Which weakness planes will be activating and how will we control them? Get better in predicting the potential fault/fracture network. If we have a vision of what kind of structural architecture exists we should be able to model energy release and improve the flexibility of our mine design accordingly.

116. In trying to understand the potential energy release on faults, should we not have an understanding of the stored energy on these faults in advance? How can we estimate that? (D. Duff)

117. Is a two-fold thing. Next workshop will deal with stiffnesses, etc-is the spring stiff or is it soft, for example? The other element is that a lot of energy is being consumed in structures as they fail but we don't have the ability to determine which of the existing ones are more at risk. There's even more difficulty in knowing this for those faults we create. (P. Kaiser)

118. We should perhaps pay more attention to man-made stress- such as evidenced by disking in some boreholes and other anomalous stress situations. Getting a better handle on their distribution with respect to some of the problem faults and understanding the shapes of the anomalies and how they shift may be important to do (J. Fedorowich)

119. In a block we would be instrumenting, for example as part of our international test site approach,, it's easier to measure stress changes in conjunction with some geophysical techniques. Televiewers etc produce a lot of information on what structures are being activated and the implications for stress change etc. Indirect measurements may be necessary because drilling more holes may not be an option. (P. Kaiser)

Detailed Feedback, cont.

Part II: Fault/Fracture growth and propagation within an evolving stress regime induced by mining

119. cont.
    a. A systematic experiment- such as we want to design- will involve the seismicity technology developers, the geophysical tools guys to measure rock mass changes and damage accumulation, structural geologists- from whom can we learn how a structure goes from pre- peak to post-peak. The project design needs to address all these things so that mine engineers can mine into these blocks without the same risk we have today.

120. Dynamic as well as static friction shear needs to be addressed in models (R. Soliva)

121. We need to determine what the "things" associated with seismic events are (S. Cruden)
    a. What are the criteria for distinguishing new from old faults?
    b. THERE ARE OBSERVATIONAL GUIDELINES NEEDED

The following discussion is commenting on time links AVI of PKK where 2 widely spaced locations appear correlated in time links even though they are very far apart

122. What is the need for a physical connection between where stoping is occurring and an event is perpetrated?
    a. A temporal link for sure is needed but is a physical one? (U. Riller). A shockwave doesn't need a structure to pass along.

123. No actual physical connection between the two is needed (M. Diederichs)

124. Depends on where they are with respect to geology, openings and structure, and whether there's a slight dynamic change in stress at that new location due to intersection of all of these (T. Carter)

125. Something happening at two separate and distinct locations can be affected by something happening at a third location simultaneously without the first two being physically connected (G. van Aswegen)

126. Is the event correlation a one-time thing or does it occur repeatedly (R. Price)
    a. If it only happens once- is perhaps a coincidence- more than that is different.
    b. It's reproducible (P. Kaiser)

127. Broadband accelerometers can be used to solve this problem of connectivity, not microseismicity network. (B. Milkereit)
    a. There may just be a pathway needed for a stress wave to pass but no physical connection is necessary.
    b. The hypothesis can be tested by just changing the sensors in the ground.

128. The shockwave has got to be the triggering mechanism. (D. O'Donnell)
    a. Further, intersecting fault planes can fail. Intact rock between structures has to accommodate this.

COFFEE

Detailed Feedback

Part III: Integration of structural/engineering geology with geophysical imaging

B. Milkereit Presentation

129. The emerging common denominator for bringing the various fields together is "stress". A good example (at the crustal scale) is the paper by Brenguier et al. (Science, 321, 1478-1481, 2008).

In seismogenic zones, technology exists to tie displacements, seismicity and stress induced variations in physical rock properties together.

130. In the deep mine environment, boreholes can be used for long-term multi-parameter monitoring of stress & strain as well as variations in associated physical rock properties (for example, changes in compressional and shear moduli; conductivity, etc.) and seismicity.

131. Borehole instrumentation for 24/7 monitoring of stress must be broadband (in order to capture slow earthquakes (tremors) as well as temporal and spatial variations of microseismicity, tilt & strain).

132. 3D stress monitoring, tilt and displacement data can then be integrated with mine geology, mine engineering and numerical modeling.

133. The technology is out there now to allow exchange of our data/information
    a. 24/7 monitoring from boreholes is now possible

134. But some boreholes squeeze and close (C. Davis)

135. Not an issue- holes can be lined and seismometers are now cheap. There is emerging technology in this area (B. Milkereit)

Lessons learned:

- +/- 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 (B. Milkereit)

Detailed Feedback

Workshop Discussion Review

SUMMARY

- We already know the issues we need to deal with. We don't know how to define them but do know what the problem is.
- Integration between structural geology and mining folks became separated more than 30 years ago- we need to get re-acquainted and get back to some basic geology.
- We are at a similar watershed to the mid-1970s' when we developed RM classification system
- We need guidelines/protocols to assist in proper data collection/mapping etc
  - Needs documentation as a process to move forward with so mines can more efficiently manage these problems.

- Talked a lot about paleostress/tectogenesis and pros and cons of it. Every method has flaws but this one has some value.
  - Tectogenesis and paleostress are useful techniques to perhaps focus on

- Geologists need to be more empowered without risk of being put down.
  - A need for synergy- geology/modeling and issues of how geo info is taken into mine plans has to be addressed. Not being done well now.
  - We have the problem on the table and have some tools to help solve it.
  - We see some of the gaps but are not going to answer everything. Faults are too complex a problem.

(Trevor Carter)

- Paleostress discussion was helpful in determining what role it can play- at least to help determine fault patterns in pre-mining blocks.
- Needed more discussion on fault property classification and behaviour classification
- Found out about a new tool- Poly 3D- perhaps there's a role in our work
- Discussion on whether time linked events need a physical connection was an important contribution

(Damien Duff)

Post-Workshop Comments

S.Falconer, Xstrata Nickel

I recognize that the problem in understanding and controlling Fault-Slip events at depth is widely encompassing and would just like to mention that the area that I am probably best suited to comment on, is the geology side, or the data acquisition stage. To further focus my thoughts, I see the initiative as being broken down into two main areas.

1. The ability to identify and characterize structures in a deep green field type project based on limited drilling information/conceptual geological models and perhaps Mining Camp history,…i.e. Onaping Depth, *And*
2. The ability to anticipate which structures are critical faults along which fault-slip events are prone to occur in a more brown fields type project. Information is based on substantially more data as the resource is either a new zone adjacent to active mining horizons or an extension of a known ore zone …i.e. Creighton Depth. In this scenario, I am assuming that many of the structures have already been identified and characterized as players or not and that at this point it is the Geotech who is more involved.

Being more familiar with the Craig Mine experience, most of my comments will be biased towards scenario #1 or the Onaping Depth type setting. My notes basically follow the agenda from day 2.

The Importance of Faulting and other Structural Information

- T. Carter opened the floor with the importance of data acquisition. A reoccurring theme is "why don't the geologists collect the required structural data at the start of a program?"
- In our own defense, geologists have different objectives at the early stages of a drill program
- Proper acquisition of geotechnical data at the early stages can increase costs substantially. Good to communicate the benefits of absorbing the costs up front vs. the risk of unexpected costs and possible losses later on!
- There needs to be a decision point (perhaps as part of NI 43-101 as mentioned by D. O'Donnel) after which it has been determined that there is resource potential, that geotechnical type data acquisition must be conducted to a certain level. It must spell out what level of confidence is required, i.e., a certain drill density to also cover an area outside of the mineralization, a certain % confidence in oriented core, a certain level of geotech type geophysical surveys, etc...
- There needs to be an education/awareness program with geologists to better understand the geotech's needs and vice versa. Damien, I liked your comment that the Geotechs shouldn't be scared to put there boots on once in awhile.
- Geotechs need to make management aware of the importance of the required data and make sure the resources are available ($ and manpower)

Post-Workshop Comments, cont.

S.Falconer, Xstrata Nickel cont.

The importance of having an understanding of the regional and local tectonic history

- Just a comment that I liked U. Riller's presentation on day 1 about Paleostress. I think that it helps in our understanding of the regional geology and in this case, the deformation of the Sudbury Basin (I should have asked him about his results along the east end of the Basin and the effects the much younger Lake Wanapitei Impact may have had on them)
- There were comments by others that paleostress is no longer an issue and that we should no longer concern ourselves with it. However, it is part of our regional exploration model and helps us to try and understand what the ore forming processes may have been. It may also aide in our classification of the faulting.
- Paleostress may not be important in the day to day operation but we shouldn't ignore it.

Assessing the likely structure of a pre-mining block in the absence of sufficient data/information

- The big picture mirrors the small picture and vice versa. Using data acquired regionally should be compared with say outcrop or drift data. Based on that information, a fault model can be proposed for the resource and further drilling can be designed based on it to either prove or disprove it. It is a good starting point.
- Good point made D. O'Donnel and to remember is that engineers will always put there designs where there are no faults but the simple truth is that those areas typically have no drilling. Again – perhaps a good standard should be that all mine designs must have a minimum drill density to pass a certain hurdle in the approval process, i.e. 50m x 50m

Making the Proper Observations and Measurements

- Lots of comments about the quality of geology being put out today with computers and how it has deteriorated over the years as compared to the old mylar "works of art". I tend to agree but this is simply a sign of the times. In the past we probably had twice the staff with less workload. Today's Geologists are multitasking at the best of times – time is money – and it is a get in and get out or go big or go home type scenario. I admit that the old guys were masters and I have seen some beautiful 3D work but I don't think it has the flexibility of our 3D computer generated work of today. All in all, it is a good point though. Perhaps something that the universities should be made aware of.

The tools currently in use by Structural Geologists

- Again, some comments about how geologists are sometimes afraid to interpret a fault on a map. Most often, geologist's encounter numerous structures when logging core and/or mapping underground. Which ones are bad? A "bad" fault can take on many disguises from heavily gouged in the central area to almost hairlined at the tips. Typically it is only by experience and unfortunately by fault-slip events that we can begin to understand which ones to look out for. As mentioned some of the only indicators to rely on are disking, alteration, fault infilling etc…and I think that this is where the geologists can use some help from the geotechs.

Post-Workshop Comments, cont.

S.Falconer, Xstrata Nickel cont.

The importance of having an understanding of the regional and local tectonic history

- Just a comment that I liked U. Riller's presentation on day 1 about Paleostress. I think that it helps in our understanding of the regional geology and in this case, the deformation of the Sudbury Basin (I should have asked him about his results along the east end of the Basin and the effects the much younger Lake Wanapitei Impact may have had on them)
- There were comments by others that paleostress is no longer an issue and that we should no longer concern ourselves with it. However, it is part of our regional exploration model and helps us to try and understand what the ore forming processes may have been. It may also aide in our classification of the faulting.
- Paleostress may not be important in the day to day operation but we shouldn't ignore it.

Assessing the likely structure of a pre-mining block in the absence of sufficient data/information

- The big picture mirrors the small picture and vice versa. Using data acquired regionally should be compared with say outcrop or drift data. Based on that information, a fault model can be proposed for the resource and further drilling can be designed based on it to either prove or disprove it. It is a good starting point.
- Good point made D. O'Donnel and to remember is that engineers will always put there designs where there are no faults but the simple truth is that those areas typically have no drilling. Again – perhaps a good standard should be that all mine designs must have a minimum drill density to pass a certain hurdle in the approval process, i.e. 50m x 50m

Making the Proper Observations and Measurements

- Lots of comments about the quality of geology being put out today with computers and how it has deteriorated over the years as compared to the old mylar "works of art". I tend to agree but this is simply a sign of the times. In the past we probably had twice the staff with less workload. Today's Geologists are multitasking at the best of times – time is money – and it is a get in and get out or go big or go home type scenario. I admit that the old guys were masters and I have seen some beautiful 3D work but I don't think it has the flexibility of our 3D computer generated work of today. All in all, it is a good point though. Perhaps something that the universities should be made aware of.

The tools currently in use by Structural Geologists

- Again, some comments about how geologists are sometimes afraid to interpret a fault on a map. Most often, geologist's encounter numerous structures when logging core and/or mapping underground. Which ones are bad? A "bad" fault can take on many disguises from heavily gouged in the central area to almost hairlined at the tips. Typically it is only by experience and unfortunately by fault-slip events that we can begin to understand which ones to look out for. As mentioned some of the only indicators to rely on are disking, alteration, fault infilling etc…and I think that this is where the geologists can use some help from the geotechs.

Post-Workshop Comments, cont.

S.Falconer, Xstrata Nickel cont.

- As a starting point, if we can build a "cookbook" type system for modeling structures starting with the logging/mapping as per a certain standards capturing all required fault characteristics (i.e., as mentioned by R. Lisle) and somehow numerically model them thus taking the guess work and risk out of the geologists interpretation. This is something that engineers tend to understand better (interpretations based on numbers or real data).

Rock Mass and Fault property/behaviour classification. Identifying Fault-slip prone structures

- The cookbook mentality (as per above) could be useful in classifying faults as far as confidence goes, i.e. similar to a proven or probable type classification based on the amount of and confidence of data applied.
- There will be many differences between mine sites but in my experience the best tell-tales in identifying Fault-Slip prone structures initially in core is by the amount of associated disking. Complimentary to that and something that I fully support is the use of Acoustical and/or Optical televiewer surveys and their measurement of the break outs to assess the degree of stress in the ground. This is real data giving high confidence in the fault orientation, the condition of the ground on either side and ultimately its interpretation/classification.

Rock Factors Influencing Fault Behaviour

- Faults can display quite differing characteristics and behave quite differently depending upon which lithology they are hosted by or crossing
- Of special interest will be contacts btw rocks with high contrasts (stiff vs. soft) and obviously their intersection with the faults. These "hot spots" will have a higher risk of events as identified in J. McGaughey's work on Craig Mine. This is all good stuff to follow up on with numerical modeling taking away some of the "guess work". Follow up programs can be designed to prove or disprove it.

Data Interpretation and the importance of paleostress Analysis

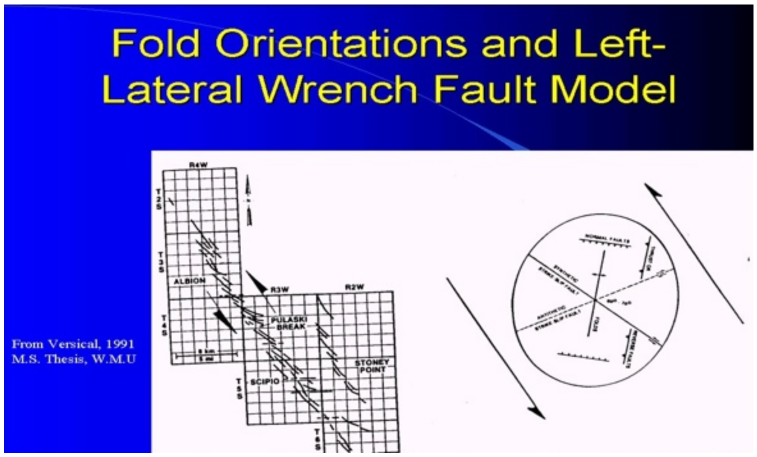
- Not sure here. I guess that you will always be comparing your latest interpretations back to your original model which could have included or should have taken into consideration a paleostress analysis
- How has my model changed? – does it make sense? – what do the numbers show?

Understanding how cracks/fractures/faults are initiated and then propagate

- One common theme that I saw between the sites experiencing Fault-Slip events was the presence on an en echelon type fault system.
- Some good examples were shown especially the "Text Book" example of the Reidel Shear which displays a lot of similarities with the Craig Mine example.

Post-Workshop Comments, cont.

S.Falconer, Xstrata Nickel cont.



Fault/fracture growth and propagation within an evolving stress regime

- The Poly-3D discussion seemed interesting but I must admit that I didn’t quite catch all that was said. Probably worth looking into, seeing as they have put so much work into it and acquired some experience with it
- B. Valley’s discussion on Slip and Rupture Tendency – can we say that faults that slip all have a system to them? – never one planar fault
- G. V Aswegen’s discussion on Ortlepp Shears - Mining Induced Faults. Very good discussion by Gerrie and obviously he has a lot of experience with them in the South African Camp. However, I am not completely sold on this as being a main focus for going forward. We have a big enough initiative on our plates as it is which kind of leads back to my initial breakdown of the initiative into the two areas. Certainly in area No 2 where deep mining is chasing down the zone (i.e. Creighton) this may be applicable, however in Instance No 1, i.e. an Onaping Depth, it may not be as applicable – possibly some consideration can be given to it in the design process.
    - If we think of these structures as being part of a system then it is easy to imagine that mining induced fractures could simply be the extension of one fault tip to another
    - Knowing their pattern lends to prediction

Post-Workshop Comments, cont.

S.Falconer, Xstrata Nickel cont.

Path Forward

- In search of a potential test site(s) at depth in seismically active mines within a reasonable distance, two come to mind; Onaping Depth and Creighton Deep, both of which fall into one of the two previously proposed focus areas.
- Being more familiar with Onaping Depth, I will focus on it.
    - Access can be had to a 500m x 500m x500m test volume through Craig Mine (Craig Mine is currently on Care and Maintenance but access could still be had)
    - Full access with no hindrance from production
    - Craig Mine had been seismically active while in production
    - A known fault system exists at Craig and may be related to or mimic a system at Onaping Depth
    - A number of test boreholes are accessible but may require cleaning
    - New drilling could be an option
    - Opportunity to expand upon the current modeling compiled through Mira
    - Big opportunity to write the book on how to identify/classify fault/fault systems in deep settings (for geologists)
    - Significant value for research project sponsors by reducing the biggest risk to this project (geotech)
    - Increased chance of securing funding

- Re-evaluate regional geology/fault model and simulate over the resource area
- Review current drill data and confidence in interpretation
- Design and drill new ddh program to cover untested areas (typically where infrastructure would be – and also high risk areas)
- Install new state of the art sensors in existing deep holes – could use blasting events from nearby FNX mines to measure responses – or - initiate new blasts from Onaping/Craig specifically designed to activate the faults
- Test new oriented core/**Televiewer** technology for higher confidence of structure orientations/ characteristics, build database of local stress orientations thru break outs (nothing worse than spending a lot of time and effort on trying to oriente core with little confidence in the results)
- Test new geophysical technology from known to unknown ground
- Test numerical modeling of ground with newly compiled data with and without fault model testing proposed designs or evaluate preferred orientation for new designs
- Review/re-design and test alternate mining methods with model
- Ultimate goal is to reduce and quantify the geotechnical risk with Onaping Depth and the measure of our success would be a go or no go decision

Post-Workshop Comments, cont.

Benoît Valley, CEMI

Please find here under some bullet notes on our structural geology workshop.

- One main gap to me is how to go from fault characteristics (measurable on the field and/or UG) as describe by Lisle to fault behavior and appropriate numerical models and parameters properly representing this fault behavior. On-going work (Bewick) on fault classification is critical for this. Within the various characteristics presented by Lisle, I thought that fault maturity could be a critical parameter to consider (see also attached Choy paper 2004).
- Another opportunity I could see is some synergy between poly3D and map3D. Both software are based on the same theory (BEM) but one is optimized to compute mining induce stresses (Map3D) and the other fault stability (poly3D). Merging both, i.e. profiting from both mining expertise (Map3D) and structural geology expertise (poly3D) could be very valuable. Also it sounds like poly3D has a very efficient solver (1300 models run in about 20 minutes). Such efficiency could be used to make probabilistic (sensitivity) studies. Limitation of both codes is linear elasticity only (no plasticity).
- Another opportunity which came out of a discussion with D. Goldsack and D.O'Donnel is the possible coupling of rockbursting activity and earth tide. I am following up on this topic and will let you know when I have more information.

As said: a day of very interesting discussion, but hard to extract practical action items….

Luiz Castro, Golder Associates Ltd.

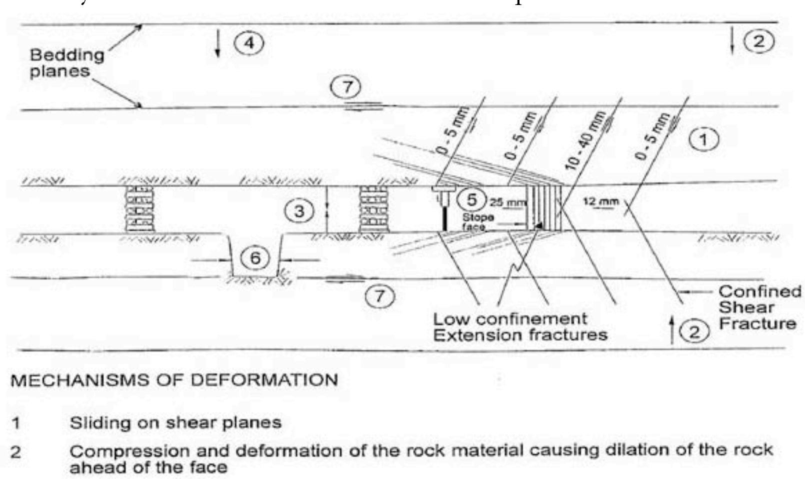
I'd like to add a few comments:

- We seem to have knowledge of fault behavior on two extreme scenarios: 1) discrete structures which are in most occasions near surface (say less than 1000 m, except on the plate tectonics) and 2) exploitation of existing faults/shears and formation of new fault/shears in deep, highly stressed environment (e.g., South Africa – 3000 m deep). The Canadian mines are probably in between, and the question would be how close we are from scenario 2. Are the Canadian mines ever going to get there, as the mines progress deeper and the extraction ratios increase?
- At high confining pressure, do we still need to treat the fault as discrete structures or will have to consider both discrete and equivalent "shear band" type of rock mass (e.g., at the tip/end of the faults)?
- Fault-slip on a discrete fault or through a shear band (with portions formed through the intact rock) will likely depend on the mobilized shear strength (at failure) which is a function not only of the intrinsic fault properties but also of a large number of characteristics of the overall geometric, stiffness and loading system involved. These characteristics could involve, for example, the orientation and "fabric" of the structures and proximity to the UG openings, loading rate, stress path, mining method, extraction rate and many other ones, that we do not know at this stage. In a paper, prepared with Dougal M. and Peter K. – ISRM Japan 1995, because the mobilized peak strength value depends strongly on this complex array of system characteristics, it was referred to as the system strength of the rock mass (σ_c) sys, when we were analyzing the rock mass behavior around the excavations.

Post-Workshop Comments, cont.

Luiz Castro, Golder Associates Ltd.

- The S. Africa experience and the formation of the Ortlepp shears can be important to find out the factors or conditions that led to the formation of those shears. I am not expecting that similar Ortlepp shears would occur here (different system characteristics), but it would be worthwhile to back-analyze the factors/conditions. I have a section in my thesis on S. A. experience, but it does not include information prior to Ortlepp publications. Perhaps, the connections with ISS and S. A. could be valuable to find information on earlier stage of mining the reefs (say when they were at 1000 m and 2000 m) and find out if they saw those Ortlepp shears and conditions, and/or what were the problems faced.
- Like the deviatoric stress approach (sig1 - sig3)/UCS, which is now commonly used to evaluate damage initiation in the rock mass around the openings, I think that we could create a screening approach to define which mines and at what stage fault-slip rockburst could become a concern. This screening should then assist in focus where additional information would be required (i.e., where to put the resources) and when (i.e., prior to excavate there). Using the experience of the deviatoric stress approach (applicable for regions under low confining pressure), we now feel more comfortable to predict at what depth, extraction ratio and zones, there could be potential for a strainburst to occur. Similarly, the behavior for a fault to slip near surface would change with increase confinement. The known surface conditions (roughness, infilling) may control the fault behavior at low confining conditions. However, these factors may not be important at greater depth (or high confinement zones), where potential for unclamping, rock bridges between structures network, stiffness of the rock mass and the system, rock mass degradation, will likely control their behaviours. Also, the commonly used estimate for storage of strain energy alone may not provide the information required for evaluating the potential for a fault-slip to occur.
- As pointed out in one of my slides, I think we should investigate if there are other means to evaluate rather than assume that strain energy is the answer (which is basically what most of the mines talk about). For example, from S.A., the mechanisms of deformation were also considered important to evaluate fault behavior. Probably this might assist in explaining some of the microseismic events in remote locations, PKK agreed and already has some ideas on the deformation process for the events at Creighton.



Brummer, R.K. (1987). Fracturing and deformation at the edges of tabular gold mining excavations and the development of a numerical model describing such phenomena. Ph.D. Thesis submitted to the Rand Afrikaans University, S. Africa. (Richard Brummer, Itasca (Sudbury).

- For the next CEMI numerical modelling meeting, suggest you invite Joe Carvalho to participate.

Post-Workshop Comments, cont.

Brad Simser, Xstrata Nickel

- Unrealistic to expect typical mines to have the in-house expertise to handle many of these complex issues.
- We need a framework that will allow academia, consultants etc to provide us with the guidance we need. Will also help in highly qualified personnel (HQP) development [at mines].

John Henning, Goldcorp

- Guidelines for recording fault characteristics needed
  - As the core is being initially logged
- Guidelines for mapping faults underground needed
  - Lots of joint info. Can be collected, for example: Dip, dip direction, [persistence, spacing, alteration?
- What is mapped when we map faults?
  - Dip, dip direction?
  - What about recording slip direction etc?
- Would be nice to have a digital scan of diamond drill core from boreholes (rather than just taking photos
- There is a big gap between exploration geology and production geology. The former only look at regional-scale lithology and structure patterns whereas the latter are more focused on mapping only in the ore zone. [The issue is one of both groups operating at different scales and not combining/integrating their collective knowledge]

Roger Soliva, Université Montpellier

- For the evaluation of stress perturbation and triggering [of seismic events] two kinds of models should be used:

1. Quasi-static model (e.g. Poly 3D) and
2. Dynamic model- such as used by seismologists

- Both approaches are worth considering

Mark Diederichs, Queen's University cont.

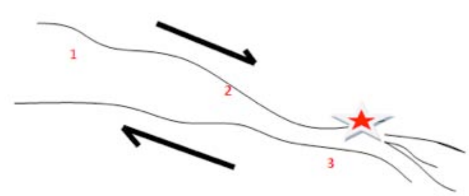
On Characterization:

- Need to describe the faults. At the 1-metre scale; c-ϕ; d, age, width. At the 100m-scale-offset, curvature etc. At the regional scale- are the faults mine-activated or do they have a regional influence?

On Fault Systems:

- We need information on all faults [comprising the system]

1. Energy generators (ductile)
2. Energy storage/transfer
3. Energy release (brittle)



Suggested Reading

Bennett, E.H. and R. Venkatakrishnan, 1982. *A palinspastic reconstruction of the Coeur d'Alene Mining District based on ore deposits and structural data*. Economic Geology, 77, 1851-1866.

Blenkinsop,T., Lisle,R., and Ferrill, D., 2006. *Introduction to the Special Issue on New Dynamics in Palaeostress Analysis.* Journal of Structural Geology 28,941-942.

Choy1, G.L., Kirby, S.H., 2004. *Apparent stress, fault maturity and seismic hazard for normal-fault earthquakes at subduction zones.* Geophysical Journal International, 159, 991-1012.

Liesa, C.L. and Lisle, R.J., 2004. *Reliability of methods to separate stress tensors from heterogeneous fault-slip data.* Journal of Structural Geology, 26, 559–572.

Lisle, R.J., 1979. *The representation and calculation of the deviatoric component of the geological stress tensor*. Journal of Structural Geology 1, 317–321.

Lisle, R. J., 1987. *Report on a meeting of the Tectonic Studies Group on paleostresses and fault systems.* Journal of Structural Geology, 9, 1053-1054

Lisle, R.J., 1988. *Romsa: a basic program for paleostress analysis using fault-striation data*. Computers and Geosciences, 14, 255-259.

Lisle, R., Orife, T., and Arlegui, L., 2001. *A stress inversion method requiring only fault slip sense.* Journal of Geophysical Research, 106B, 2281–2289.

Lisle, R.J., Orife, O., Arlegui, L., Liesa, C., and Srivastava, D.C. *Favoured states of palaeostress in the Earth's crust: Evidence from fault-slip data.* Journal of Structural Geology, Special Issue "New Dynamics in Palaeostress" Eds (Blenkinsop and Lisle), 28, 1051-1066.

Lisle, R.J., Srivastava, D.C., 2004. *Test of the frictional reactivation theory for faults and validity of fault-slip analysis.* Geology, 32, 569–572.

Nemcok, M., Lisle, R.J., 1995. *A stress inversion procedure for polyphase fault/slip data sets*. Journal of Structural Geology, 17, 1445-1453.

Nemcok, M., Lisle, 1999. *A stress inversion procedure for polyphase calcite twin and fault/slip data sets.* Journal of Structural Geology, 21, 597-611.

Orife, T., Lisle, R.J., 2006. *Assessing the statistical significance of palaeostress estimates: simulations using random fault-slips*. Journal of Structural Geololgy, 28, 952–956.

Srivastava, D.C., Lisle, R.J., Vandycke, S., 1995. *Shear zones as a new type of palaeostress indicator.* Journal of Struct Geology, 17, 663–676.

Suggested Reading, cont.

Srivastava, D.C., Lisle, R.J., Imran, M., Kandpal, R., 1999. *A new approach for paleostress analysis from kink bands—application of fault-slip methods*. Journal of Structural Geology, 107, 165–176.

Venkatakrishnan, R., Bennett, E.H., 1988. *Structural Controls of the Couer D'Alene Ore Veins Shoshone County, Idaho.* In Proceedings of North American Conference on Tectonic Control of Ore Deposits and the Vertical and Horizontal Extent of Ore Systems, 125-133. Rolla Missouri: University of Missouri-Rolla.

From left to right:
John Fedorowich; Steve Falconer; Dennis O'Donnell; John Henning; Bernd Milkereit; Chris Davis; Gerrie van Aswegen; Scott Carlisle; Luiz Castro; Brad Simser; Damien Duff; Rob Bewick; Doug Goldsack; Steve McKinnon; Ray Price; Benoit Valley; Peter Kaiser; Mark Diederichs; Richard Lisle; Trevor Carter; Jonathan Hordo; Phil Dight; Sandie Cruden; Ulrich Riller; Jim Martin; Denis Thibodeau

CEMI
Centre for Excellence in Mining Innovation

Centre for Excellence in Mining Innovation (CEMI)
935 Ramsey Lake Road
Sudbury, Ontario, Canada
P3E 2C6

P **705.673.6568** | F **705.671.3878**

www.miningexcellence.ca
info@miningexcellence.ca