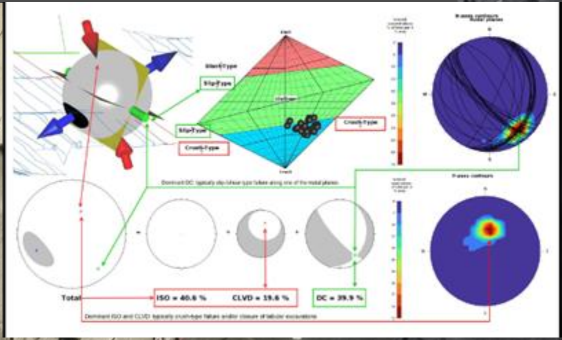

FOGAP Seismic Phase 1:

Project 1: Review of current seismic risk management practice

Prepared By: William Joughin
Johan Hanekom, Heinrich Greeff, Friedemann Essrich, Johan Wesseloo, Peter Mikula, Lindsay Linzer, Patrick Linzer, Olaf Goldbach

Date: 2024/06/11

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Scope of Work (Overall project)

Phase 1: Review of current seismic risk management practice

Outcomes will be presented today

Phase 2: Alternative methods for Short Term Seismic Hazard Analysis

To be discussed today

Phase 3: Guidelines on Seismic Risk Management Practice

Phase 4: Implementation on Champion mines

Phase 5: Development of Seismic Risk Management Plan

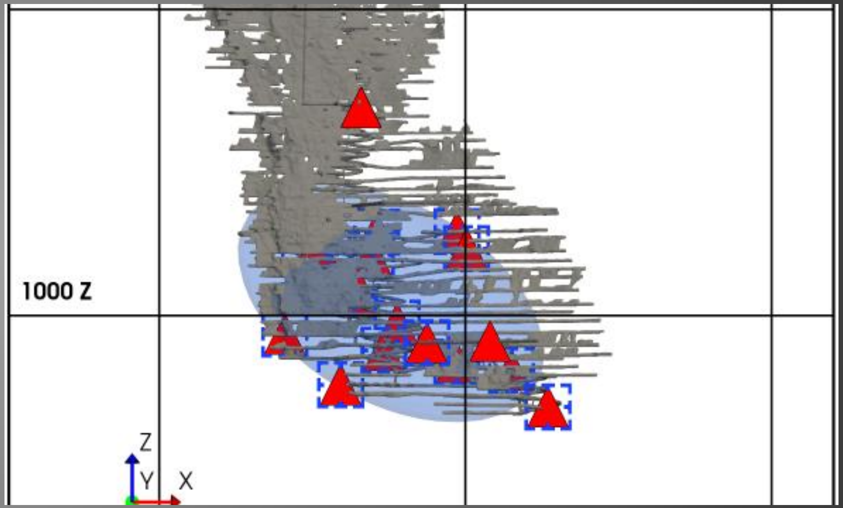
Scope of Work

Phase 1: Review of current seismic risk management practice

- Review of accident statistics
  - Minerals Council – Challenges obtaining meaningful data
- Review of Seismic networks (locally and internationally)
  - Benchmarking of seismic networks locally and internationally. Collation of specifications and data for local and international networks (IMS, ESG, and PRISM networks). This will include sensor arrays, data quality and application of Q .
  - Recommend minimum network objectives and specifications, based on the seismic hazard levels anticipated or experienced. Provide practical recommendations, based on the review, such as using existing geological holes to improve / augment sensor configuration
  - ~~IMS (information only)~~, ACG & SRK - Complete
- Review of local and international seismic risk management practice
  - Summarise current seismic risk management practice (local and international), including seismic hazard assessment, ground motion, source mechanisms, damage mechanisms, geotechnical data used, modelling, mine design, support systems, re-entry protocols, TARP systems, etc. Short-, medium-, and long-term risk management strategies should also be examined.
  - The review should include the education level, skills, and experience of personnel responsible for seismically active operations.
  - IMS (information only), CSIR, ACG, SRK - Complete
- Gap Analysis
  - Identify aspects of seismic networks and seismic risk management practice where South Africa needs to improve, based on findings from above tasks
  - CSIR, SRK – Complete
- Workshop to present findings of Project 1
  - CSIR, ACG, CSIR – Today

REVIEW OF SEISMIC NETWORKS (LOCALLY AND INTERNATIONALLY)

Johan Wesseloo
Lindsay Linzer
Patrick Linzer
William Joughin



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Data Sources

South African mines:

- Anglo Platinum:
  - Dishaba
  - Tumela
- Harmony:
  - Doornkop
  - Joel
  - Kusasalethu
  - Masimong
  - Moab Khotsong
  - Mponeng
  - Target
  - Tsepong
- Sibanye-Stillwater:
  - Beatrix
  - Driefontein
  - Kloof
- Goldfields
  - South Deep
- Impala:

International mines (anonymous)

- Africa (outside of RSA)
- Canada
- Australia
- Sweden

Data Collected

Array configuration

- Sensor location (x, y, z).
- Sensor configuration (uniaxial/triaxial).
- Sensor type (geophone/accelerometers).
- Frequency (natural frequency for geophones, lower frequency for accelerometers.

Seismic events

- Location.
- Moment.
- Local magnitude.
- Calculated Moment magnitude (M_w)

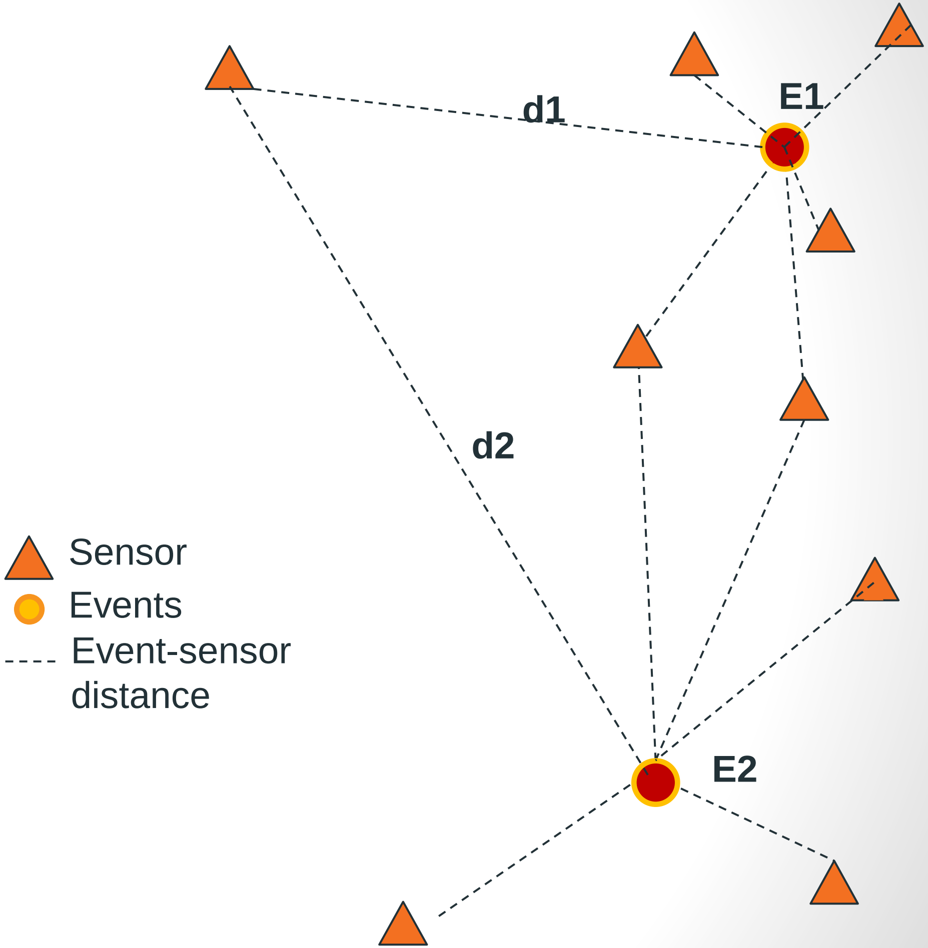
Mining layouts and geometry

- Survey files of mine workings.
- Orebody structure and geometry.
- Host rock properties.
- Sensor distance to orebody could not be assessed:
  - Complex geometries not comparable – tabular, multiple orebodies, pipe shaped, folded

Array metrics

Event to 6th sensor distance

- In this study, the most recently recorded events > M_{w0} were used.
- Minimum 6 sensors required for a well constrained location
- Insensitive to outliers (both sensors and events).
- Several statistics from the distribution can be used for comparisons among systems:
- Median, mean, stdev, etc.
- Does not penalise large, high-density arrays



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Principal Component Analysis

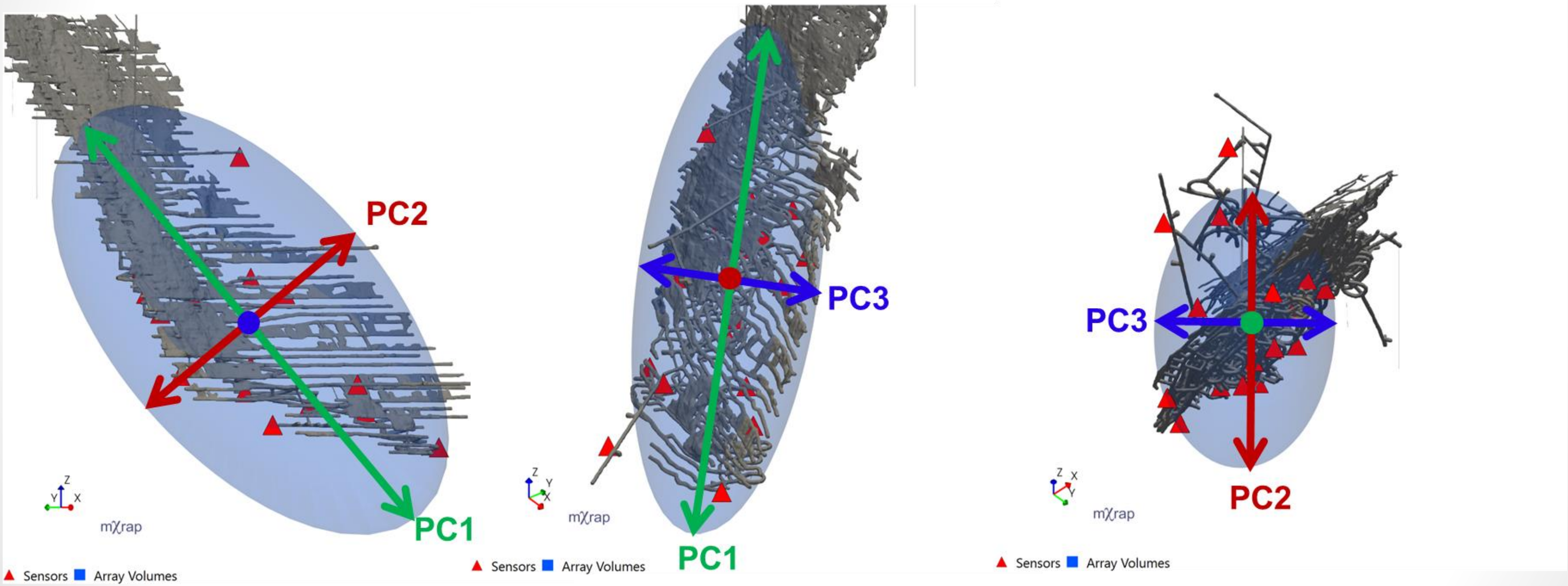
Largest projected area A_{LP}, :

$$A_{LP} = \frac{\pi}{4} \cdot PC_1 \cdot PC_2$$

Planarity:

PC2 / PC3.

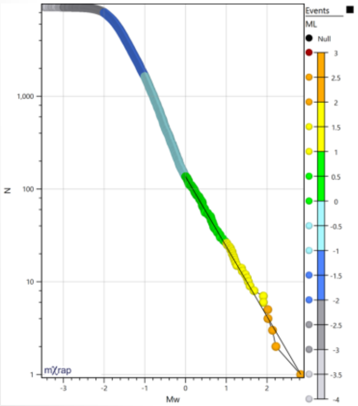
(PC1 x PC2) /PC3^2



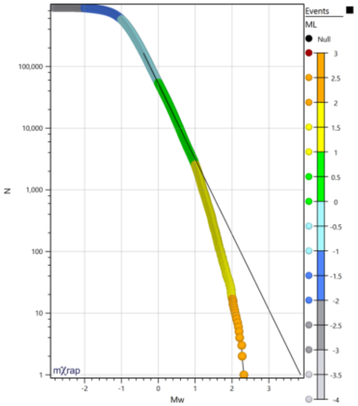
Hazard Level Metrics

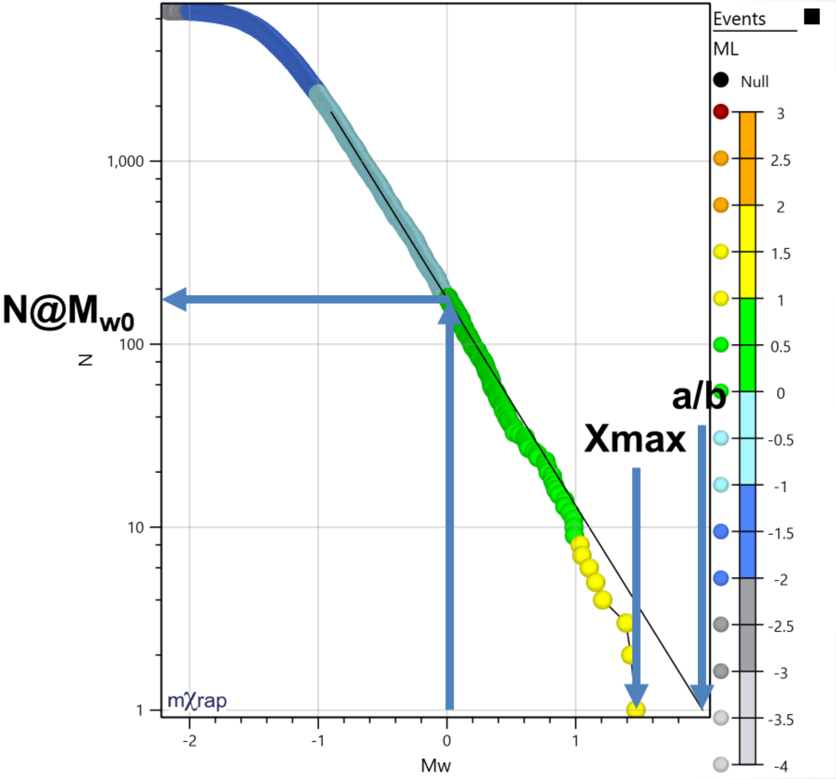
a/b provides a robust metric for the relative hazard level found at different mines.
1 year data for all operations

Fit to larger magnitude portion of a bimodal distribution



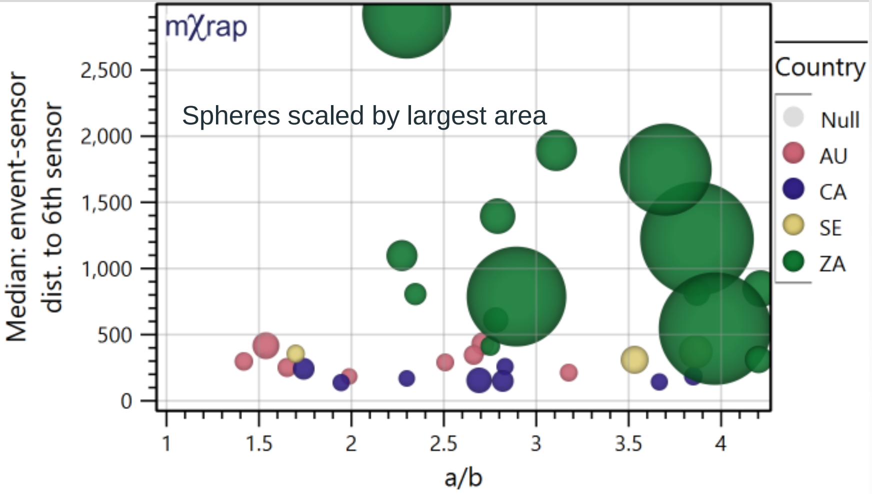
Fit to lower magnitude portion when magnitudes under-recorded

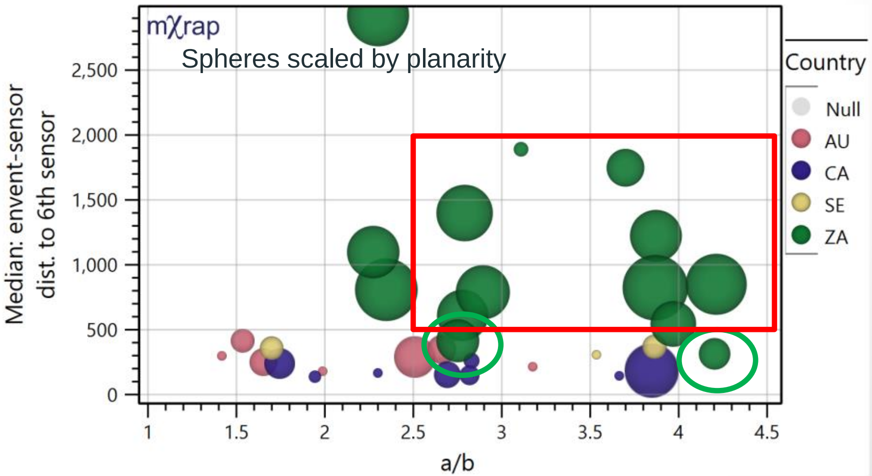




Summary of array results

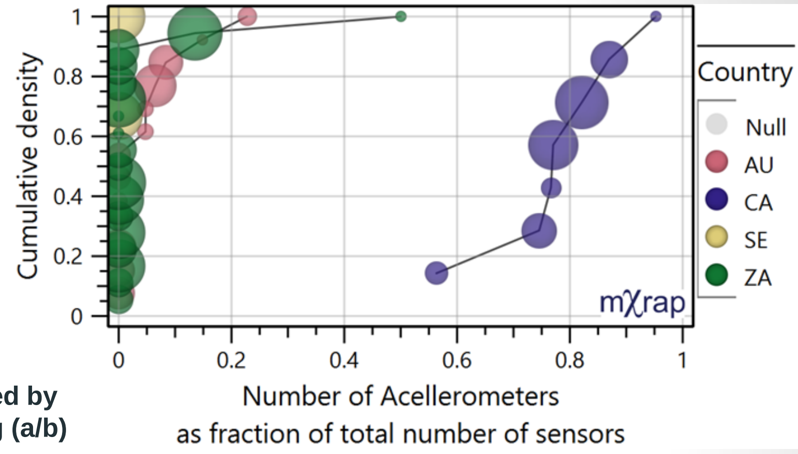
- Two Canadian and two Swedish mines have very high hazard a/b > 3.5 – like deepest SA mines
- Canadians, Australians and Swedes monitor relatively low hazard mines
- ZA mine sensor arrays are the least dense
  - Two are below 500m (event to 6th sensor) – like international mines
  - Several are > 1500 – even high hazard
- ZA mines have the largest projected area per seismic network
- ZA mine sensor arrays are very planar, but so are one or two international mines – orebody geometry
- Dense, non-planar arrays provide the best sensitivity and location accuracy
- Achievable target for SA mines?
  - Median event to 6th sensor < 500 m
  - Planarity = 2?



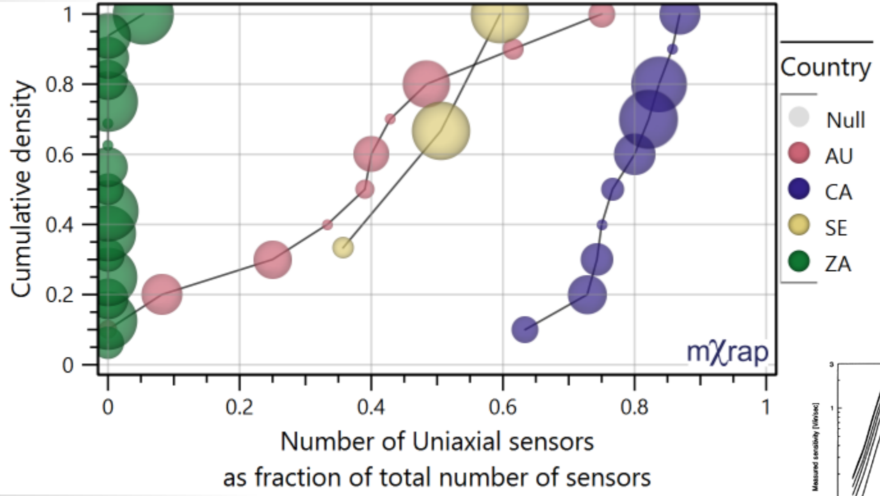


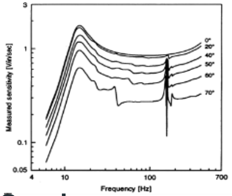
Summary of sensors

- **South Africa** - mostly 4.5 Hz geophones – most IMS systems (Impala – Prism) - large events (except largest -1Hz) – small events (M<0) recorded by 4.5Hz sensors, but not suitable for source parameters (spurious responses give randomly higher energy and sometimes moment)
- **Australia & Sweden** – mix of triaxial and uniaxial geophones – mix of high and low frequency geophones – most IMS systems – reasonable for large and small events
- **Canada** –most ESG Hyperion systems – (uniaxial and triaxial accelerometers) –source parameters for small events – Separate ESG Paladin system for large events (4.5Hz, sometimes 1Hz)

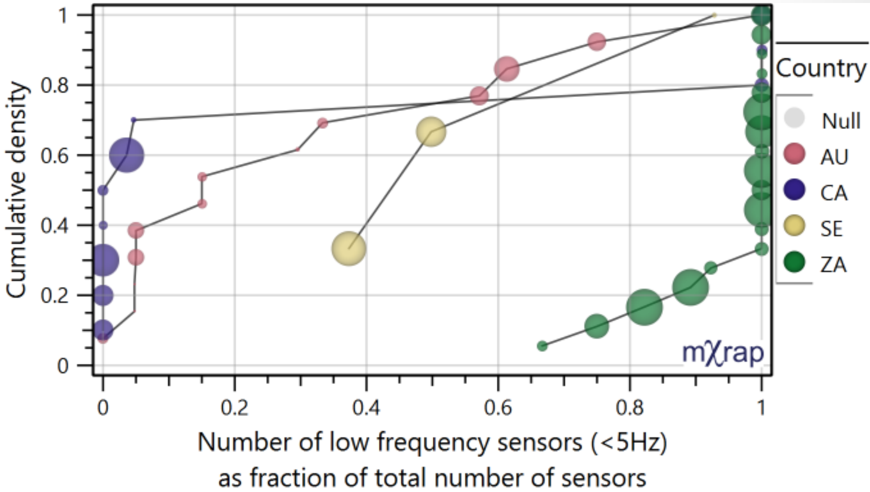


Spheres scaled by Hazard Rating (a/b)



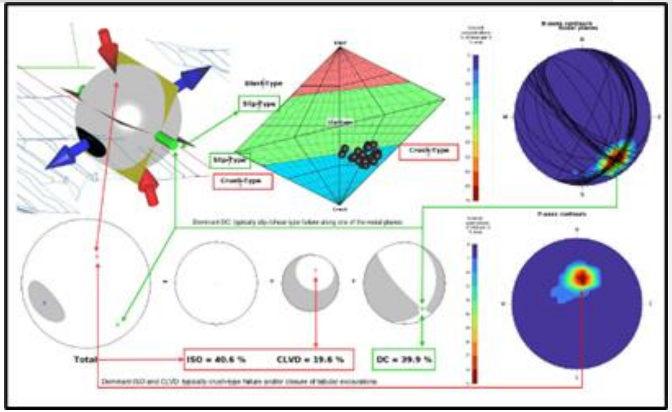


Spurious response

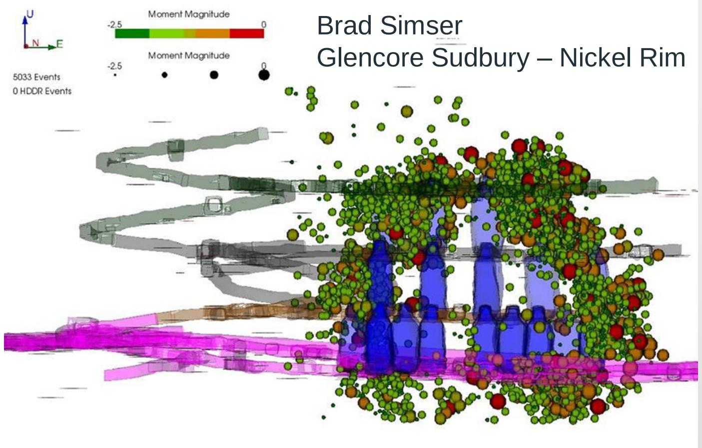


Improving seismic networks

- Why improve location accuracy?
  - Better interpretation of rock mass response (wrong location, wrong interpretation).
  - Identification and assessment of hazardous geological structures
  - Delineation of unmapped geological structures
  - Improved source parameters (distance and attenuation)
  - Moment tensor – source mechanism – principal stress directions
  - Yielded rock mass – crush/yield pillars, stope face and remnants (initially active, then aseismic)
  - Identification of asperities (seismic gaps)
  - Activity rates and exclusion zones
- How to improve location accuracy?
  - Increase sensor density and configuration where required
    - Plan to migrate network in advance based on planned mining
    - Install additional sensors (can be uniaxial)
    - Abutment sensors beyond mining face
  - Sensors in hangingwall
    - Drill long holes from raises/stope gullies/end of crosscuts and install high frequency geophones (non-vertical) – measure orientation - grouted for long term or sacrificial – can be uniaxial
    - Drill long holes from development ahead of the stope face (sacrificial)
    - Geological exploration holes?
  - Install deep footwall sensors near shaft
  - 3D velocity model
    - Adapted as mining changes using development blasts
    - Geology model
  - Good processing practices
    - Using directions (reliable sensors orientations required
- DAS (distributed acoustic sensing)?



Poor location – low quality?

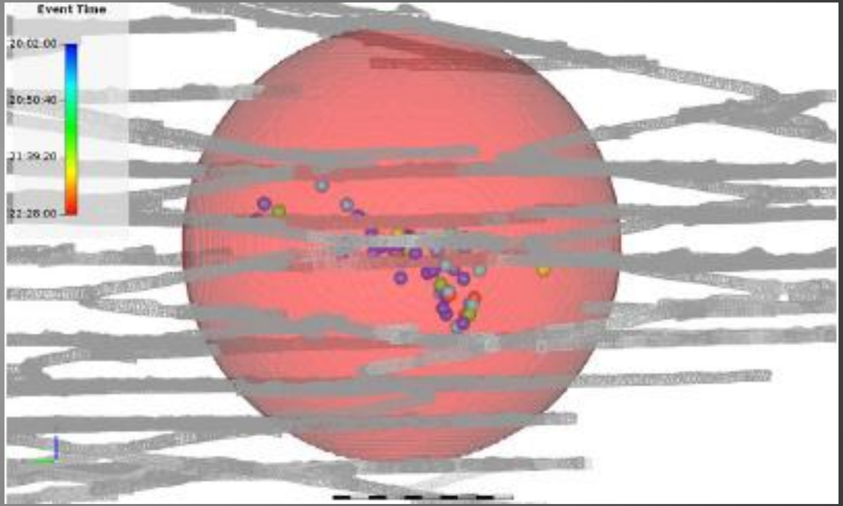


Brad Simser
Glencore Sudbury – Nickel Rim

Good location and sensitivity – yielded rock

REVIEW OF LOCAL AND INTERNATIONAL SEISMIC RISK MANAGEMENT PRACTICE

Peter Mikula
Heinrich Greeff
Friedemann Essrich
Johan Hanekom
Olaf Goldbach
Johan Wesseloo
William Joughin



Review of SRMP documents

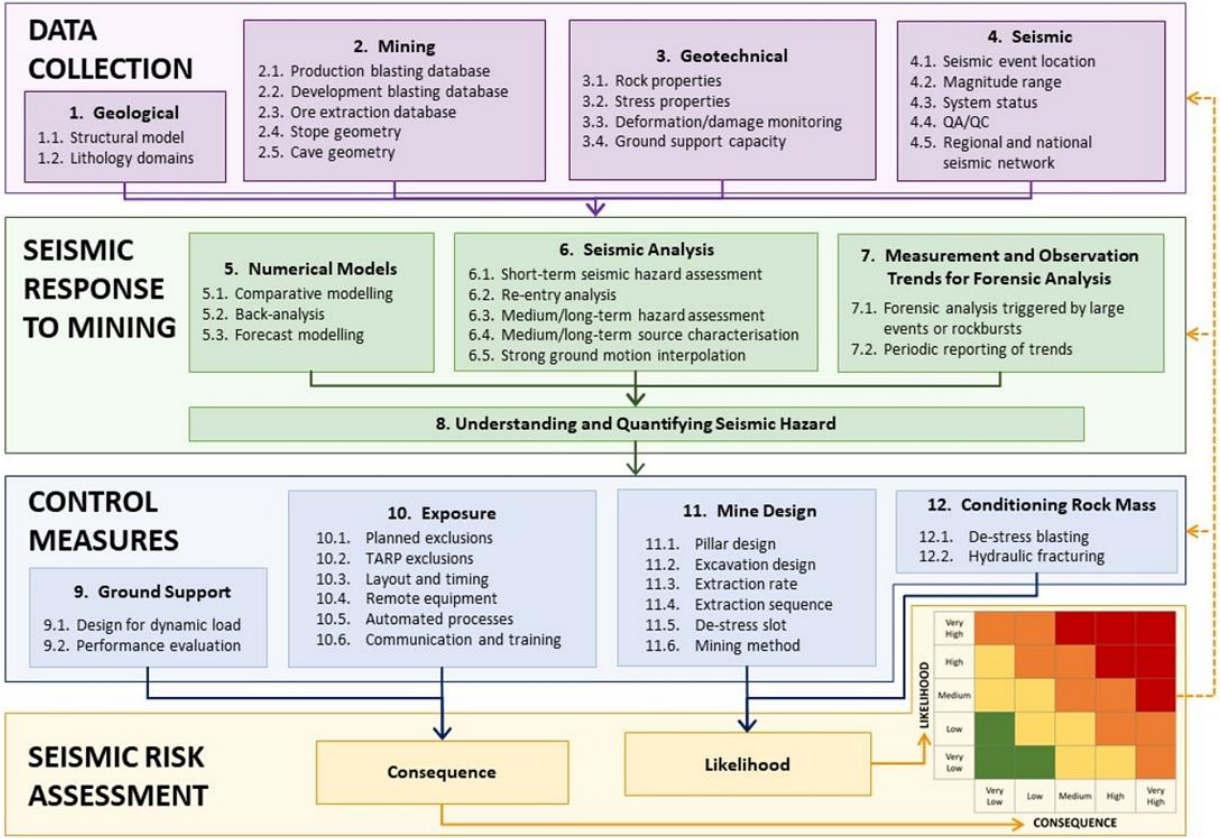
- Twelve SRMP or equivalent documents were reviewed.
  - 5 from Australia, 5 from Canada, 1 from Mali, 1 from Saudi Arabia
  - A total of 73 individual strategies or protocols were identified.
  - Additional 1 from Canada
  - Personal involvement in El Teniente, Chile and Kiruna, Sweden – no formal SRMPs
- Three Legislation/Regulation documents were also reviewed:
  - NSW and WA Australia, and Ontario Canada.
- Qualifiers:
  - The documents generally give no indication of whether a strategy is or was effective.
  - No mine has implemented all the strategies – nor do they need to. Can be due to past history, past practice, their consultant, or not relevant to their needs.
  - Mines may not adequately implement the strategies that they claim.
  - Mines may have strategies that they do not list in their SRMP.
  - Some significant technical errors were found across several SRMP documents.

Strategy Classification #1

The SRMP strategies were found to classify well into one of the steps recommended by the **AS/NZS 4360** Risk Management Standard:

- 1 communicate and consult (make all stakeholders aware)
- 2 establish context (the target or aim of the work)
- 3 identify risk (characteristics of the hazard) – Geomechanical
- 4 identify risk (characteristics of the hazard) – Seismic Monitoring System (SMS)
- 5 analyse risk (likelihood & consequence)
- 6 evaluate risk (tolerable or not)
- 7 treat risk (controls)
- 8 monitor, review, feedback effectiveness

Strategy Classification #2



Strategy usefulness rating

Guidance from Australian Regulators who have moved towards a Duty of Care safety framework:

- All hazards must be identified and controlled
- Controls are "Practicable" to the extent they are effective for mitigating a hazard. For example if a Control (e.g. ground support) is known to work elsewhere, then it is practicable.
- Controls are "Reasonable" to the extent that the cost of implementing a control is low compared to the cost if the hazard were to materialise (as is the case for ground support)
- If a control is Practicable and Reasonable, it MUST be implemented (unless another more effective control is adopted)
- Lack of time, personnel and resources are NOT acceptable reasons for not implementing such a control. If the control cannot be implemented, the activity giving rise to the hazard must not be done.
- Everyone is accountable according to their ability to influence or have influenced an outcome. Legal consequences are very punitive.

SRMP comment: No mines stated that they assessed strategies by the extent of being Reasonable and Practicable – despite this being the new legislative requirement in WA.

Strategy ranking (first three AS/NZS 4360 steps)

AS NZS Step	POTVIN SRMP	Rating system 0 Adverse to 5 Favourable 0 no effect to 5 major effect		Strategy Name x70 Strategy Name	Practicable (risk effective) rating (0 worst to 5 best)	Reasonable (cost effective) rating (0 worst to 5 best)	Industry adoption score	Regulator adoption score
		Communicate and Consult		**Communicate and Consult x2**				
1a	10.6 Communication and training	Workforce communication, training, awareness	1	Communication and training	4.3	4.2	58	67
1b	7.2 Periodic reporting of trends	Information reports: daily, weekly, monthly seismicity reports, covering seismic history and trends, to workforce and other stakeholders	2	Periodic reporting of trends	2.0	4.0	92	0
		Establish Context		**Establish Context x2**				
2a		Specify criteria for seismic activity, against which risk is to be evaluated. What is or is not acceptable? What level of seismic risk would trigger what kind of action?	1	Risk evaluation criteria	5.0	4.0	17	33
2b		Specify roles and responsibilities of personnel	2	Personnel roles	5.0	3.5	67	33
		Identify Risk – Geomechanical Environment Vulnerability		**Identify Risk – Geomechanical Environment Vulnerability x4**				
3a	1.2 Lithology domains 2.4 Stope geometry 2.5 Cave geometry 3.1 Rock properties 3.2 Stress properties	Rocktype domains: Prior to excavation, identify vulnerability and mode of seismic failure associated with stress level and mining geometry, e.g. stiffness contrasts can be associated with seismicity	1	Lithology geomechanical vulnerability	3.9	3.4	83	0
3b	1.1 Structural model 2.4 Stope geometry 2.5 Cave geometry 3.2 Stress properties	Structural domains: prior to excavation, identify vulnerability of faults, structures, unfavourable geological features, and mode of failure associated with stress level and mining geometry, e.g. bifurcated lenses, porphyry contacts, unclamped faults	2	Structure geomechanical vulnerability	4.0	3.6	75	0
3c	1.1 Structural model 2.4 Stope geometry 2.5 Cave geometry 3.2 Stress properties	Detect existence of seismically active structures based on lineation of events with consistent moment tensors (even if not seen in core or mapping). Warning: many such structures are illusionary artefacts of poor sensor array and waveform processing.	3	Structure discovery from seismic event lineation	2.0	4.0	8	0
3d		Seismic history trends: Identify stress hotspots and structural hotspots from seismic event data (typically from SMS analysis, sometimes from rock noise reporting). (Only gives guidance on likelihood of hazard)	4	Stress and structure hotspot (seismically active) discovery from seismic history	2.4	3.4	75	0

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Strategy ranking (AS/NZS 4360 step 4: Identify Risk – SMS)

Seismic Monitoring System (SMS) protocols

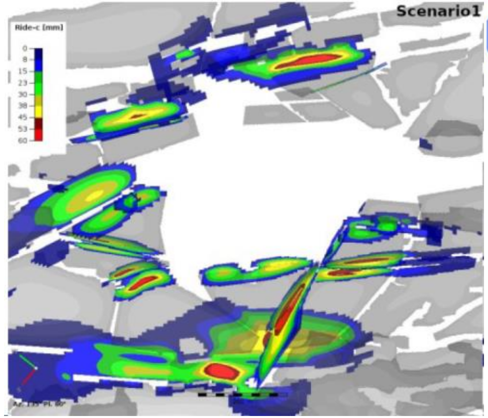
- Sensitivity and location accuracy needs improvement in South Africa
- All operations locally and internationally could improve on planning network expansions – some have protocols in their SRMP
- System health guidelines are generally good in South Africa and comparable with international operations
- Management of system health does vary on different operations – available resources – priority?
- Useful details in the benchmarking exercise that could be used to improve our guidelines

AS NZS Step	POTVIN SRMP	Rating system 0 Adverse to 5 Favourable 0 no effect to 5 major effect		Strategy Name x70 Strategy Name	Practicable (risk effective) rating (0 worst to 5 best)	Reasonable (cost effective) rating (0 worst to 5 best)	Industry adoption score	Regulator adoption score
		Identify Risk – Seismic Monitoring System (SMS)		Identify Risk – Seismic Monitoring System (SMS) x12				
4a	4.1 Seismic event location 4.2 Magnitude range	Install and use Seismic Monitoring System: for monitoring and recording of mining induced seismic activity.	1	Seismic Monitoring System (SMS) for event location, magnitude and other source parameters	4.3	4.0	100	100
4b	4.1 Seismic event location 4.2 Magnitude range	Protocol for processing of SMS waveform data for adequate confidence in event location and source parameters. Usually outsourced to the Vendor for manual review of auto-processing result (however, that processing often done by personnel who have never seen the mine.) Checked by site SMS operator	2	Protocol for SMS waveform data processing	3.3	3.4	67	67
4c	4.3 System status	Protocol for retention of SMS history and maintenance (log of system commissioning and changes, sensor changes, software upgrades, configuration changes, velocity model changes)	3	Protocol for SMS history and maintenance log	4.0	4.3	25	0
4d		SMS site operation manual. A reference document for any site users or stakeholders. (Contains sufficient guidance needed by a new operator to operate the system, conduct troubleshooting, and produce a high quality event dataset.)	4	SMS site operation manual	4.0	3.3	17	0
4e		SMS system training: provide site operators with skills in basic troubleshooting, data processing, data analysis. (Normally provided by the Vendor as part of the support contract)	5	SMS training in operation, data analysis, troubleshooting	5.0	3.3	33	0
4f		SMS “dummies” operation sheet. A guideline to enable an untrained person to rapidly obtain location and magnitude details of a just-occurred event, in cases when the regular system operator is absent from site.	6	SMS simple operation guideline for untrained persons	4.0	4.0	0	0
4g	4.3 System status	Protocol to minimise SMS downtime. Can include: 1> Auto-advice of system health problems 2> Detailed system electrical diagrams 3> Critical spare parts for swap and for troubleshooting 4> Rapid response priority (SMS regarded as critical) 5> Remote access troubleshooting by SMS vendor 6> Waveform processing can be fully actioned on site (in case of loss of remote access to SMS vendor) 7> Backup standalone power 8> Provision for loss of a sensor (damaged, corrupted) (drill surplus installation boreholes at each sensor location site) 9> Redundancy of data transfer (optical fibre as a ring main, remains functional despite failure at a point in the ring)	7	Protocol to minimise SMS downtime	5.0	2.8	83	67
4h	4.3 System status	Protocol for SMS expansion or upgrade: 1> Anticipated in hardware design and selection 2> Anticipated via drilling boreholes for additional sensors well ahead of stoping (drill at least monthly, via the normal workplan system of the mine, and drill three boreholes per location to enable future replacement sensors) 3> Anticipated in budgeting and achieved in short time frame	8	Protocol for SMS expansion or upgrade	5.0	2.5	58	33
4i	4.4 QA/QC	Protocol to ensure sufficiency and quality of SMS raw data: hardware and software (adequate sensor type/numbers, avoid planar arrays, correct sensor location information, adequate sensitivity)	9	Protocol for QA and QC of SMS raw data (adequate hardware and software)	4.0	3.5	67	33
			10	4.5 Hz sensor installed to capture Strong Ground Motion	4.3	3.0	67	0
4j	4.4 QA/QC	Protocol for SMS calibration (velocity model, Ground Motion Prediction Equation (GMPE)	11	Protocol for SMS calibration (velocity model)	3.3	3.8	75	0
4k	4.4 QA/QC	Checks and methods to ensure SMS event dataset is not contaminated (i.e. by positively identifying ore pass noise, blasts, popping blasts, stope overbreak, cave material flow)	12	Protocol for QA and QC of SMS processed event dataset (adequate removal of blasts etc)	4.3	4.3	58	33
4l	4.5 Regional and national seismic network	Access to regional and/or national seismic networks, in case large events occur regionally, or while the mine SMS is off line.	13	Access to regional or national seismic networks	1.7	5.0	25	0

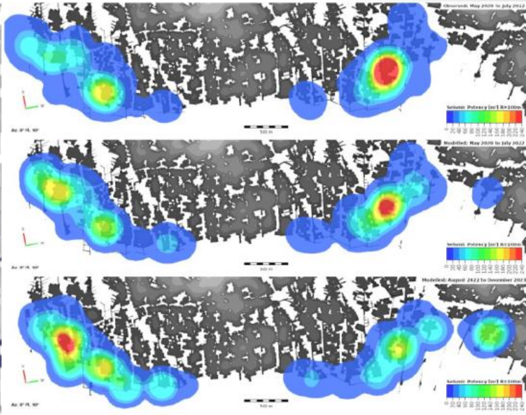
Modelling and seismicity (5: Analysing risk)

- Correlation with seismic events and other data
  - Location, location, location
    - Structures, pillars, abutments, yielded rock
  - Damage thresholds (static and dynamic) – records of damage required
  - Deformation measurements/observations
  - Old published criteria do not conform with current risk tolerance
- Comparative modelling to determine best layout and sequence
- Simulating planned layouts to evaluate risk
- South Africa modelling
  - Elastic DD and FF (Map3D, ISSM, MinSim/Besol?) - σ_1, ERR, VER, Closure, ESS, Ride, Potency, RCF
  - Fit for purpose

ESS and Ride

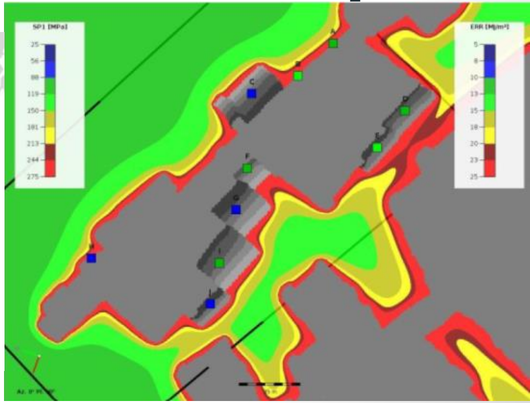


Seismic Potency



RCF

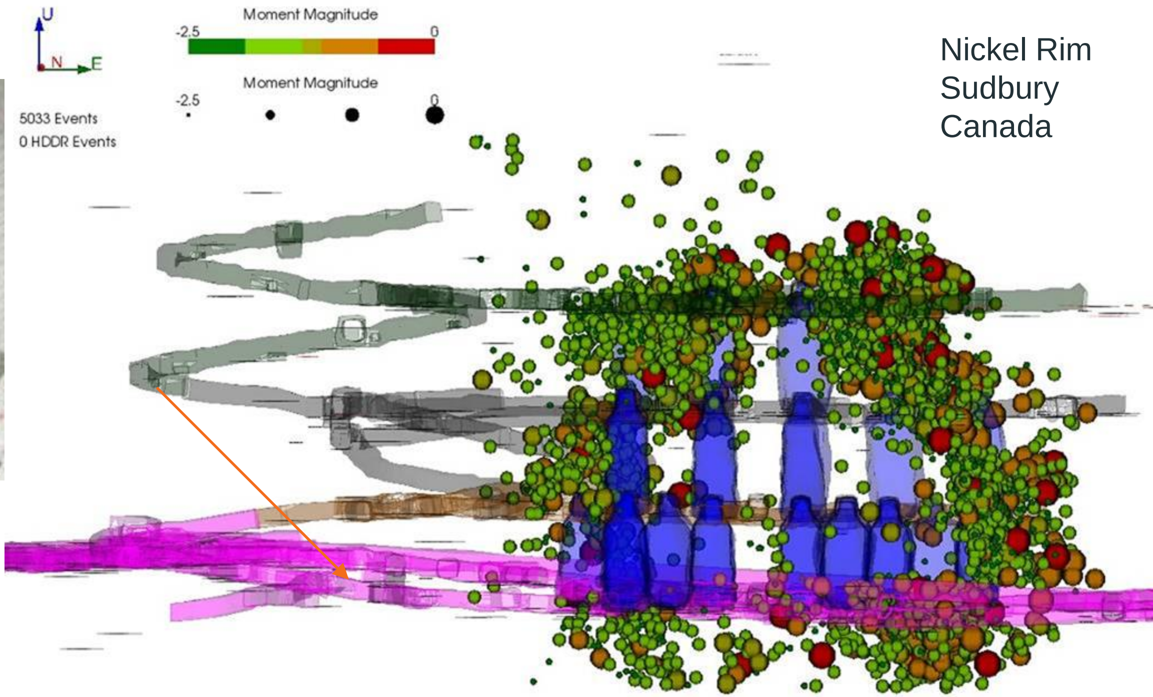
ERR and σ_1



Analysing yielded rock (5: Analysing risk)

M<0 seismic events used to show progression of stress damage around stopes
Good location and sensitivity required to verify yielded rock

Development in “high stress” abutments and pillars taking advantage of yielded rock around big stopes.



Nickel Rim
Sudbury
Canada

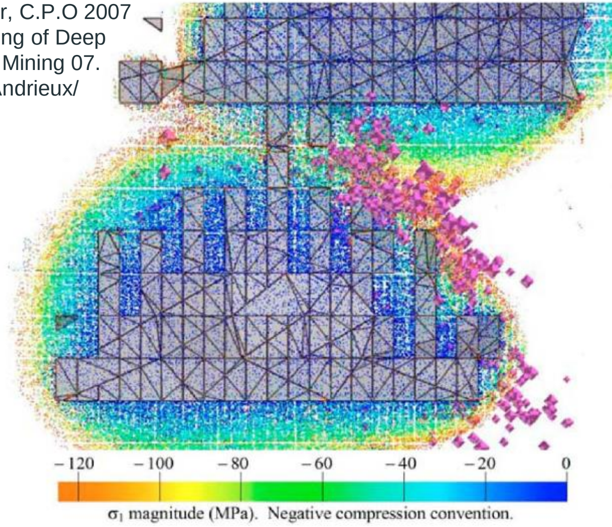
Jalbout, A. and Simser, B 2014. Rock mechanics tools for mining in high stress ground conditions at Nickel Rim South Mine. Deep Mining 2014 – M Hudyma and Y Potvin (eds).ACG. Perth, ISBN 978-0-9870937-9-0. doi:10.36487/ACG_rep/1410_11_Jalbout

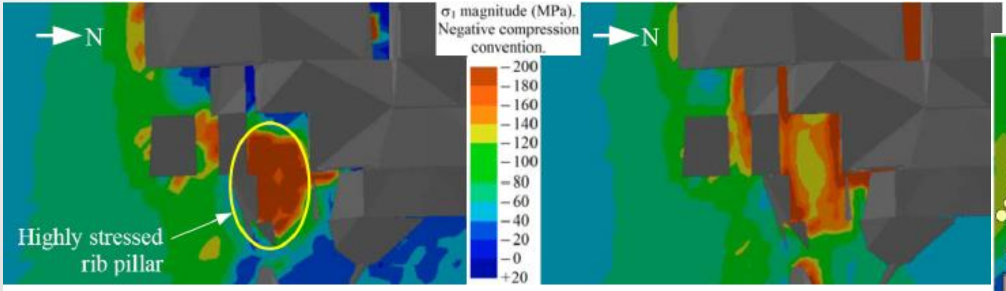
Are there opportunities to use good quality data to verify yielding of remnants or yielding ahead of the stope face (faceburst risk)?

Modelling and seismicity (5: Analysing risk)

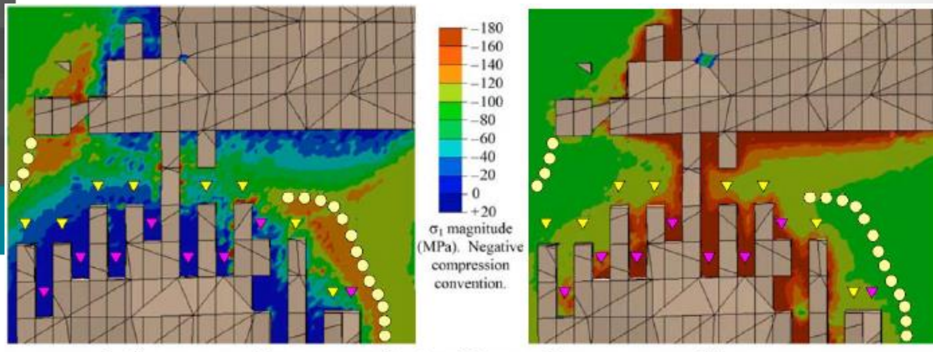
- International modelling
  - Elastic (Map3D, ISSM, EX3, RS3) - σ_1, $\sigma_{\theta max}$, VER, ESS, Ride, Depth of failure -bulking
  - Elasto-plastic, coupled models (FLAC3D, Abaqus, RS3) – Constitutive models (perfectly plastic, strain softening, Hoek-Brown, Spalling) - Energy release, σ_1, deviatoric stress, plastic strain, etc.
  - Elastic-plastic is necessary when there are large volumes of stress damage. Coupled models used to represent cave propagation and associated stress re-distribution.
  - Will it help to understand your rock mass behaviour better?

Andrieux, P. Brummer, R.K., Li, H, Connor, C.P.O 2007 Elastic Versus Inelastic Numerical Modelling of Deep and Highly Stressed Mining Fronts. Deep Mining 07. https://papers.acg.uwa.edu.au/p/711_4_Andrieux/





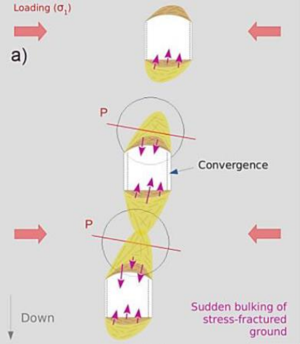
(a) Inelastic strain-softening. (b) Elastic.



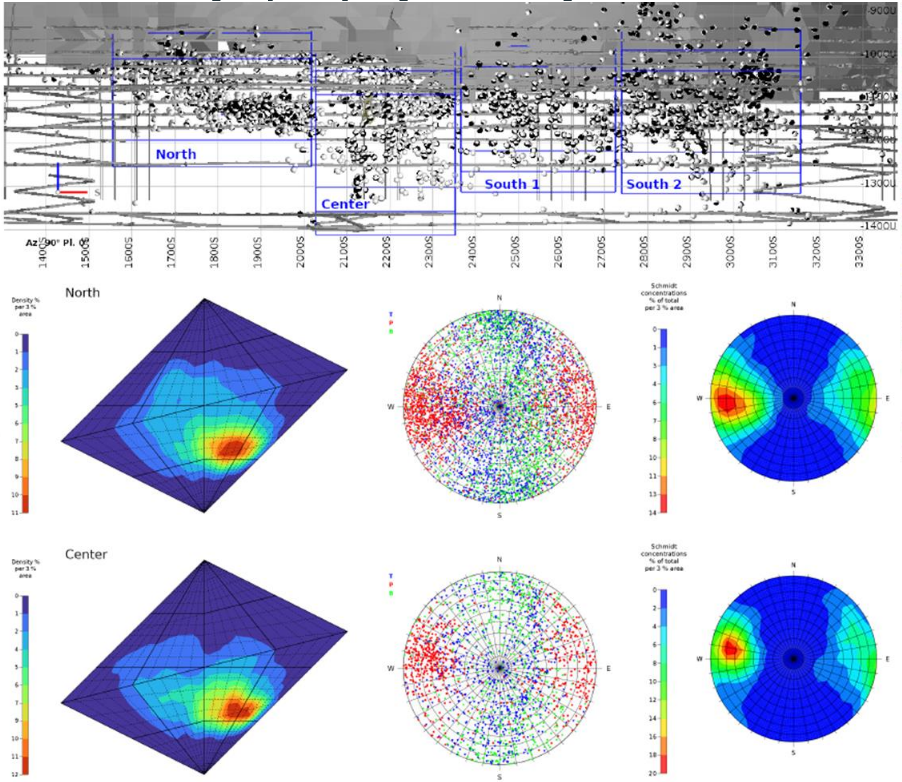
Inelastic strain-softening. (b) At mining step B. Elastic.

Source mechanisms - moment tensor (5: Analysing risk)

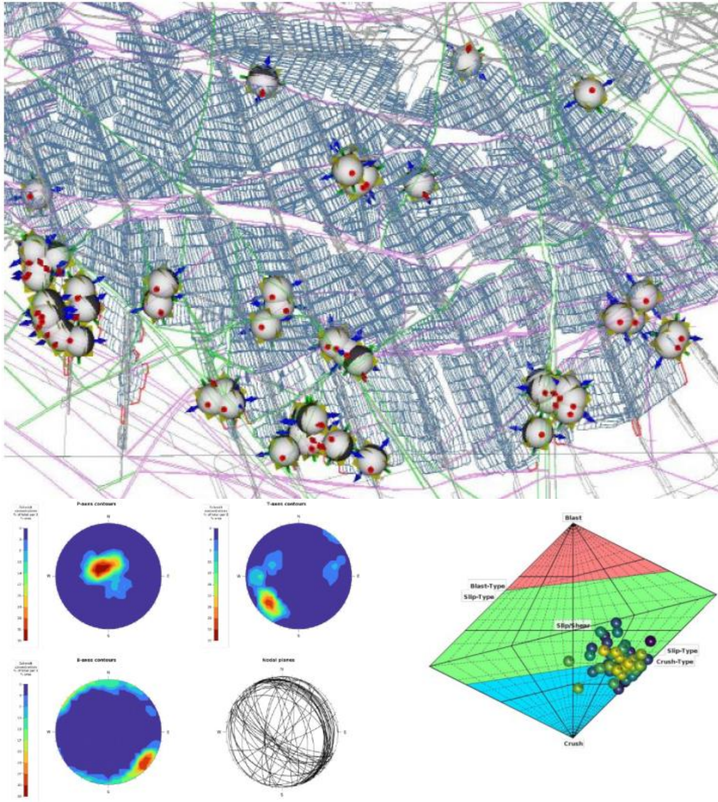
Damage interpretation



High quality – good configuration



Low quality – poor configuration?



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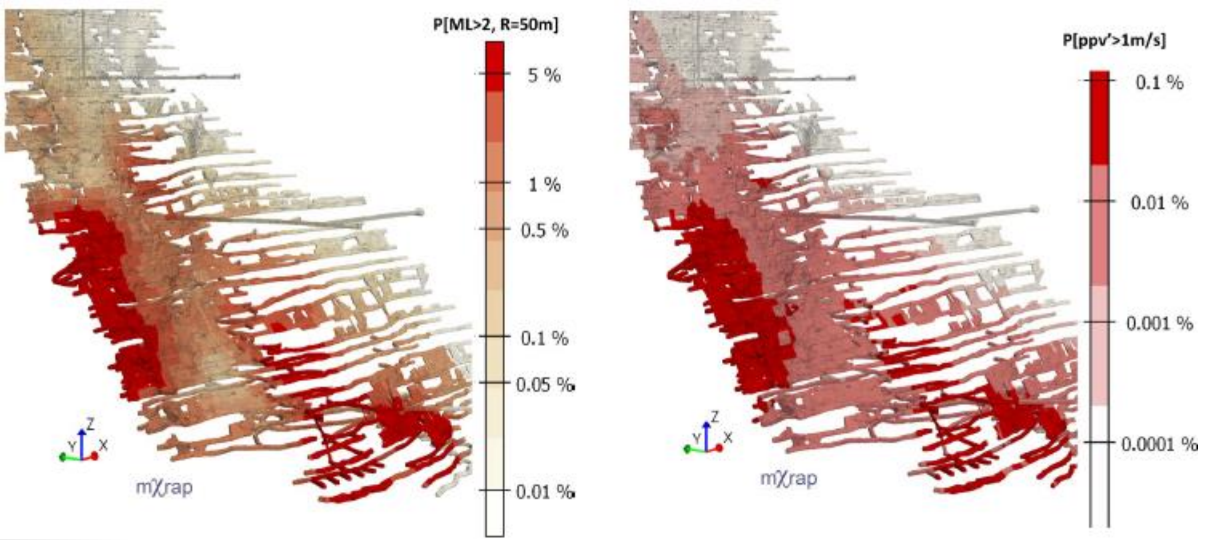
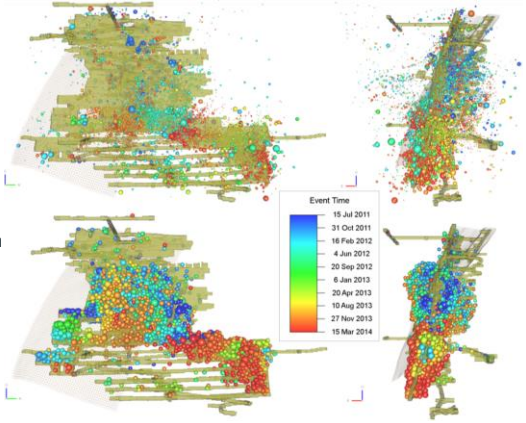
Boskovic, M 2022. 'Challenges of Resuming the production after a major seismic event at LKAB's Kiirunavaara mine', Proceedings of the Tenth Conference on Rockburst and Seismicity in Mines, Society for Mining, Metallurgy & Exploration, Englewood.

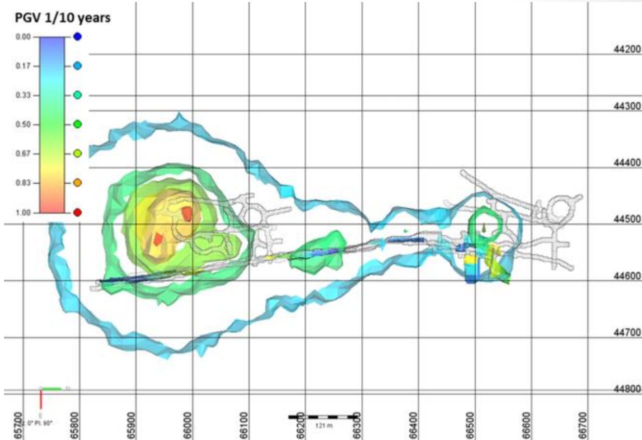
Wesseloo, J 2018. The Spatial Assessment of the Current Seismic Hazard State for Hard Rock Underground Mines. Rock Mechanics and Rock Engineering. https://doi.org/10.1007/s00603-018-1430-4



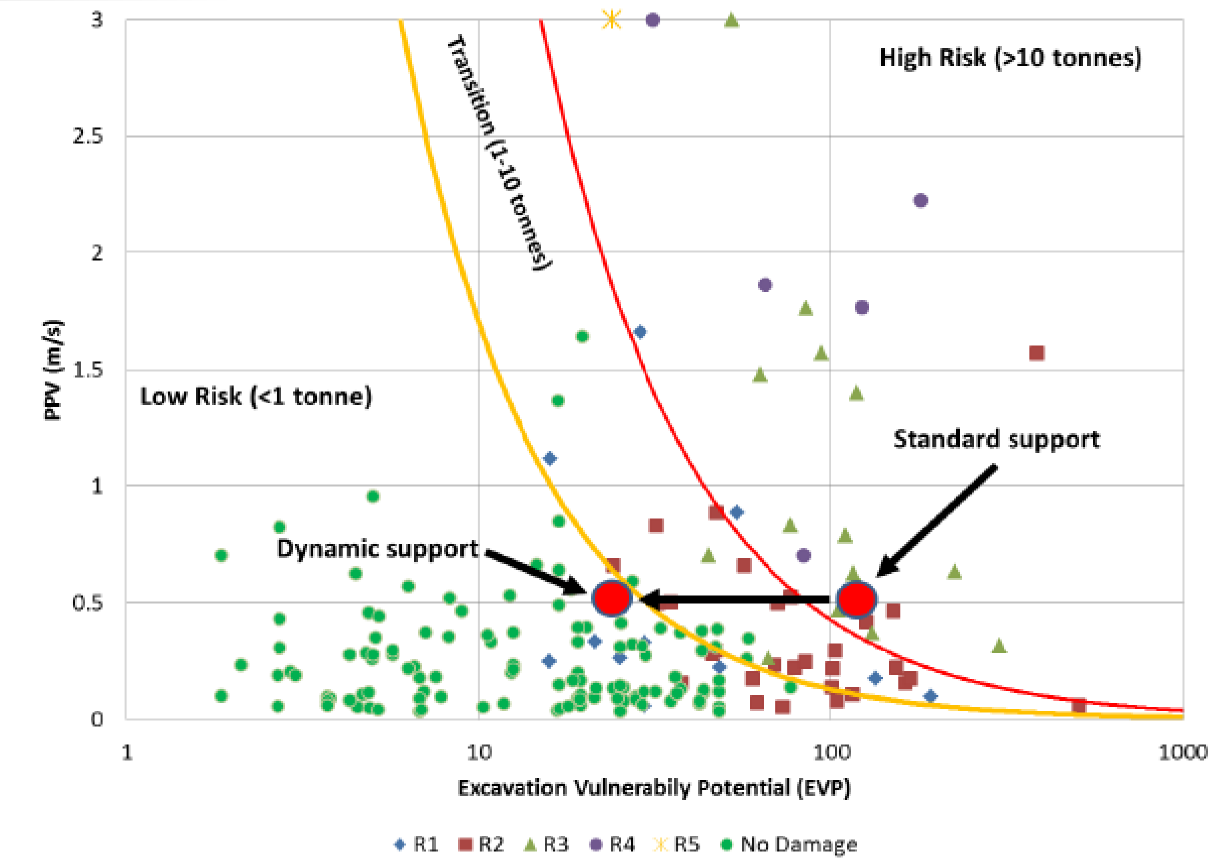
Malovichko, DA & Basson, G 2014 'Simulation of mining-induced seismicity using Salamon-Linkov method', in M Hudyma & Y Potvin (eds), Proceedings of the Seventh International Seminar on Deep and High Stress Mining, 16–18 September 2014, Sudbury, Australian Centre for Geomechanics, Perth, pp. 667–680.

Malovichko, DA 2017 'Assessment and testing of seismic hazard for planned mining sequences', in J Wesseloo (ed.), Proceedings of the Eighth International Conference on Deep and High Stress Mining, 28–30 Marchn2017, Perth, Australian Centre for Geomechanics, Perth.





Assessing Rockburst Damage Potential (5: Analysing risk)



Using rockburst database to evaluate damage potential

Excavation vulnerability potential

EVP = (E1/E2)x(E3/E4)

E1: Stress /Strength

E2: Ground Support

E3: Excavation Span

E4: Geological structures

Heal, D, Potvin, Y & Hudyma, M 2006, 'Evaluating rockburst damage potential in underground mining', in DP Yale (ed.), Proceedings of the 41st U.S. Symposium on Rock Mechanics (Golden Rocks 2006): 50 Years of Rock Mechanics – Landmarks and Future Challenges, vol. 2, American Rock Mechanics Association, Alexandria, pp. 1221-1232.

Concept good – factors outdated – develop your own factors

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Turcotte. P. 2014. Practical applications of a rockburst database to ground support design at LaRonde Mine. Deep Mining 2014 – M Hudyma and Y Potvin (eds). Perth, ISBN 978-0-9870937-9-0.doi:10.36487/ACG_rep/1410_03_Turcotte

Seismic Hazard Assessment Surveys – South Africa

Comments received

- The quality of Moment Tensors is normally low.
- It remains an issue to get reliable seismic source mechanisms.
- Rating systems can only add value when there are foreshocks or accelerated deformation before large events.
- Short-term assessments are regarded as unreliable and seen as problematic for production employees.
- Not to predict, but to raise awareness of seismic damage potential.

User – self rating

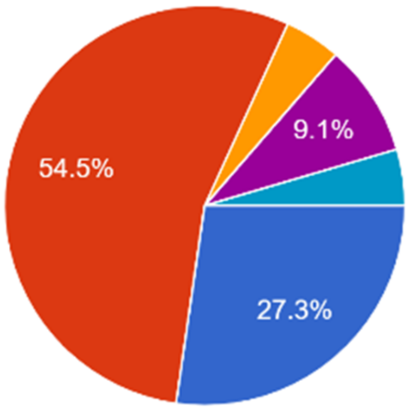
Objective	Procedure	Implemented Yes/No	Performance		
			Min	Median	Max
Data quality assurance	Internal/external audits and reviews	100%	3	4	5
Prevention & back analysis	Routine moment tensors	100%	1	4	5
Short-term hazard assessment	Daily seismic hazard ratings, minimum exclusion zones for large events	71%	2	3	5
Intermediate- & long-term hazard assessment	Estimate next record-breaking event, probabilities of occurrence in time and volume-mined domain	86%	2	4	5
Alerts	24/7 auto-rater, large event notifications, short-term activity tracker	57%	1	5	5
Rescue	Large event notifications, standby seismologist	86%	4	5	5

*Score on a scale of 1 to 5: **1=not successful/inaccurate/no value-add** and **5=successful/reliable/objectives met**

Confidence placed on received alerts

When you receive a seismic report which is "RED" or there are "CRITICAL ALERTS" which according to protocol, stops a working place and withdraws the crew, which option best describes the re-entry procedure you are most comfortable with:

22 responses

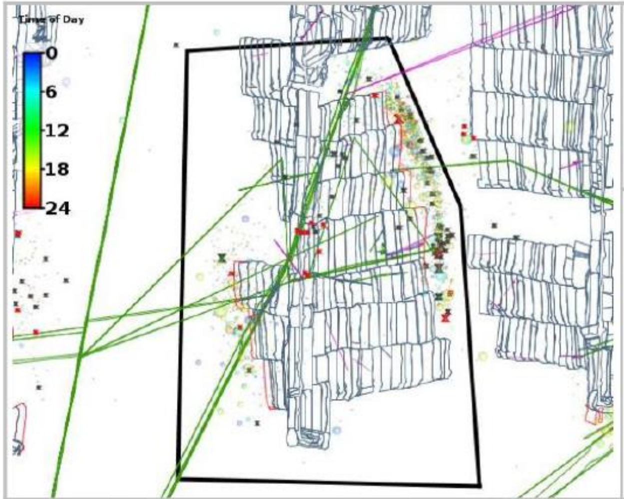


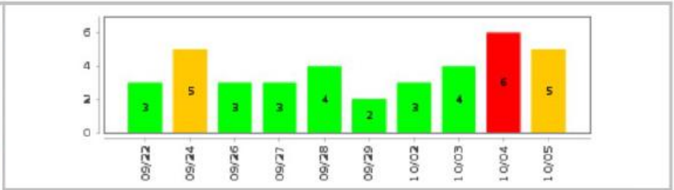
- The seismologist will let me know when critical parameters have recovered, and if it is safe for the mining operations to continue. I trust expert recommendation and will only allow crews to re-enter based on the seismologist feedback
- The seismologist monitors seismic activity and updates me of changes at which point I will conduct my own seismic analysis and/or discuss it with my peers or manager before authorizing re-entry. This is not a decision I feel comfortable making in isolation.
- I will provide my manager with the latest available information from the seismologist but ultimately expect them to make the call on when re-entry is safe.
- I do not rely on further feedback from the seismologist; I am familiar with my Rock / Geotechnical mass response to mining and will make the call for re-entry when I believe it is safe to do so.
- This is not a decision that can be made from the surface, and Rock / Geotechnical Engineering will visit the working place underground to determine if it is safe for the crew to resume production.

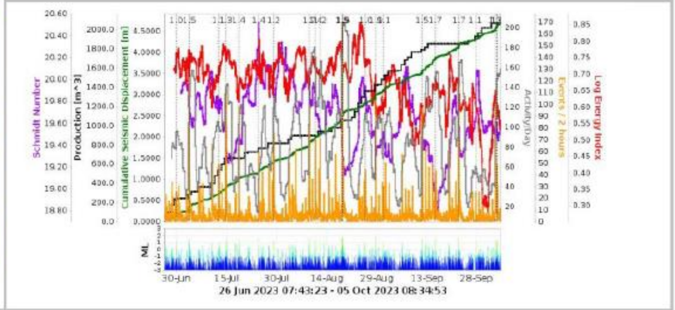
Short term seismic hazard assessment

- Location accuracy and sensitivity? – definition of polygons is subjective?
- Production vs cumulative displacement is interesting.
- Activity rate possibly useful
- Small events (M<0) and 4.5 Hz sensors – beyond sensor specs. (Energy Index and Apparent Stress)
- Schmidt number?
- Subjective adjustment of filters and thresholds, low reliability
- Spottiswoode paper – no evidence of precursory activity – none of the international mines thought it was possible to predict
- Too complex, does it truly represent rock failure processes as implied theoretically? What does this really mean?
- Alert criteria are subjective.
- Re-entry criteria are not obvious.
- Is the expectation correct?

Short-Term Seismic Hazard (days) [Hazard Assessment]







Last event Date and Time:	05 Oct 08:29:935
Number of new events:	74
Total Energy:	8.4e+03 J
Total Moment:	1.7e+10 Nm
Sum M + E expressed as magnitude:	0.1
P(M1.0) during the next 5 days:	0.42
P(M0.5) during the next 5 days:	0.77
No of events between 0.0 and 0.5:	0
No of events larger than 0.5:	0
Current normalized activity rate:	71.44
Medium term normalized activity rate:	86.18

A few small out of blast time events were recorded.
Yesterday: ml1.4 was recorded near the top of the raise followed by a ml1.0 at thr bottom. A strong increase in the short term seismic strain rate was observed.

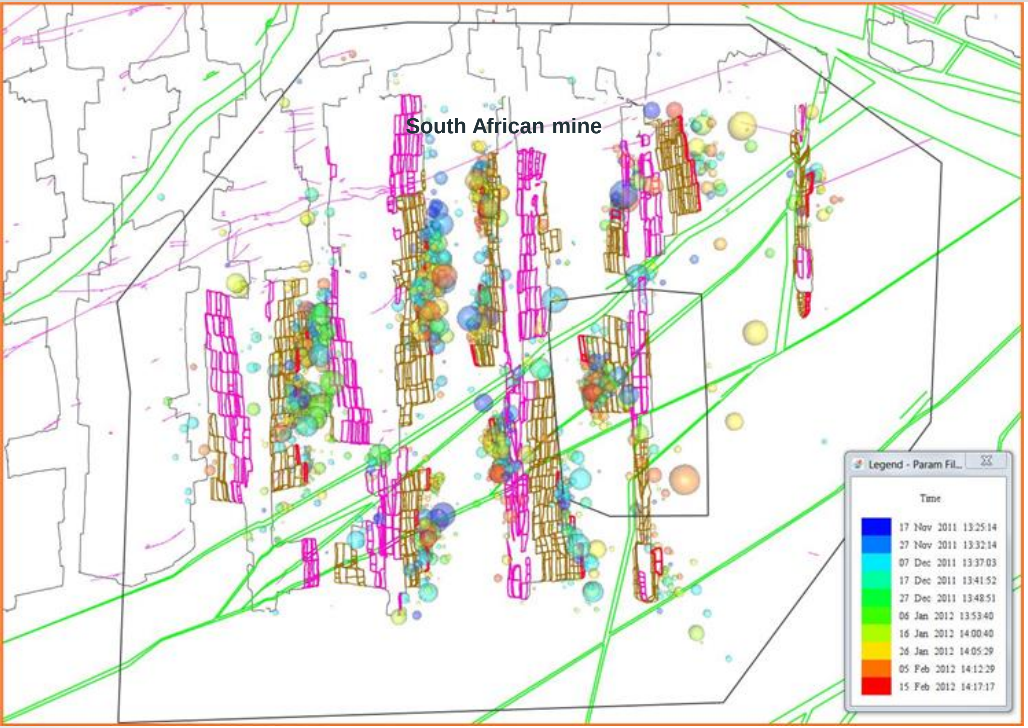
Only in South Africa

Not prediction – how do we use it?

Tarps (including exclusion zones and re-entry) (6: Evaluating risk)

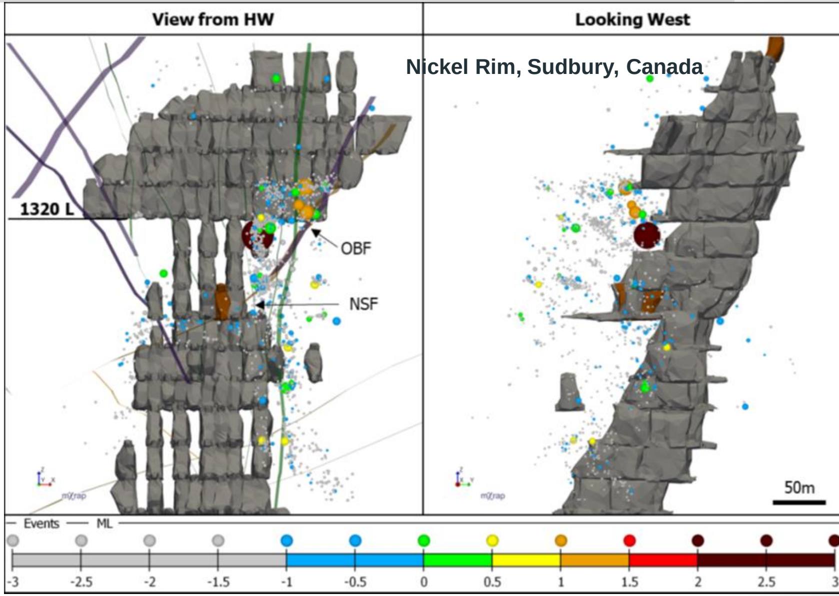
AS NZS Step	POTVIN SRMP	Rating system 0 Adverse to 5 Favourable 0 no effect to 5 major effect		Strategy Name x70 Strategy Name	Practicable (risk effective) rating (0 worst to 5 best)	Reasonable (cost effective) rating (0 worst to 5 best)	Industry adoption score	Regulator adoption score
		Evaluate Risk		**Evaluate Risk x9**				
6a	10.2 TARP exclusions	TARP: Trigger Action Response Protocols to guide immediate response to various seismic triggers	1	Trigger Action Response Protocol (TARP) guiding response to seismic triggers	4.5	4.2	92	100
6b	10.2 TARP exclusions	TARP for re-entry time and space exclusion period, applied in real time. To allow for sudden increase in event rate or magnitude. Uses SMS data at the specific time.	2	TARP protocol includes time and space exclusion triggered by real time activity	4.0	4.4	50	33
6c	10.2 TARP exclusions	For IMS: Re-entry based on STAT traffic light system (probabilities of event rate higher than background). For ESG: Re-entry based on SeisWatch system (event rate and Seismic Work Rate higher than background).	3	STAT system as a triggering criteria within TARP	2.8	4.0	42	33
6d		Supervisor / workforce access to basic seismic event visualiser and STAT or SeisWatch status	4	Supervisor & workforce access to seismic event visualiser and STAT status	4.0	4.8	50	0
6e		TARP for SMS downtime. To trigger removal of personnel from areas of high susceptibility to significant seismicity, for a set period (similar to an exclusion zone) or until SMS is back on line.	5	TARP protocol includes time and space exclusion triggered by SMS downtime	3.5	4.0	17	0
6f		If ongoing TARP alert, review situation at least daily with site stakeholders	6	Provision for review if TARP alert is ongoing without resolution	4.0	3.0	17	0
6g		Protocol for “Seismic Clearance” (geotechnical inspection of potentially damaged areas after significant seismicity, before opening areas to general access, and monitor for changes)	7	Protocol for “seismic clearance” (geotechnical inspection after damaging event)	4.5	3.8	33	0
6h		TARP for upgrade of support. Triggered or anticipated instigation of upgrade of GSS in response to a change in seismic hazard, prior to damaging seismicity	8	Protocol for ground support upgrade, triggered by seismic hazard increasing above a criteria level	4.0	3.4	25	0
6i		TARP for repair of SMS degraded function (e.g. minimum number of operating sensors) or SMS downtime (equipment failure).	9	TARP protocol includes rapid repair of SMS degraded function, triggered by SMS downtime	5.0	4.2	17	0
			10	TARP to check surface infrastructure (e.g. tailings dams) after seismic shaking	4.5	4.0	8	0

Blast re-entry and exclusion zones (6: Evaluating risk)



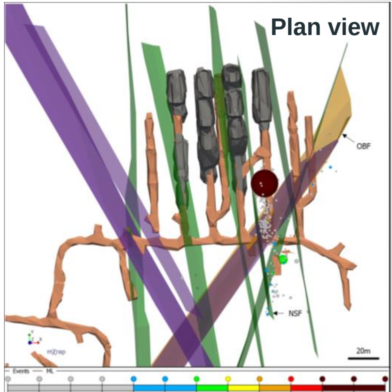
- Blast 50 to 100 small stopes /day
- Energy release spread out across the whole mine (centralized blasting?)
- Blast re-entry between shifts generally sufficient (time of day analysis)

Largest seismic events often occur randomly and outside of exclusion windows (% above threshold)



- Blast 1-5 large stopes /day
- Concentrated energy release
- Prolonged response to blast if stopes are "hot" –(unfavourable fault geometry or mining geometry)
- Barricade off exclusion zone before blast
- Possibly days to weeks – 12 hourly reviews

Ollila, B. 2021. Time distance analysis of a mine scale event. MASc Thesis. Laurention University, Sudbury, Canada.



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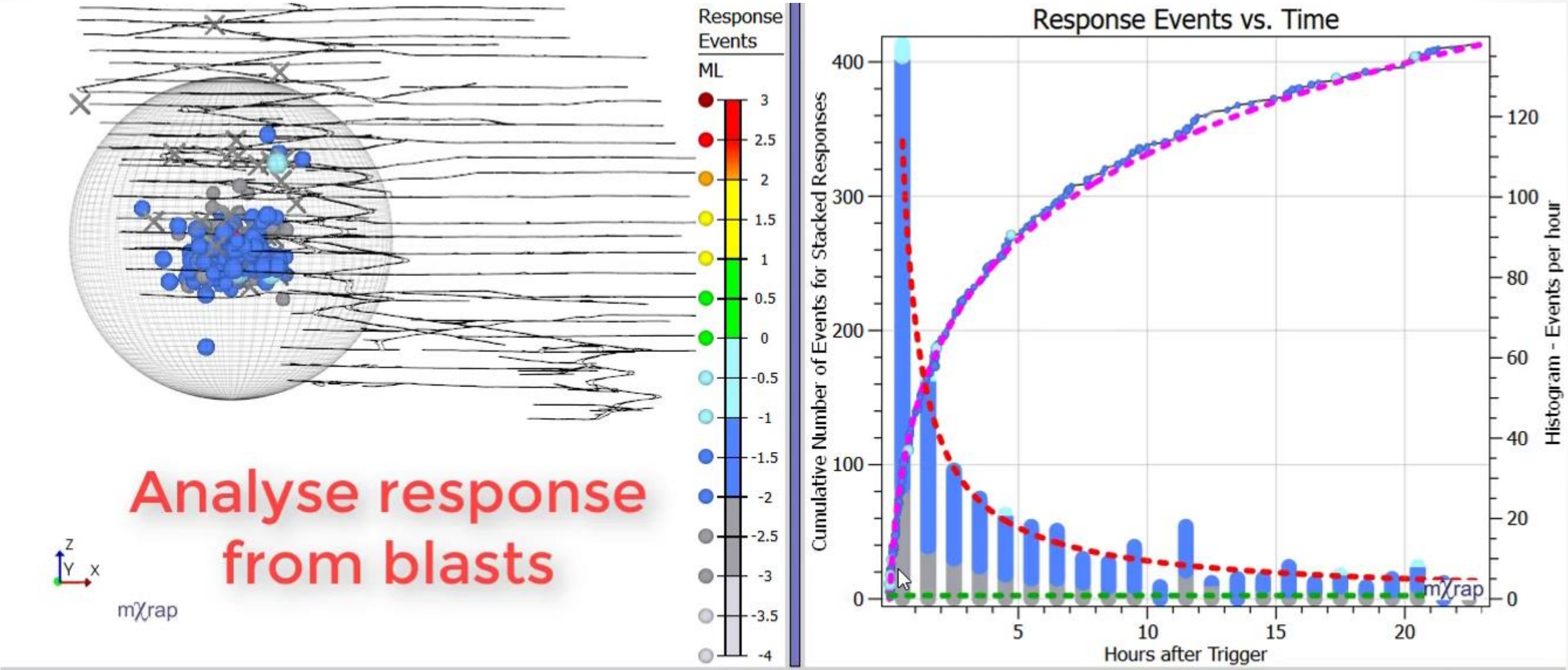
Rock engineering protocols for identifying exclusion zones?

Blast re-entry – Omori analysis (6: Evaluating risk)



Look for deviations from the normal pattern

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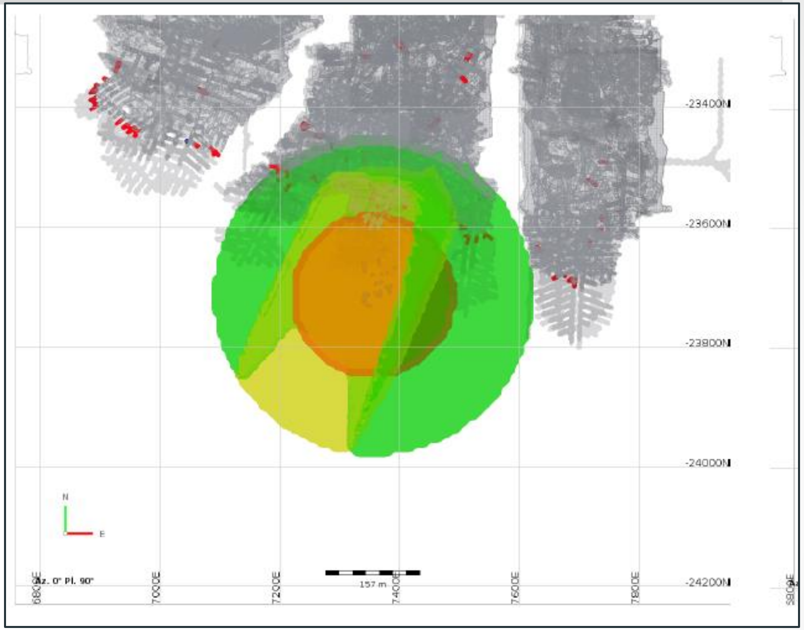
Large Event exclusion/Re-entry tools (6: Evaluating risk)

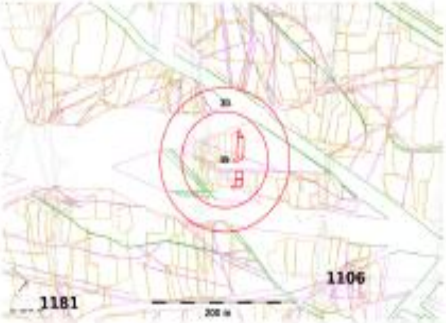
A Seismic Event of $M_L \geq 2.0$ occurs and an exclusion zone is displayed on Ticker3D screen with the affected de-stress workplaces.

GMPE



1. The exclusion rules (using all seismic events), as derived in this report, with minimum exclusion time (*in minutes*) and radius (*in meters*) are given in the table below for blasts at Top Mine:

Blast Type	Exclusion Rule
Production	1) 90 m for 30 min 2) 60 m for 45 min

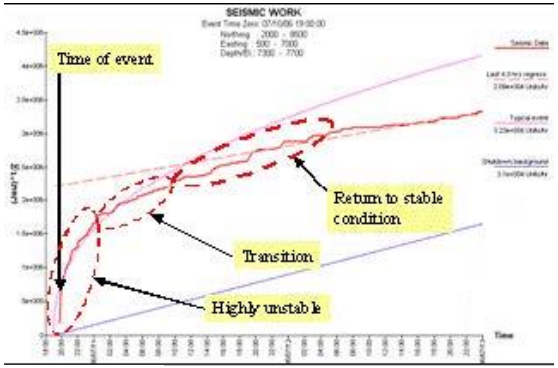


Is the threshold based on damage reports?

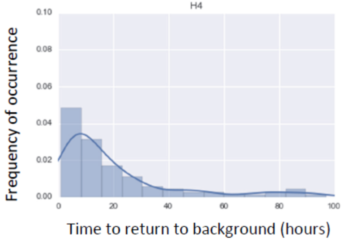
Exclusion/Re-entry tools (6: Evaluating risk)

SeisWatch
ESG
Based on Activity Rate
Vale Mines, Canada

Malek, F & Leslie, IS 2006, 'Using seismic data for rockburst re-entry protocol at Inco's copper cliff north mine', Proceedings of the 41st US Symposium on Rock Mechanics (USRMS): ARMS.



SeisWatch parameters	Proportional to
Event decay rate	Event number and time
Seismic work (and work rate)	Strength and time
Clustering	Location and time
Strain rate	Strength, location and time
Event level frequency	Depth, location and time



Abolfazlzadeh, Y., Smith-Boughner, L. Anderson, Z, Jalbout, A.Mataseje. 2019. Calibration of a seismic hazard assessment tool using velocity fields and geotechnical data. Mining Geomechanical Risk. doi:10.36487/ACG_rep/1905_12_Abolfazlzadeh

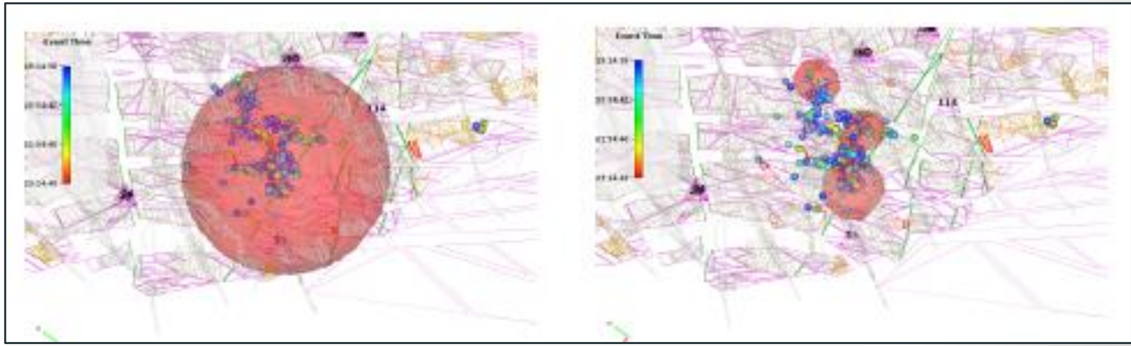
Short Term Seismic Activity Tracker (STAT)
IMS – Based on Activity Rate
Australian SRMPs

if $\Pr(\lambda_2/\lambda_1 > 1) \leq 0.5$

if $0.5 < \Pr(\lambda_2/\lambda_1 > 1) < 0.75$

if $\Pr(\lambda_2/\lambda_1 > 1) \geq 0.75$

Ground Motion Assessment program (GMAP) IMS
Cumulative Absolute Inelastic Displacement (CAID) –interesting concept
Strong Ground Motion - based on GMPE – not in SRMPs yet



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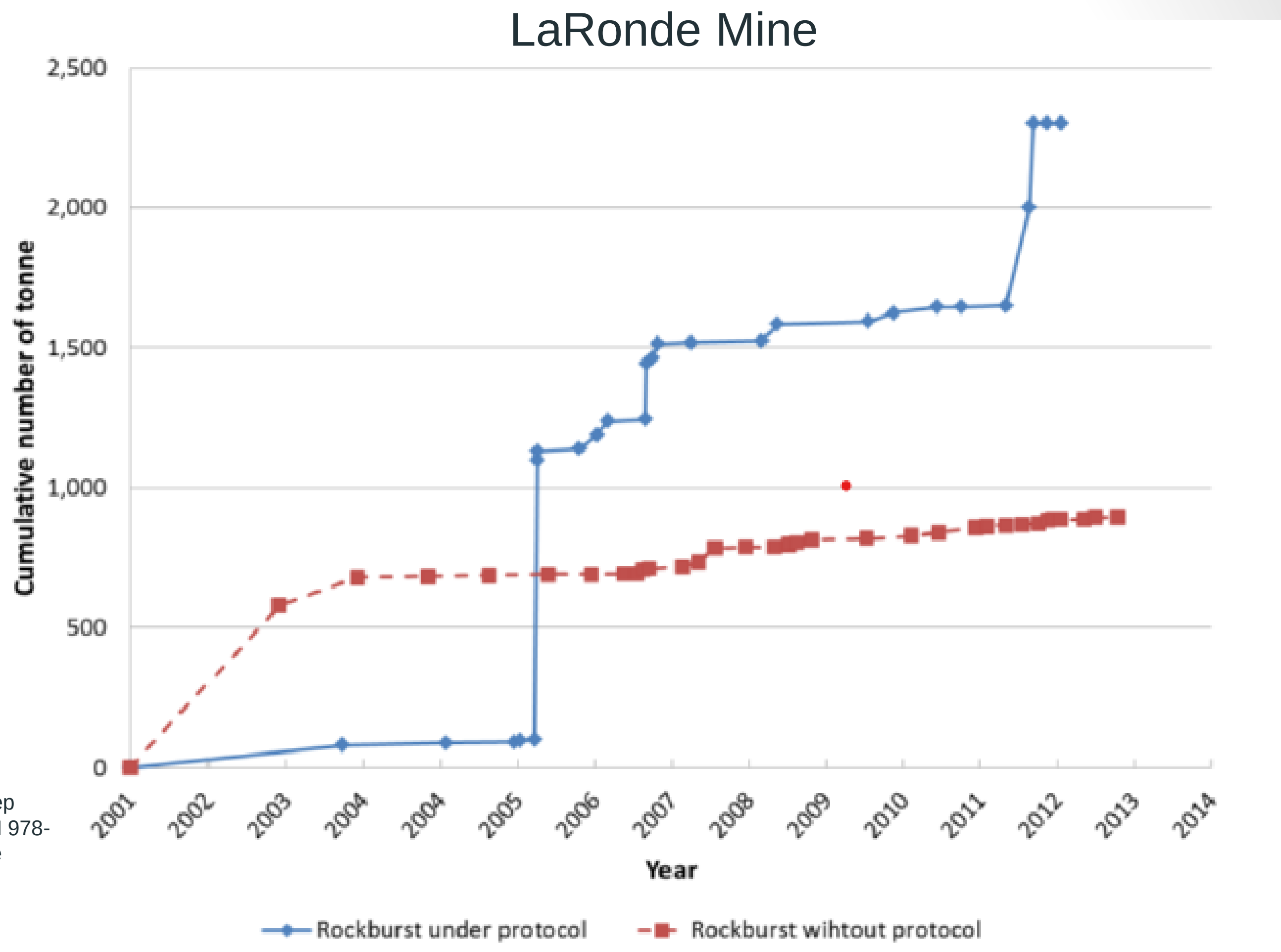
Not prediction or forecasting, measurement of what is happening now!

Exclusion Zone Success Rate (6: Evaluating risk)

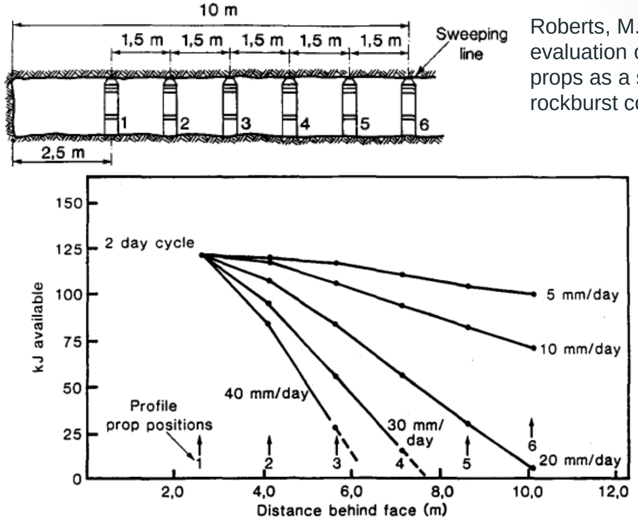
What proportion of large events (M?) / rockbursts occur outside of exclusion protocols?



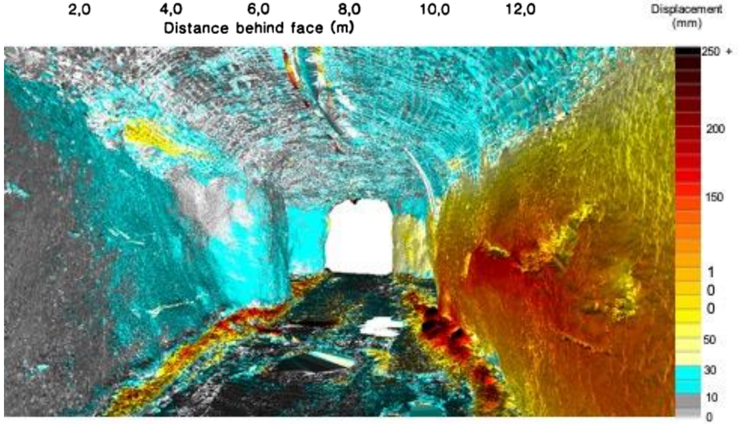
Turcotte. P. 2014. Practical applications of a rockburst database to ground support design at LaRonde Mine. Deep Mining 2014 – M Hudyma and Y Potvin (eds). Perth, ISBN 978-0-9870937-9-0. doi:10.36487/ACG_rep/1410_03_Turcotte

Rockburst Support (7: Treat Risk)

- Energy Absorption
  - Demand – v=3m/s? mass? 95% fall out height? subjective
  - Energy absorption capacity? (axial loading, shear, buckling)
  - Additive (bolts+mesh+straps) or weakest link?
  - Theoretical calculation to justify support ……even if the support system fails
- Deformation based support design and preventative support maintenance (Kaiser et al.)
  - Stope closure and support consumption (hydraulic and timber props) – important, particularly if you don't have backfill
  - Lidar surveys in tunnels to measure deformation over time is becoming more popular – processing still takes too long. Important in tunnels where you have stress bulking and deformation, possibly influenced by repeated strainbursts – support consumption
  - In some cases, there is no deformation prior to rockburst (not required or useful)
  - IMS CAID – interesting concept - will it become a useful estimate of deformation?



Roberts, M.K.C. 1991. An evaluation of yielding timber props as a support system in rockburst conditions. JSAIMM



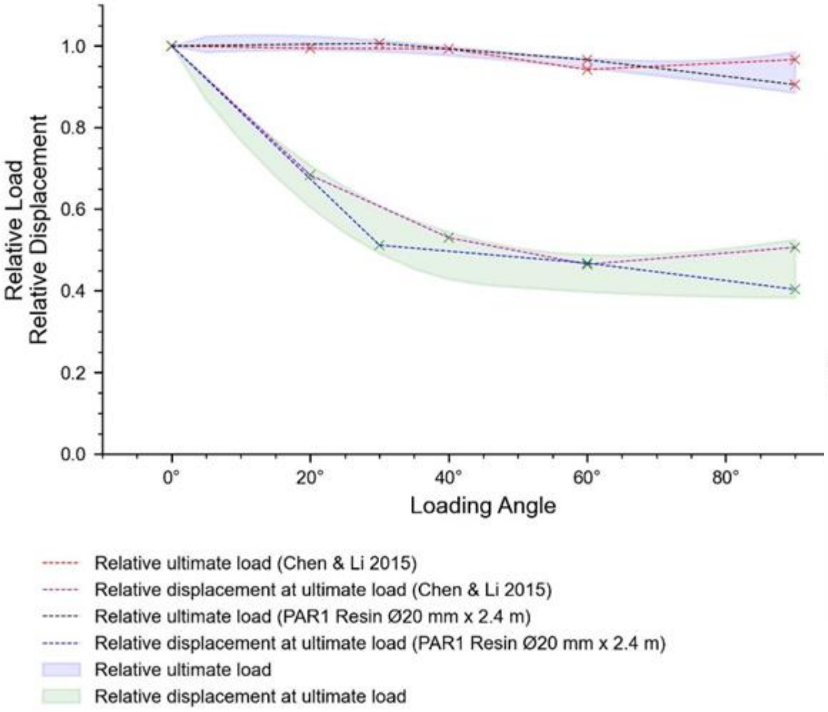
Kaiser, P.K and Moss, A. 2021. Deformation-based support design for highly stressed ground with a focus on rockburst damage mitigation. DOI: 10.1016/j.jrmge.2021.05.007

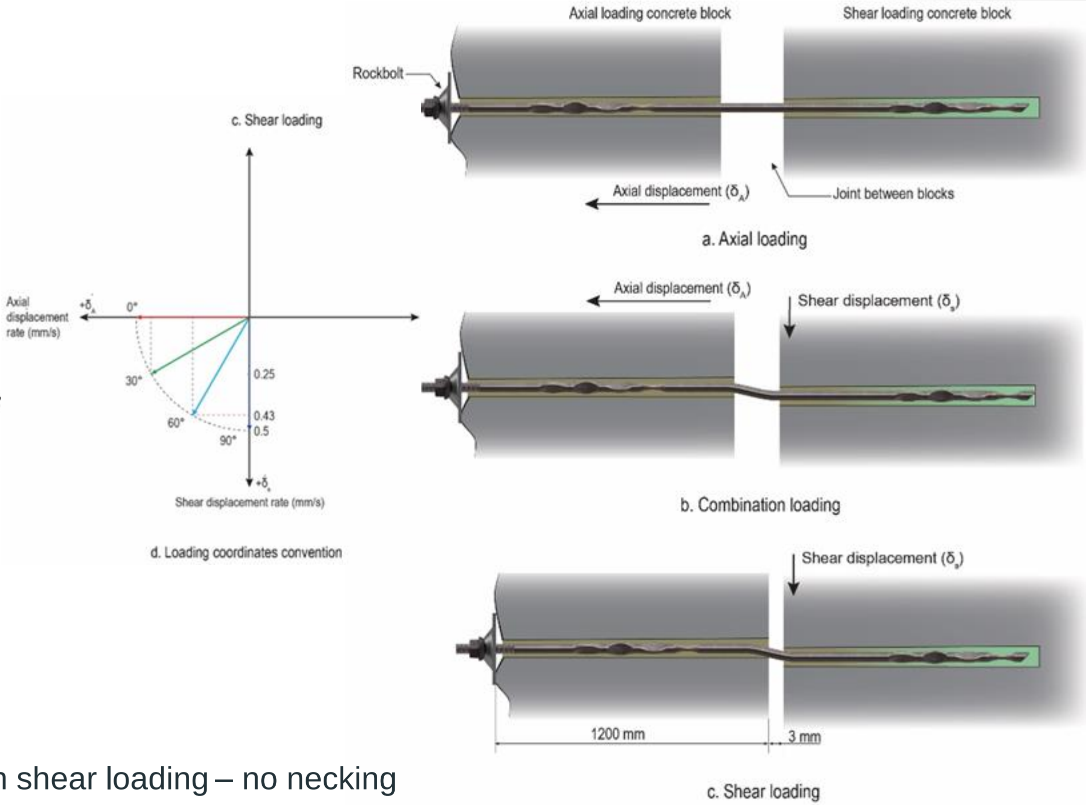
Rockburst Support (7: Treat Risk)

- Weakest link (review rockburst support failures and improve components of system) – 4 things to consider
  - Bolt / prop failure (mode of failure)?
  - Length of bolt?
  - Areal support (mesh/net) failure?
  - Failure of attachments?
- Face support for facebursts (tunnels and stopes)?
  - Bolts and mesh?
  - Are face nets effective?

Simser, B 2007. The Weakest Link — Ground Support Observations at Some Canadian Shield Hard Rock Mines. Deep Mining 07 — Y. Potvin (ed). https://papers.acg.uwa.edu.au/p/711_25_Simser/

Rockburst Support – failure modes (7: Treat Risk)





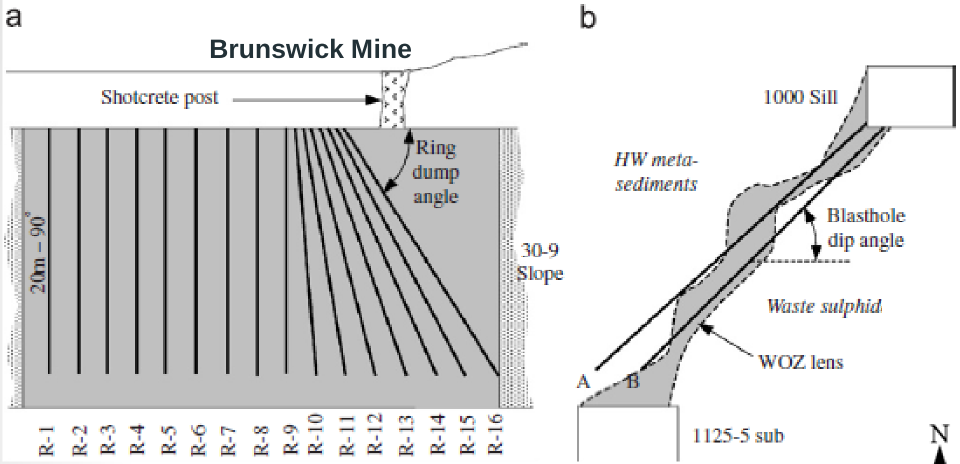
Low strain materials (<15%), even less deformation in shear loading – no necking

Knox, G and Hadjigeorgiou, J. 2024 in prep. Behaviour of paddled energy-absorbing rockbolts under complex loading laboratory conditions. JSAIMM

Destress slot blasting (7: Treat Risk)

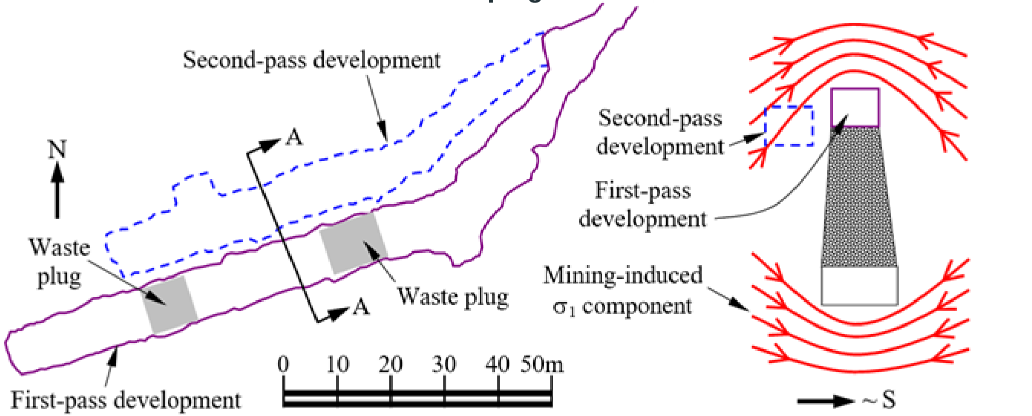
Longhole slot blast to destress development.

Brunswick Mine



Andrieux, P., Hadjigeorgiou, J., 2007. The destressability index methodology for the assessment of the likelihood of success of a large-scale confined destress blast in an underground mine pillar. International Journal of Rock Mechanics & Mining Sciences 45 (2008) 407–421.

Onaping



(a) Plan view (to scale) showing the drifts as eventually driven.

(b). Schematic cross-section A-A (not to scale) showing the stress-shadowing effect sought after.

Andrieux, P., Hadjigeorgiou, J., Sampson-Forsythe, A., Simser, B., Turichshev, A. Brummer, B. 2010. Recent case histories of the application of the empirical destressability index methodology. Deep Mining 2010 — M. Van Sint Jan and Y. Potvin (eds). © 2010 Australian Centre for Geomechanics, Perth, ISBN 978-0-9806154-5-6.

Tunnel destress blasting (preconditioning) (7: Treat Risk)

Not new concept, but good quality data used to confirm the effect of preconditioning

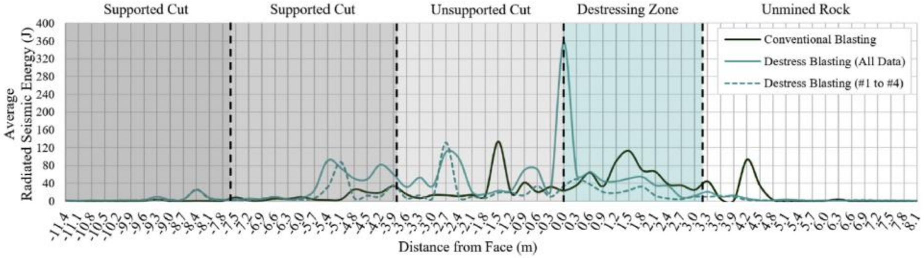


Fig. 8. Average seismic energy release per development cycle for both conventional and face destress blasting techniques.

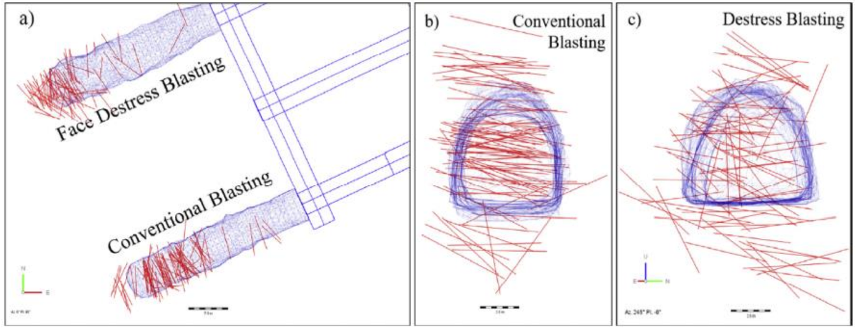


Fig. 14. P axes of the moment tensors shown in (a) plan view for both tunnels and cross-sectional view following (b) conventional and (c) face destress blasting.

Source mechanisms changed from shear to crush/implosive

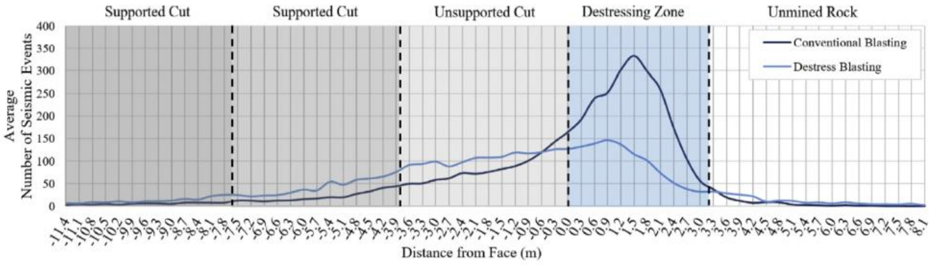


Fig. 7. Average number of seismic events per development cycle for both conventional and face destress blasting techniques.

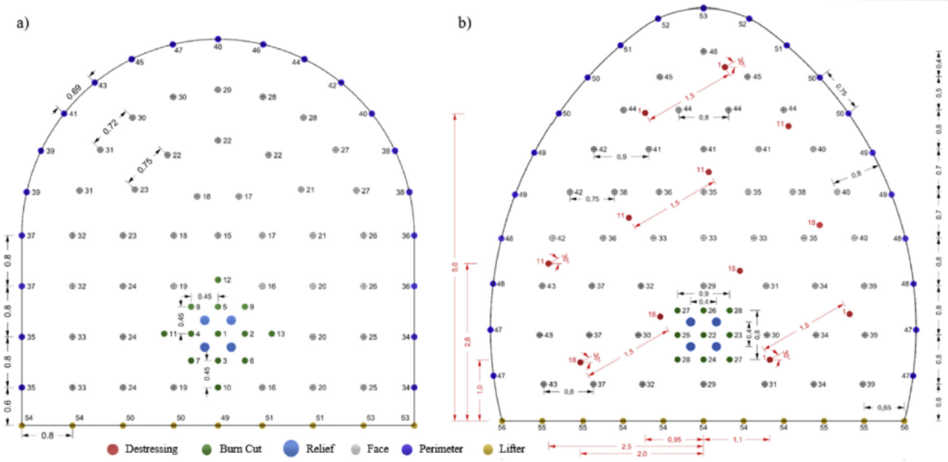


Fig. 2. (a) Southern excavation conventional shape and (b) northern excavation rounded shape with face destressing. Dimensions in meter.

Location and sensitivity!

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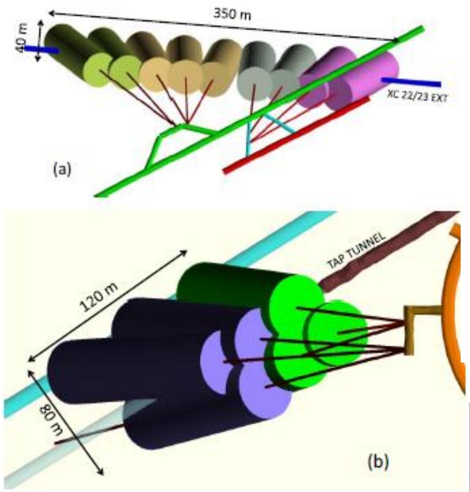
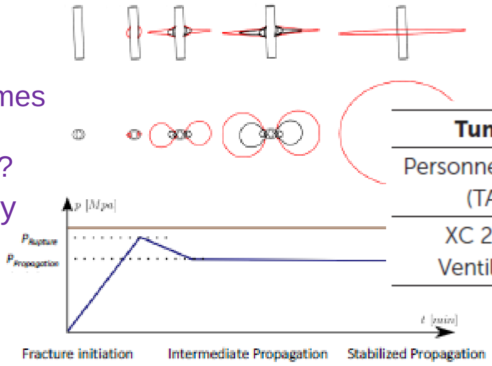
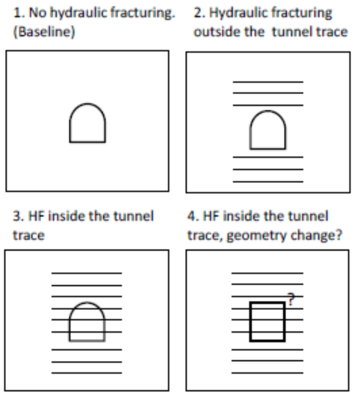
Drover C, Villaescusa E, 2019. A comparison of seismic response to conventional and face destress blasting during deep tunnel development, Journal of Rock Mechanics and Geotechnical Engineering, https://doi.org/10.1016/j.jrmge.2019.07.002

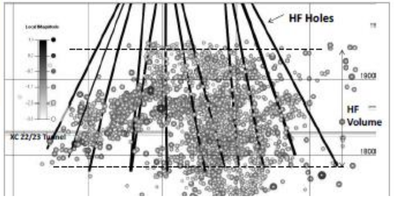
Hydraulic fracturing (7: Treat Risk)

- Reduced seismic hazard?
  - Mmax?
  - B value?
  - Period of analysis?
  - Can't mine the same ground twice.
- Activating faults?
  - Does it move asperities on structures further away?
- Altering rock mass characteristics?
  - Reduction in stiffness?
  - Brittle rock becomes more ductile?
  - More anisotropic?
- HF affect the stability of excavations?

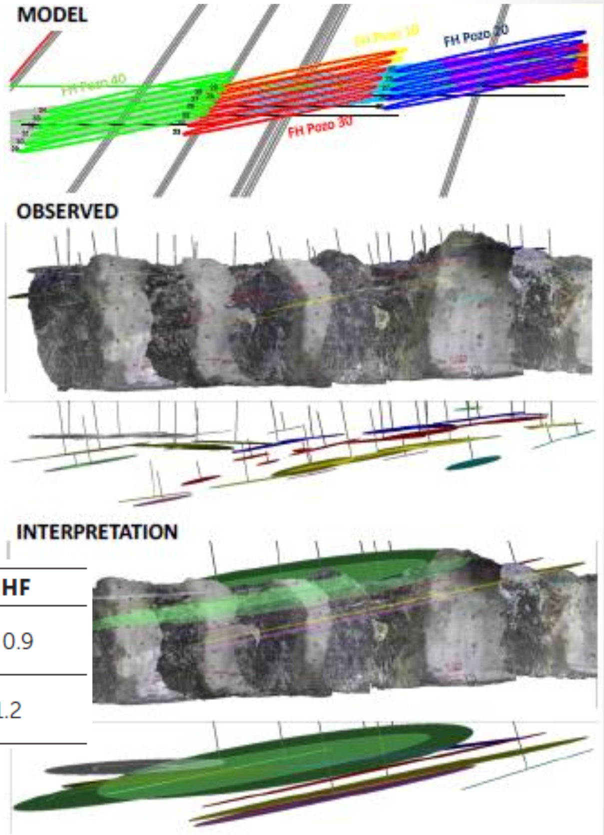








Packers used to generate fractures 2m apart down the hole



Tunnel	Before HF	After HF
Personnel Access (TAP)	Mw = 2.6	Mw = 0.9
XC 22/23 Ventilation	Mw = 2.0	Mw 1.2

Rojas, E & Landeros, P. 2017. Hydraulic fracturing applied to tunnels development at El Teniente Mine. 9th International Symposium on Rockbursts and Seismicity in Mines, Santiago..

Paste filling a tunnel (7: Treat Risk)

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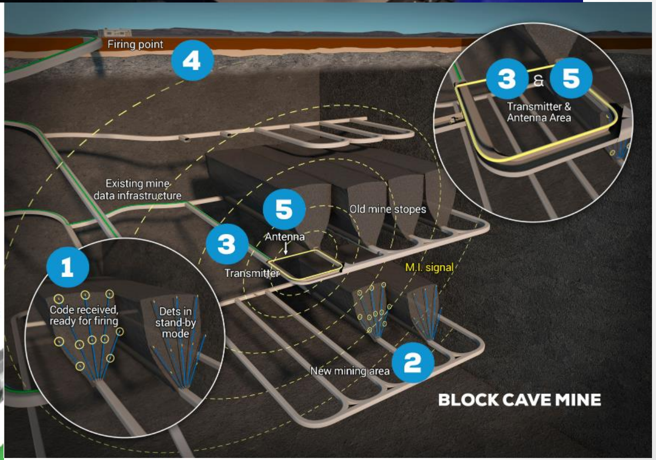
Mechanisation and Automation (7: Treat Risk)

- Remote loading (line-of-sight, tele-remote, fully automated)
- Mechanical scaling/barring (remote machines available) - beware of over scaling in high stress conditions – severe overbreak and difficult to support
- Mechanised support installation – (not always fully mechanized – some exposure, tendency to use fully mechanized (Boltec) in high risk areas)
- Mechanised drilling (remote drilling at Kiruna)
- Charging - high exposure at face – on utility vehicle (cages and face support) – El Teniente developing remote charger
- Wireless Initiation of Blasts (WebGen blasting) – Pre-charging of blastholes, reducing or eliminating the need to re-enter drawpoints to connect blastholes with wire or signal tube or re-support. Can improve sequencing.



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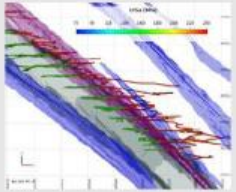
South African stopes will take time – R&D important

8: Monitor and review

AS NZS Step	POTVIN SRMP	Rating system 0 Adverse to 5 Favourable 0 no effect to 5 major effect		Strategy Name x70 Strategy Name	Practicable (risk effective) rating (0 worst to 5 best)	Reasonable (cost effective) rating (0 worst to 5 best)	Industry adoption score	Regulator adoption score
		Monitor and Review		**Monitor and Review x6**				
8a		Semi-annual or annual reporting on effectiveness of management: including SMS performance, compare seismic activity with numerical model forecasts, review hazard levels, effectiveness of controls. Includes protocol for identifying and actioning changes to enhance risk management.	1	Semi-annual or annual reporting on seismic activity and hazard management	3.7	3.6	33	0
8b		Annual Seismic Review Board (on effectiveness of management), includes comparison of forecast with actual. Is the system working? Includes protocol for identifying and actioning changes to enhance risk management.	2	Annual Seismic Review Board – wide-reaching review of effectiveness of management strategies	3.7	3.0	25	0
			3	Require sufficient personnel employed and trained to resource all SRMP requirements	5.0	3.6	25	0
8c		Verification of mine design controls during operations (as-mined to be as intended)	4	Verification of mine design implementation (that as-mined is what was intended)	4.3	4.0	0	0
8d		Verification of rock mass stability assumptions made during design, e.g. are pillars and structures and cave yield zone performing seismically as expected	5	Verification of rock mass stability assumptions made during design	3.7	3.4	8	0
8e		Audit and update the SRMP regularly – for effectiveness regarding hazard levels, communications, resourcing, gaps, good practice. Includes protocol for identifying and actioning changes to enhance risk management.	6	SRMP audit and update regularly	4.0	3.4	33	33
8f		Documentation: Ensure that relevant mine designs, methods, sequences, ground support and modelling are documented and available for review on an ongoing basis in relation to seismic outcomes.	7	Adequate documentation of all mining inputs related to seismic outcomes	4.3	3.2	8	33

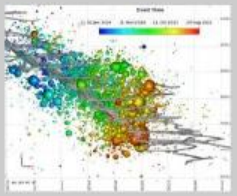
IMS Rockburst Hazard Assessment (RBHA) in Development

Rockmass properties



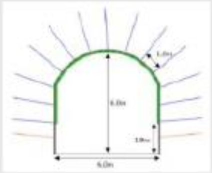
- UCS
- Rockmass density and S-wave velocity

Seismic data



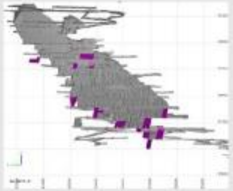
- Ground motion hazard
- Bulking duration
- Probability of strainbursting realisation
- Consumption of displacement capacity

Ground support



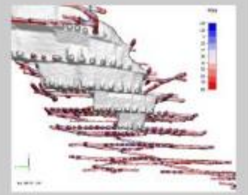
- Loading characteristics of bolts
- Parameters of ground support system

Geometry of excavations



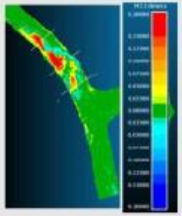
- Geometrical characteristics of tunnels
- Past mining sequence
- Planned mining sequence(s)

Stress model



- Static stress level index
- Orientation of maximum tangential stress

Underground observations

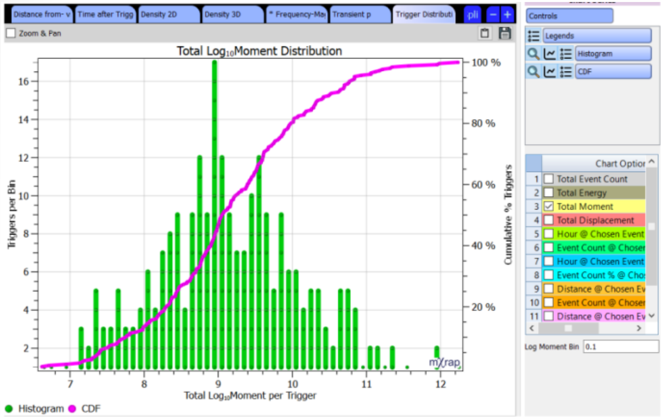


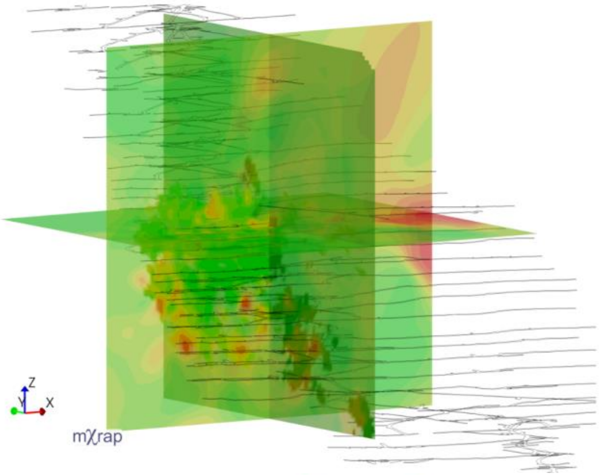
- Damage maps
- Measurements (LiDAR, etc.)

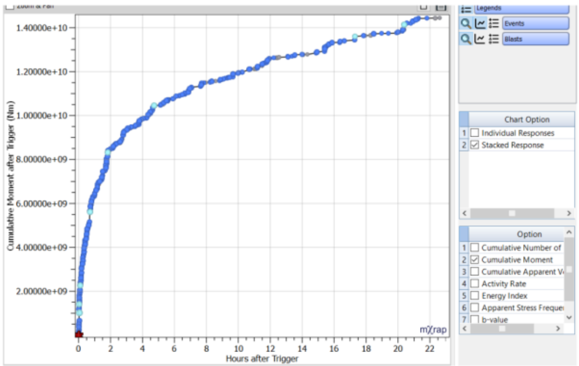
mXrap software program and research consortium

Rock Engineering approach, spatial database, includes other rock engineering tools
Can use existing tools (there are many) or custom develop your own (database & scripting)
In addition to existing service providers (IMS and ESG) – not competing
Rock Engineers use mXrap, but service providers also provide reports.

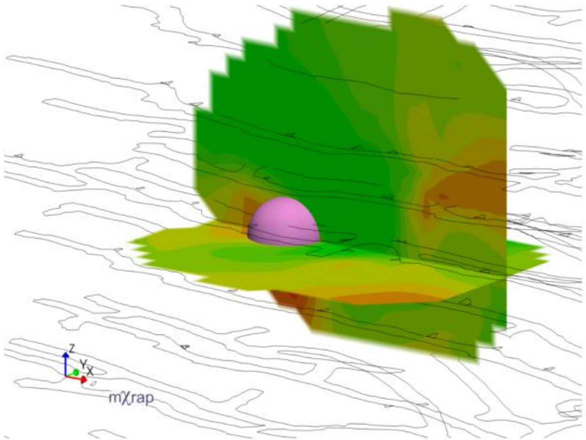
mxrap.com







Different perspective on seismic risk management?



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38 mXrap consortium members internationally
+ Licences for consultants (10) and Universities (19, includes UP & Wits)

mXrap

ACG AUSTRALIAN CENTRE FOR GEOMECHANICS

Hazard or risk assessment?

Not formalised

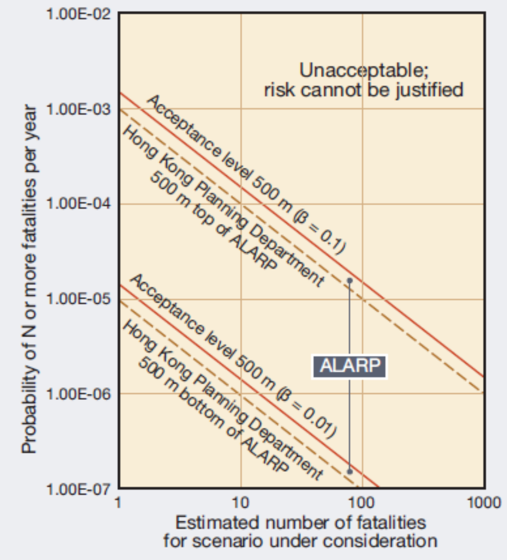
RISK = Consequence * Exposure * Probability

(C) X (E) X (P) = RISK RESULT

More than 400	Very high risk, immediate correction with high level input
200 to 400	High risk, immediate correction required
70 to 200	Substantial risk, correction needed
20 to 70	Possible risk, attention indicated
Less than 20	Risk perhaps tolerable as is

TAU LEKOA

	Consequence severity				
Likelihood	Insignificant > $0.01 M	Minor > $0.01 M	Moderate > $0.1 M	Major > $1 M	Catastrophic > $10 M
Daily to	High	High	Extreme	Extreme	Extreme
> Monthly	Medium	High	High	Extreme	Extreme
> Annually	Low	Medium	High	Extreme	Extreme
> 1 in 10	Low	Low	Medium	High	Extreme
Rare	Low	Low	Medium	Medium	High



Way forward

Phase 2: Alternative methods for Short Term Seismic Hazard Analysis

- Project 2: Machine learning Approach to Short Term Seismic Hazard Analysis (STSHA)
  - Original Scope
    - A) Seismic data sets to be provided by IMS (three mines)
    - B) Workshop on assessing and comparing models – agree on criteria
    - C) Develop machine learning methods applied to STSHA
    - D) Evaluation of machine learning methods applied to STSHA
    - E) Workshop to present to RETC
  - Revisit objectives of machine learning approaches applied to SHSA (IMS and SRK)?
    - ST SHA / prediction – effectiveness of exclusion zone and re-entry
    - Review STAT / activity rate effectiveness (do damaging events occur outside of exclusion zones and times)
    - Review GMAP effectiveness (do damaging events occur outside of exclusion zones and times)
- Project 3: Bayesian, Time-Dependent Seismic Hazard Assessment in Mines (UP (Andrzej Kijko))
  - The intention was to include rock engineering inputs and subjective engineering judgement
  - Original scope of work
    - A) Development of model
    - B) Development and testing of Matlab executable code
    - C) Demonstration software and implementation of feedback
    - D) Workshops to present technology
- Project 4: Ground Motion Monitoring System
  - Network of low cost ground motion alarm sensors (GMAS)
  - Original scope
    - A) Supply and install an array of sensors
    - B) Evaluation of GMAS