INSTITUTO DE INGENIEROS DE MINAS DEL PERU

JUEVES MINERO (LIMA)

Induced seismicity and numerical modelling in underground mining

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Outline

- Introduction
- Mechanisms
- Classification
- Analysis methods
- Microseismic monitoring
- Rockburst control
- Numerical modelling

Introduction

- Seismic events associated with mining have been reported for more than 100 years
  - They occur more frequently with increasing depth
  - They occur mostly in hard rock and coal mines
    - Rockmass stiffness and mining-induced stresses are key factors
  - They increase the cost of mining and reduce productivity
  - Rockbursts pose serious threat to worker safety
    - Outbursts: rockbursts in coal mines

Blake and Hedley 2003

Introduction

- Mining-induced seismicity (or microseismicity)
  - It is seismicity associated with mining activities in regions with little or no previous seismic activity

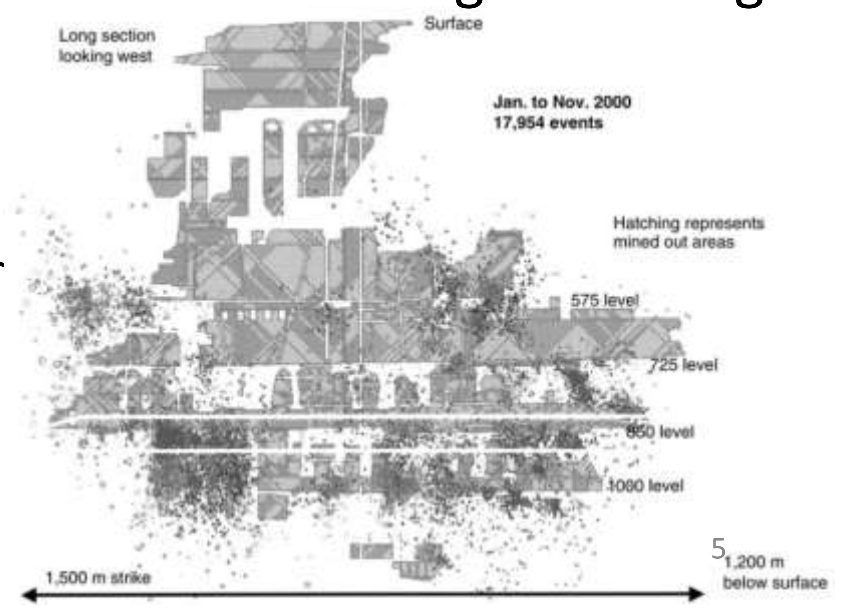

Blake and Hedley 2003

- Rockbursts
  - These are violent failures of rock that result in visible damage to underground excavations
    - All rockbursts are associated with microseismic events but not all events translate into rockbursts

Introduction

- Rockmass properties and mining-induced stresses are the two main factors to consider
  – As mining proceeds deeper, rockburst frequency and intensity will increase
    - Higher pre-mining stresses translate into higher mining-induced ones

Blake and Hedley 2003

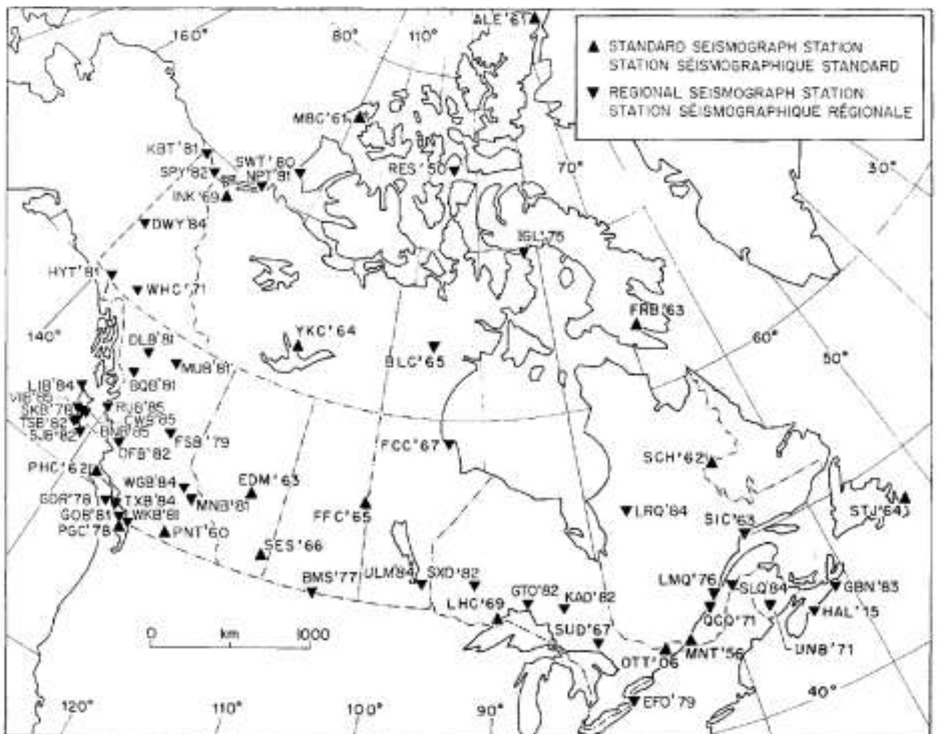


Mechanisms

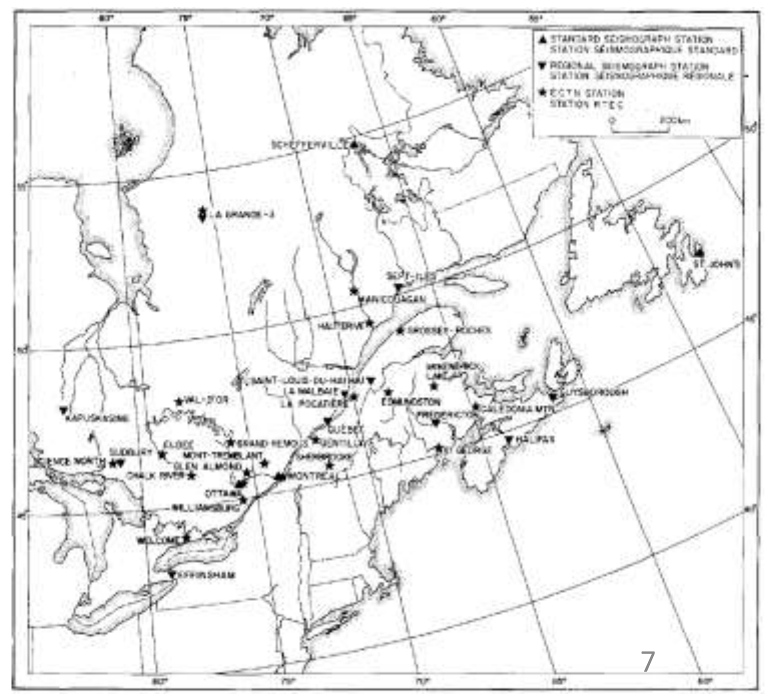
- Gibowicz (1990)
  - Induced seismicity
    - It is directly connected to mining operations and occurs at or near excavation boundaries
      - It is proportional to the scale of mining and opening sizes
      - The energy changes involved are proportional to these 2 factors
  - Triggered seismicity
    - It is associated with movement along major geological discontinuities
      - The rockmass is already geologically metastable and requires a small energy input for activation

Mechanisms

- Hasegawa et al (1989)
  - They studied three types of mines in Canada
    - Potash (SK), coal (NS), and several base metal mines (ON)



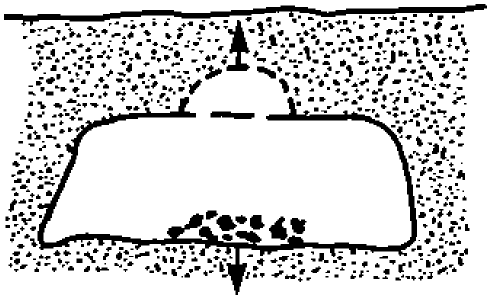
1985 CANADIAN STANDARD AND REGIONAL SEISMOGRAPH STATIONS



EASTERN CANADA TELEMETERED NETWORK-1985
and other stations

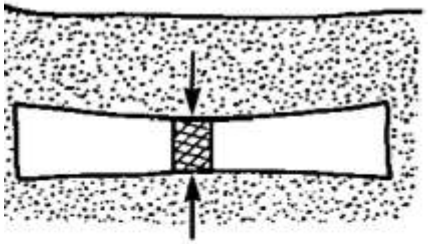
Mechanisms

- Hasegawa et al (1989)
  - Six mechanisms were proposed
    - Cavity collapse: it represents
      - … a rockburst in the roof with violent rock ejection downwards
      - … a large mass of rock loosened by mining that falls by gravity



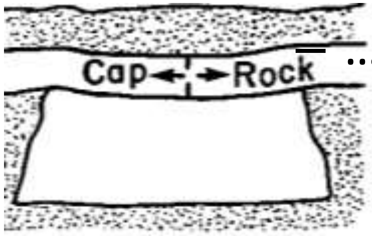
CAVITY COLLAPSE

    - Pillar burst: it is due to a combination of forces related to
      - … stope face advancement (elastic)
      - … time-dependent after-effects (inelastic)



PILLAR BURST

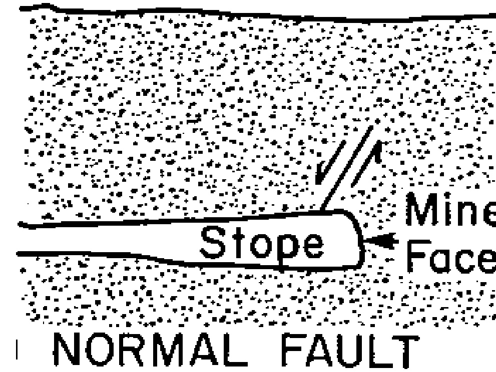
    - Tensional fault: it occurs at
      - … the middle of wide excavations where roof subsidence is max



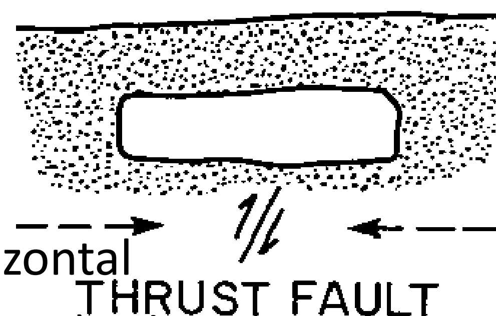
TENSIONAL FAULT

Mechanisms

- Hasegawa et al (1989)
  - Six mechanisms were proposed



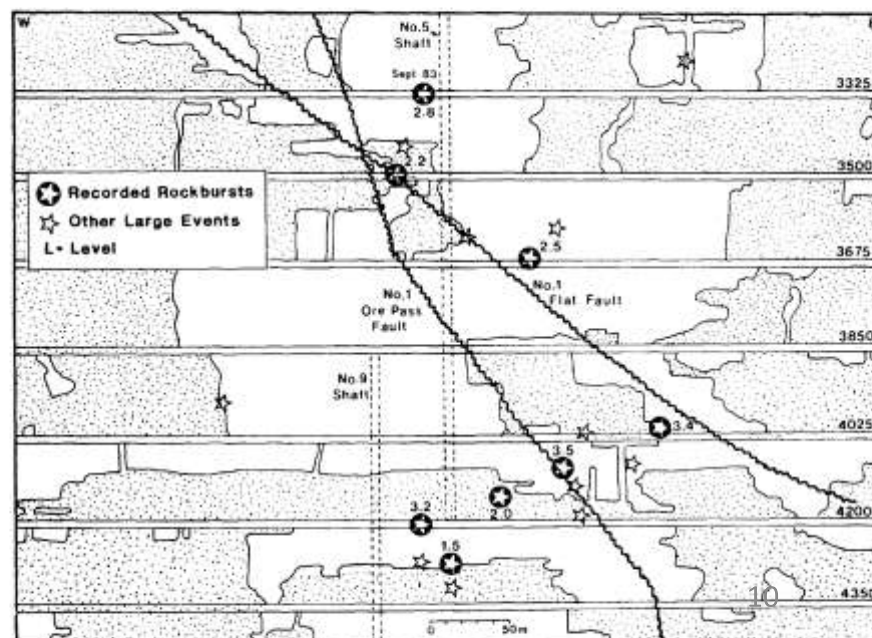
- Normal fault: it is also known as a comminuted fault
  - It occurs in intact rock and is generally of the normal type
  - It is also referred to as a strain energy burst, or strainburst
- Thrust fault: it occurs above or below an excavation



  - The maximum principal stress (σ_1) is horizontal
  - Induced stress (decrease in vertical stress σ_v) is large
    - » This initiates slip in intact material close to the floor
    - » It can also trigger a local fault at greater depths

Mechanisms

- Hasegawa et al (1989)
  - Six mechanisms were proposed
    - Shallow thrust fault: it occurs between near-horizontal layers that become “unclamped” or undergo shearing motion due to roof sag



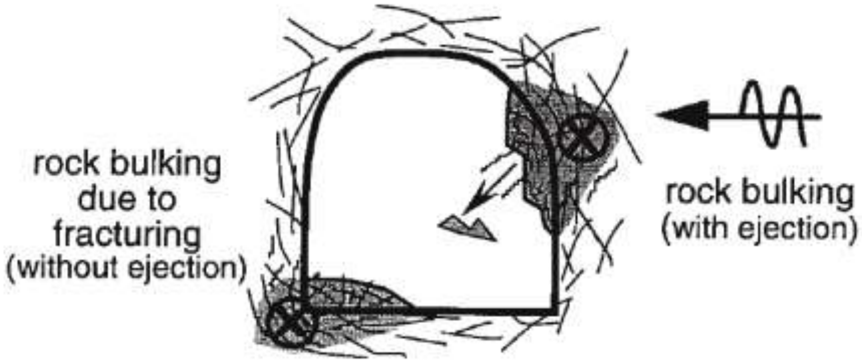
Mechanisms

- Ortlepp (1992)
  - Five mechanisms were proposed
    - Strain-bursting
    - Buckling
    - Pillar or face crush
    - Shear rupture
    - Fault-slip

Seismic Event	Postulated Source Mechanism	First Motion from Seismic Records	Richter Magnitude M_L
Strain-bursting	Superficial spalling with violent ejection of fragments	Usually undetected, could be implosive	-0,2 to 0
Buckling	Outward expulsion of larger slabs pre-existing parallel to opening	Implosive	0 to 1,5
Pillar or face crush	Sudden collapse of stope pillar, or violent expulsion of rock from tunnel face	Implosive	1,0 to 2,5
Shear rupture	Violent propagation of shear fracture through intact rockmass	Double-couple shear	2,0 to 3,5
Fault-slip	Violent renewed movement on existing fault	Double-couple shear	2,5 to 5,0

  - They are listed in ascending order of energy output
    - The last 2 types represent shear failure along a plane
      - They are completely unrelated to the drifts that are damaged
      - The others are intimately related to the nearby damaged drifts

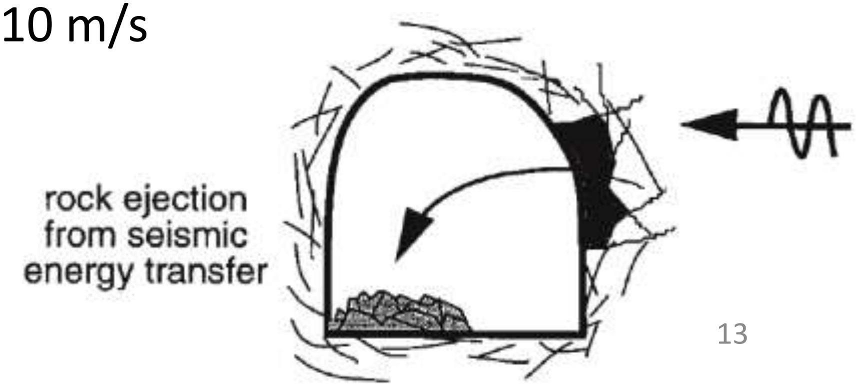
Mechanisms



- Kaiser (1993)
  - Three mechanisms were proposed
    - Rockmass bulking due to fracturing
      - It occurs when stresses near an opening exceed the strength
        - » Strainburst: for cases where the failure occurs rapidly
      - This is the most common type in underground mines
      - The primary energy source is the strain energy in the rockmass
      - Bulking damages standard support systems
      - Its risk and severity are functions of rockmass strength, in-situ stresses, rock stiffness, and drift size/shape

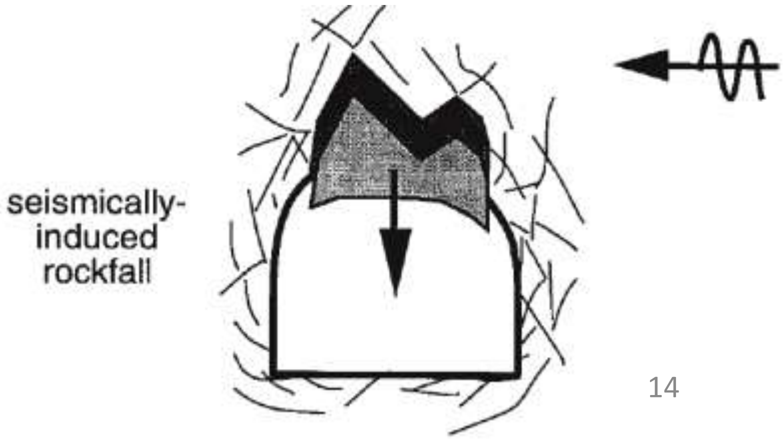
Mechanisms

- Kaiser (1993)
  - Three mechanisms were proposed
    - Rock ejection from seismic energy transfer
      - It is due to a seismic stress wave reaching an opening
      - Damage to the opening is a function of event size and proximity
      - Block ejection is more likely for well-jointed, fractured rockmass
      - Ejection velocities > 3 m/s can occur
        - » Note: in very brittle rock, bulking + ejection combine to produce velocities > 10 m/s



Mechanisms

- Kaiser (1993)
  - Three mechanisms were proposed
    - Seismically-induced rockfall
      - It occurs when a marginally stable rock volume is impacted
      - The incoming seismic wave is usually of a low frequency
      - In this case, gravity is the dominant driving force
      - It usually involves large volumes of rock and major damage



Mechanisms

- Others
  - A few other mechanisms have also been identified
    - Intact brittle rock fracture
    - Coalescence of rockmass fractures (e.g., joints)
    - High stresses in stope abutments
    - Crushing, shearing, and fracturing of pillars
    - Shear or rupture of lithological contacts
  - More than 90% of microseismic events are < $\mathbf{M_w}$ 0
    - $\mathbf{M_w}$ (or **M** or $\mathbf{m_M}$) is the moment magnitude
      - $\mathbf{M_W}$ < 0 indicates that they are smaller events than the ones mentioned by Hasegawa et al (1989) and Ortlepp (1992)

Mechanisms

- Others

Approximate Richter Magnitude	Qualitative Description
-3.0	▪ Small bangs or bumps heard nearby. Typically these events are only heard relatively close to the source of the event. ▪ This level of seismic noise is normal following development blasts in stressed ground. ▪ Events are audible but the vibration is likely too small to be felt. ▪ Not detectable by most microseismic monitoring systems.
-2.0	▪ Ground shaking felt close to the event. ▪ Felt as good thumps or rumbles. May be felt remotely from the source of the event (more than 100 metres away). ▪ Often detectable by a microseismic monitoring system.
-1.0	▪ Often felt by many workers throughout the mine. ▪ Should be detectable by a seismic monitoring system. ▪ Significant ground shaking felt close to the event. ▪ Similar vibration to a distant underground secondary blast.
0.0	▪ Vibration felt and heard throughout the mine. ▪ Bump may be felt on surface (hundreds of metres away), but may not be audible on surface. ▪ Vibrations felt on surface similar to those generated by a development round.
1.0	▪ Felt and heard very clearly on surface. ▪ Vibrations felt on surface similar to a large production blast. ▪ Events may be detected by regional seismological sensors located a few hundreds of kilometres away.
2.0	▪ Vibration felt on surface is greater than large production blasts. ▪ The Geological Survey of Canada can usually detect events of this size.
3.0	▪ Event is detected by earthquake monitors throughout the province.
4.0	▪ Largest mining-related seismic events ever recorded in Canada.

Hudyma 1995

McGill

Mechanisms

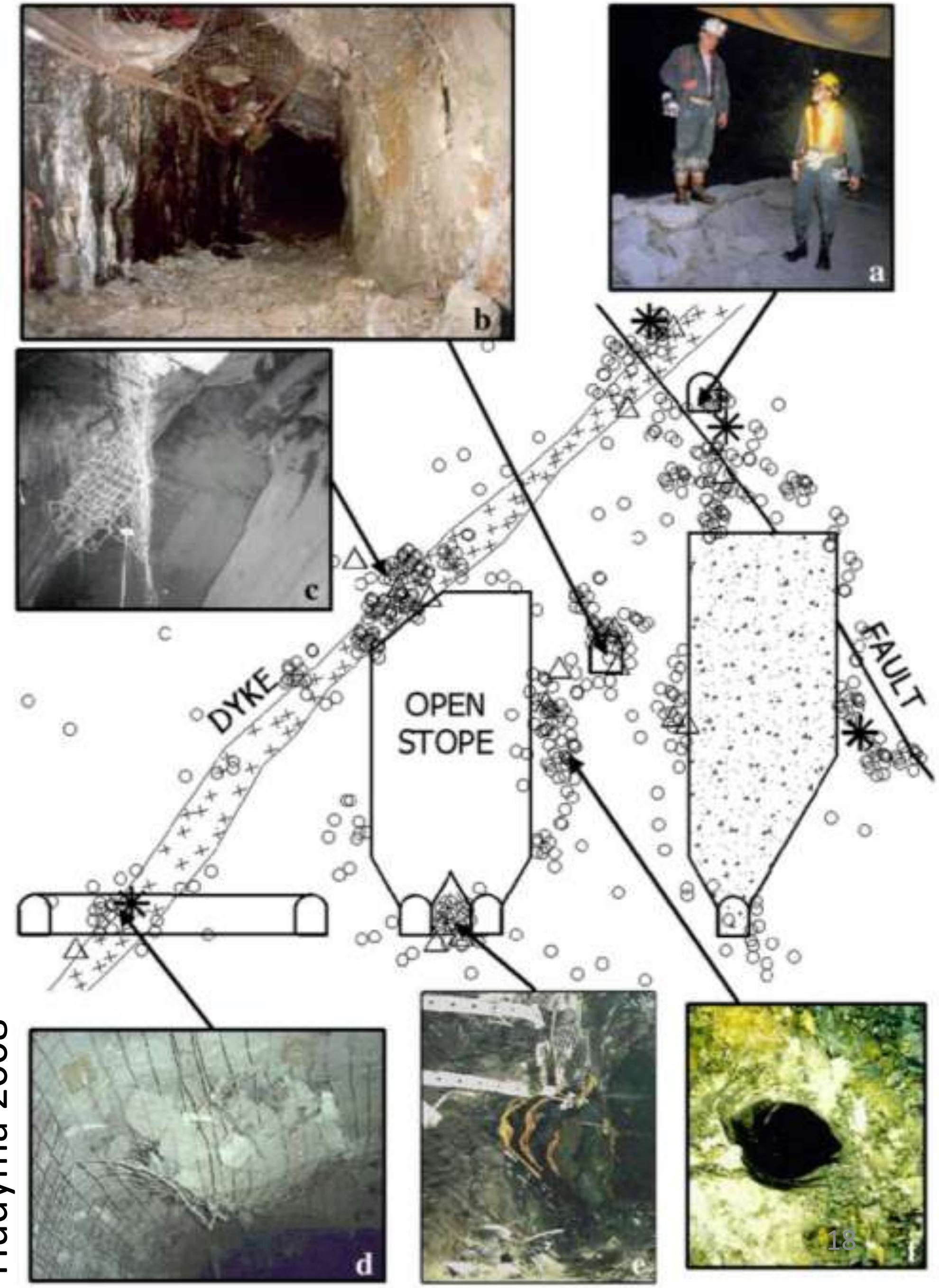
- Summary
  - Common rockmass failure mechanisms are…
    a. Fault movement
    b. Induced stresses and fracturing near excavations
    c. Stope overbreak
    d. Contrast in rockmass properties (strainbursts)
    e. Crushing of mine pillars
    f. Stress increase and rockmass deformation

Mechanisms

- Summary

Fig. 2 Schematic seismic sources or local rock mass failure caused by stress change and different geological conditions: **a** fault movement, **b** stress change causing rock mass fracturing near an excavation, **c** stope overbreak, **d** contrast in rock mass properties causing strain bursting, **e** crushing of mine pillars, **f** stress increase causing rock mass deformation (Hudyma 2008)

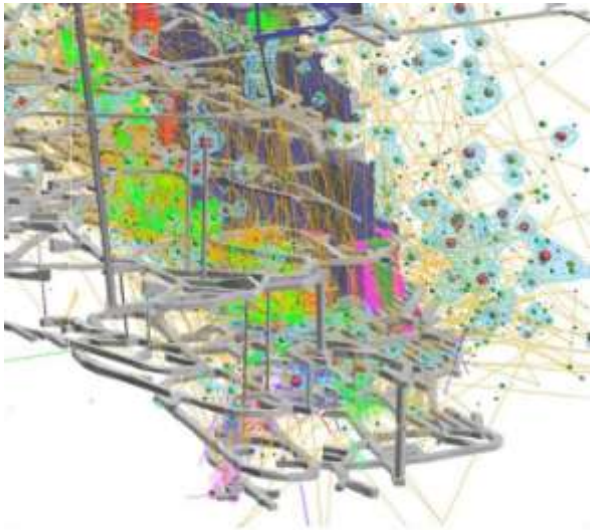
Hudyma 2008



Mechanisms

- Summary
  - Many seismic source mechanisms exist in mines
  - Different ones may occur close to each other
  - Seismic events result from local failure processes
    - Based on geophysical analysis…
      - Compressive
      - Tensile
      - Shear

Vasak and Dasys 2009



      - This is not surprising but their relative percentages may vary

Classification

- There are 3 types of rockbursts
  - It is based on a review of different mechanisms
    - It also considers the location and setting of the event
  - Fault-slip
    - Sudden, earthquake-like movement occurs along a fault
    - This causes a sudden change in the stress field
    - It radiates energy in the form of ground vibration
    - The damage is caused by…
      - … stress-induced failure to a dynamic stress increment
      - … acceleration of marginally stable rock blocks
      - … energy transfer to these blocks that causes rock ejection

Classification

- There are 3 types of rockbursts
  - Pillar burst
    - It occurs when stresses exceed strength in the pillar
      - These stresses can be static or dynamic in nature
    - Failure can be full (entire pillar) or partial (pillar skin)

Sill drift

Blake and Hedley 2003

Esterhuizen et al 2011

Classification

- There are 3 types of rockbursts
  - Strainburst
    - It occurs when stresses exceed strength in the walls
      - The damage consists of supported or unsupported rockmass
      - Loss of strength is sudden and energy is released during failure
      - Failed rock is ejected violently from the walls into the opening

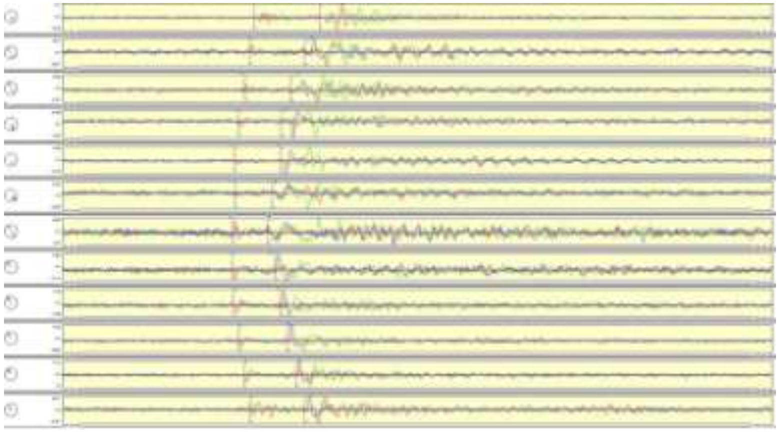
FIGURE 6.3 Detailed longitudinal section showing the November 26, 1993, rockburst locations relative to the 6723.30 stope

Blake and Hedley 2003


Burst-induced closure within stope

Analysis methods

- Identification: waveform (direct) techniques
  - Moment tensor inversion
  - First motion analysis



ESG Solutions

  - Advantages
    - Actual recorded and monitored data is analyzed
  - Disadvantages
    - High-quality seismograms and data are required
    - Data must be recorded on sufficient number of sensors
    - At least 6 triaxial sensors are needed; this is uncommon
    - It is a very slow and labour-intensive effort

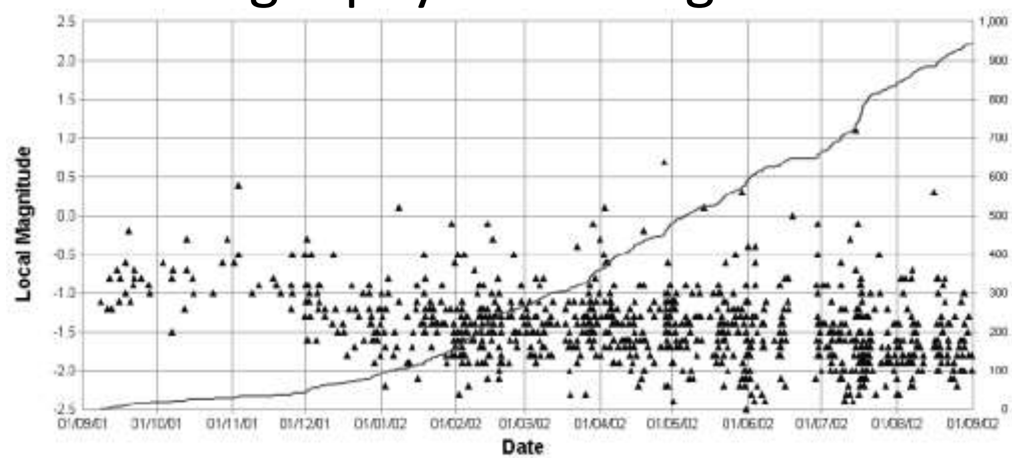
Analysis methods

- Identification: inferred (indirect) techniques
  - Event location and magnitude
  - **S**:**P** energy ratio
  - Frequency-magnitude
  - Magnitude-time history analysis
  - Instability (**EI-CAV**) analysis
  - Apparent stress time history
  - Diurnal analysis
  - Daily histogram
  - Omori re-entry analysis

ACG 2005

Analysis methods

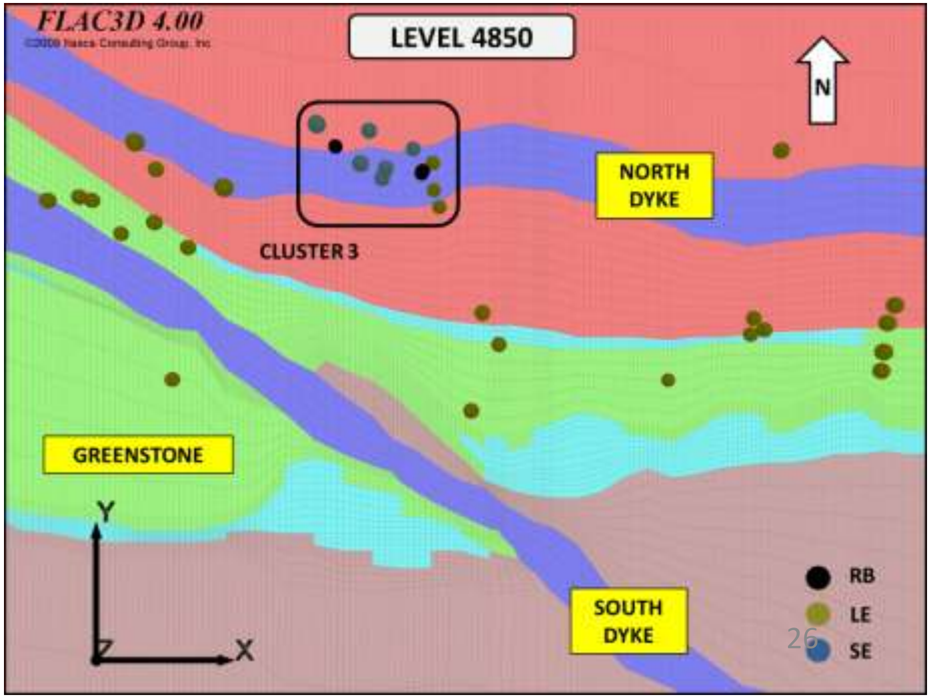
- Identification: inferred (indirect) techniques
  - Advantages
    - Relatively simple methods of analysis are employed
    - No specialized software or geophysical background is required
  - Disadvantages
    - They require a large dataset due to a statistical approach
    - Ambiguous or inconclusive results may be obtained if multiple mechanisms are at work



Hudyma et al 2003

Analysis methods

- <u>Identification</u>: inferred (indirect) techniques
  - Event location
    - It comprises looking for event clusters as this indicates that a zone is seismically more active than others

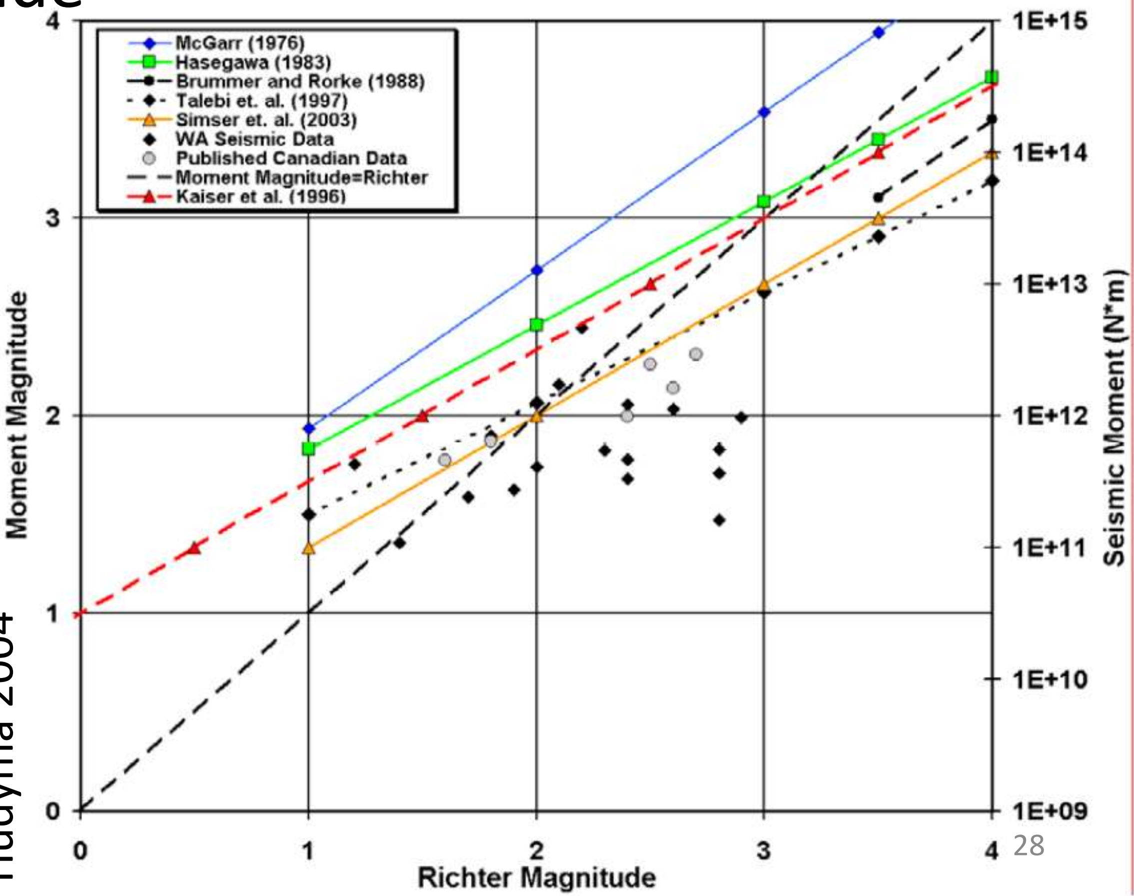


Analysis methods

- <u>Identification</u>: inferred (indirect) techniques
  - Event magnitude
    - Richter magnitude ($\mathbf{M_L}$)
      - It was developed based on earthquakes in southern California
    - Nuttli magnitude ($\mathbf{m_N}$)
      - It is used in eastern Canada by the Geological Survey
    - Moment magnitude (**M** or $\mathbf{M_w}$)
      - It is derived from seismic moment (independent parameters)
      - It is the best measure of size of a fault-slip
    - Local magnitude
      - It is used by most mines and calibrated to a local seismic monitoring system

Analysis methods

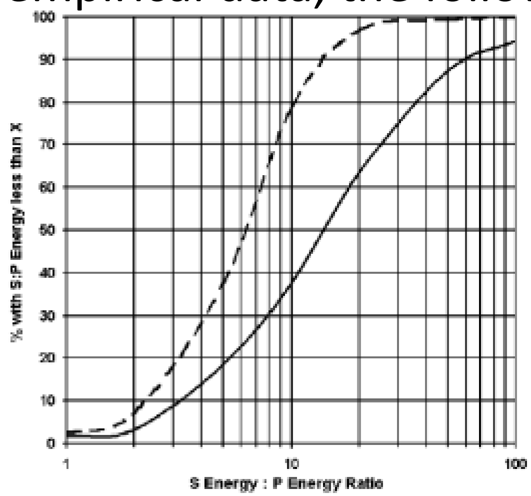
- Identification: inferred (indirect) techniques
  - Event magnitude



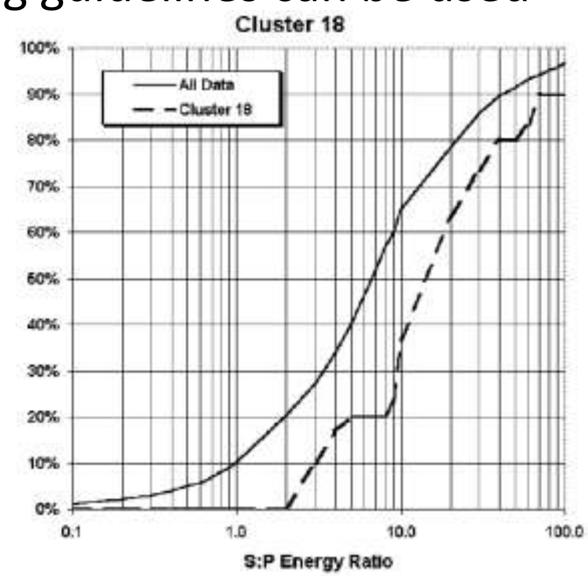
Hudyma 2004

Analysis methods

- Identification: inferred (indirect) techniques
  - **S**:**P** energy ratio
    - It is the ratio of shear **S** waves to compressive **P** waves
      - Based on empirical data, the following guidelines can be used



Hudyma et al 2003



» Fault-slips have **S**:**P** ratios > 10

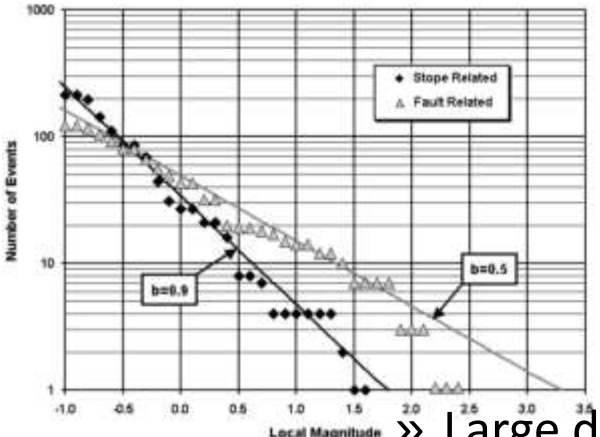
» Strainbursts have **S**:**P** ratios between 1 and 3

» The relative abundance of each indicates the primary cause

Analysis methods

- Identification: inferred (indirect) techniques
  - Frequency-magnitude
    - This is also known as the Gutenberg-Richter relation
      - It is a power law line with the slope designated as the **b**-value
      - Larger events occur rarely and smaller ones occur frequently

Hudyma 2007

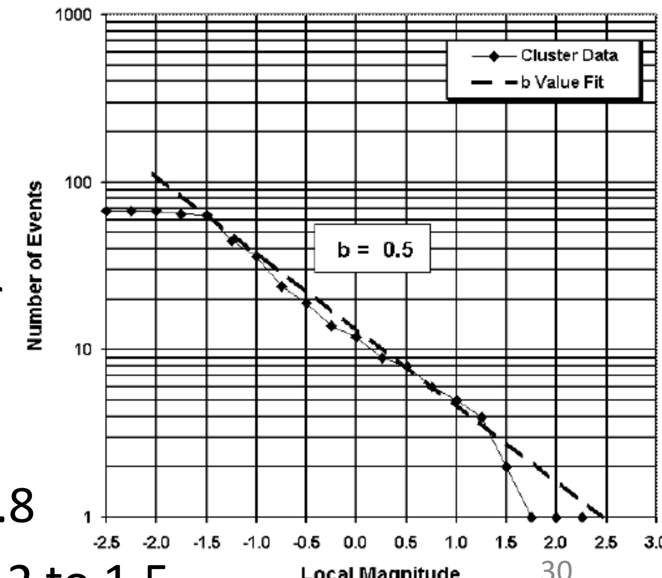


» Large dataset: **b**-value ~ 1

» Fault-slip events: **b**-value < 0.8

» Strainburst events: **b** value 1.2 to 1.5

Hudyma et al 2003



Analysis methods

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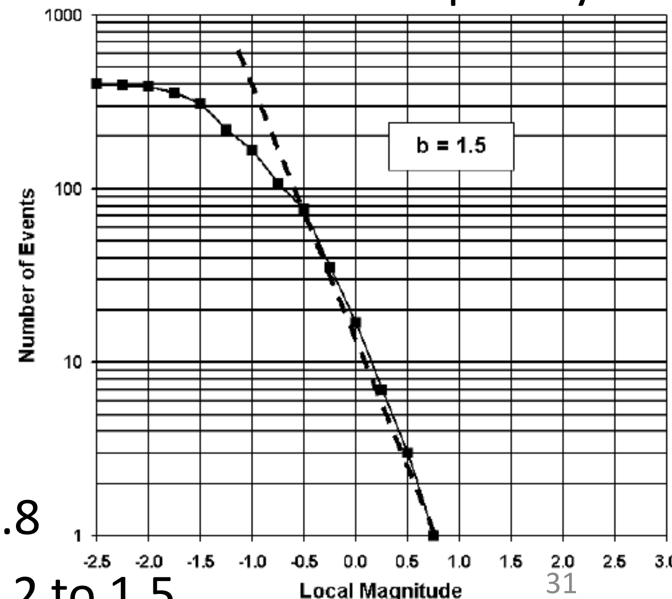
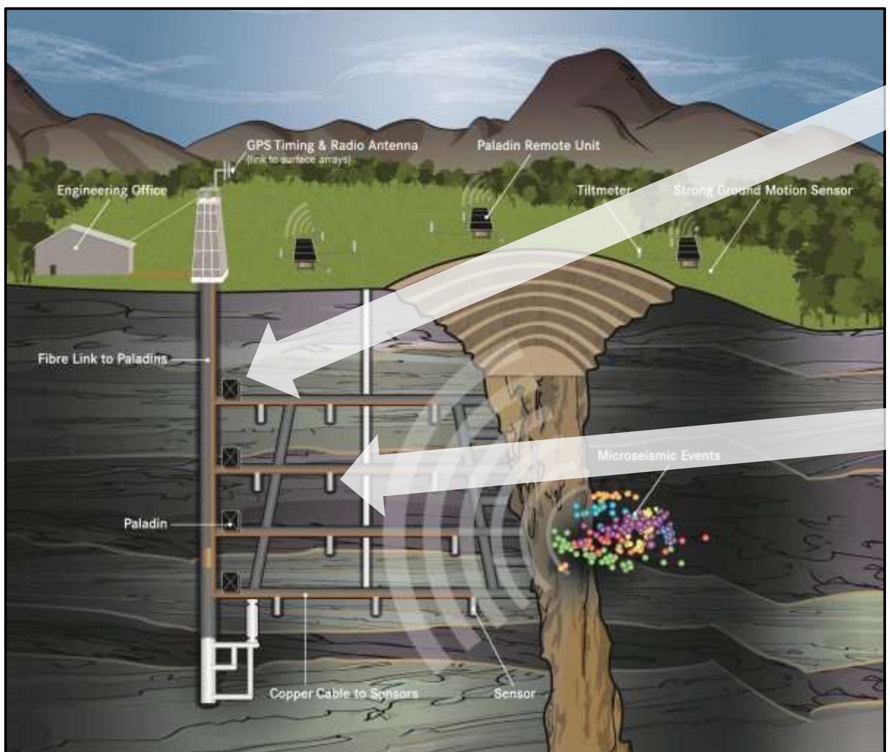
Hudyma et al 2003



Microseismic monitoring

- It is conducted by specialized systems provided by suppliers (e.g., ESG)
- Instrumentation and setup



ESG

Microseismic monitoring

Uniaxial
A1-30-1.0
30V/g
20V bias, 200Ω

- Types of sensors
  - Microseismic array (smaller events)
    - Uniaxial sensor
      - Higher location accuracy
      - Increased system sensitivity
      - 1/3 of cost of triaxial, smaller and easier to install
    - Triaxial sensor
      - More accuracy in source parameters
  - Strong ground motion sensor (larger events)
    - Uniaxial (for soft rock) and triaxial geophones
    - Useful for fault-slips and other major events

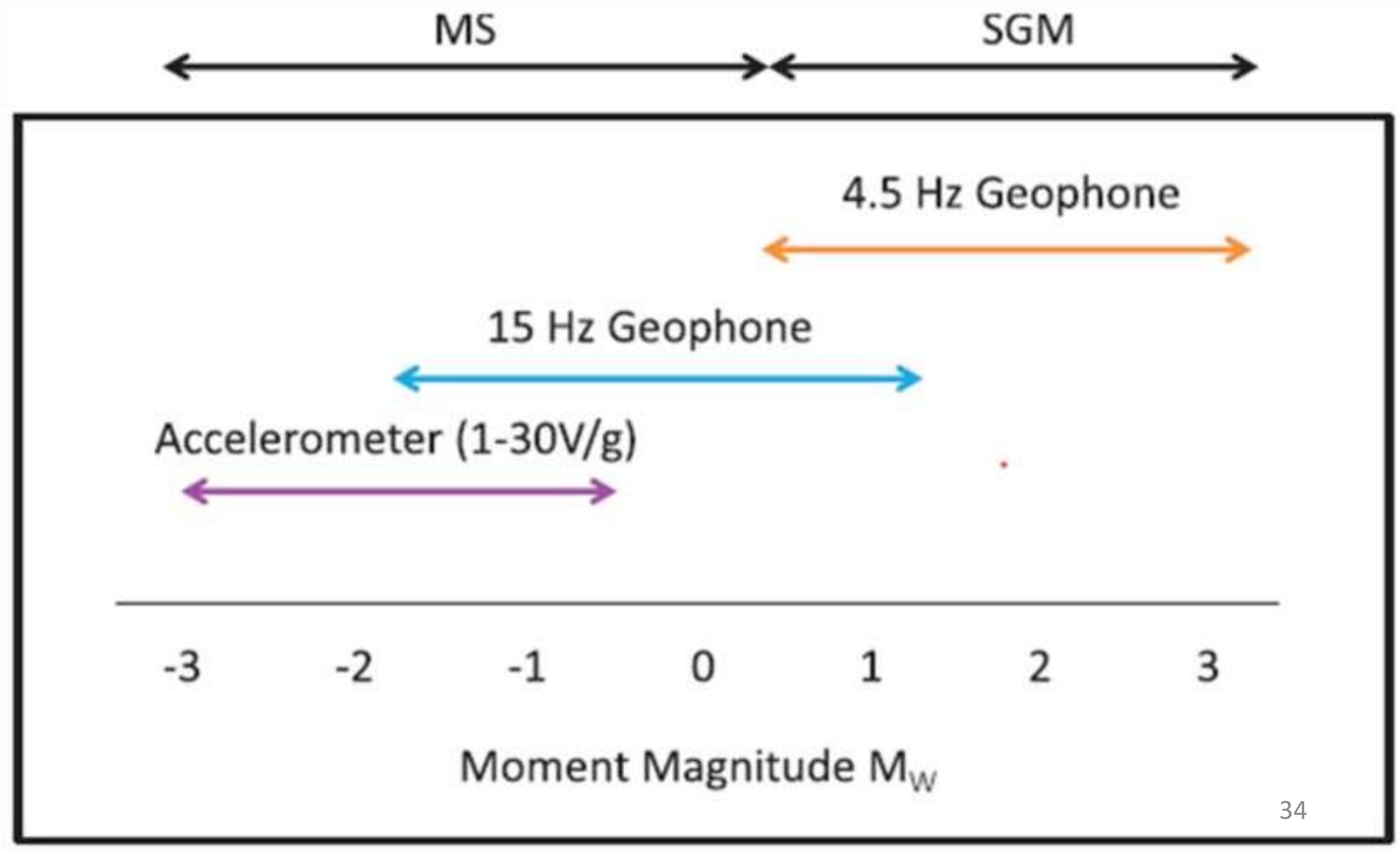
Triaxial
A3-1.0-1.25
0.5 V/g
10V bias, CCD

Triaxial
G3-0.7-2.5
0.7 V/in/s (27.6 V/m/s)
380Ω coil resistance

ESG

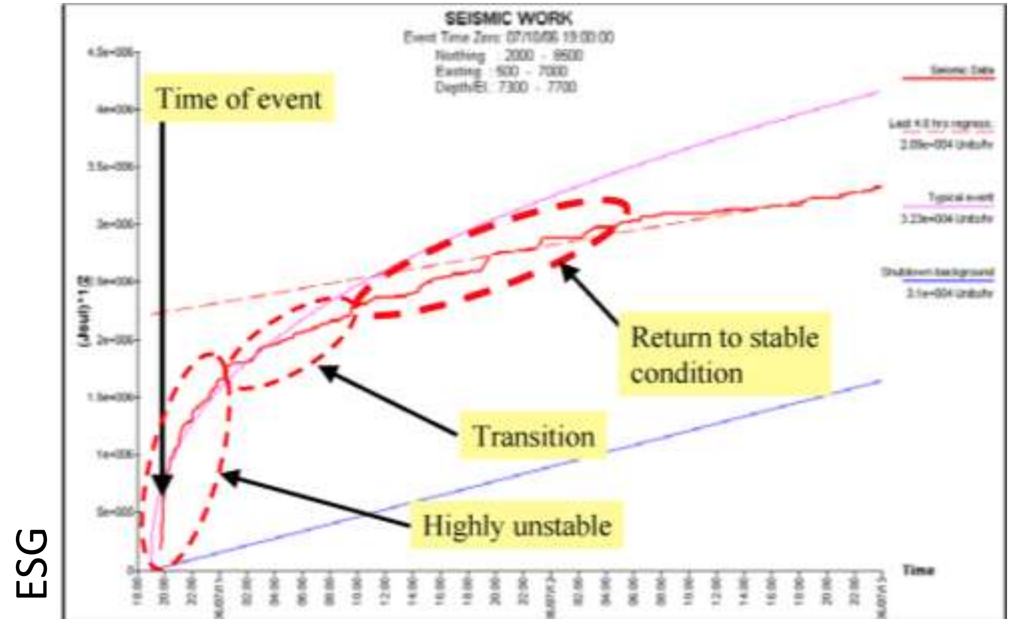
Microseismic monitoring

- Detection range of various sensors



Microseismic monitoring

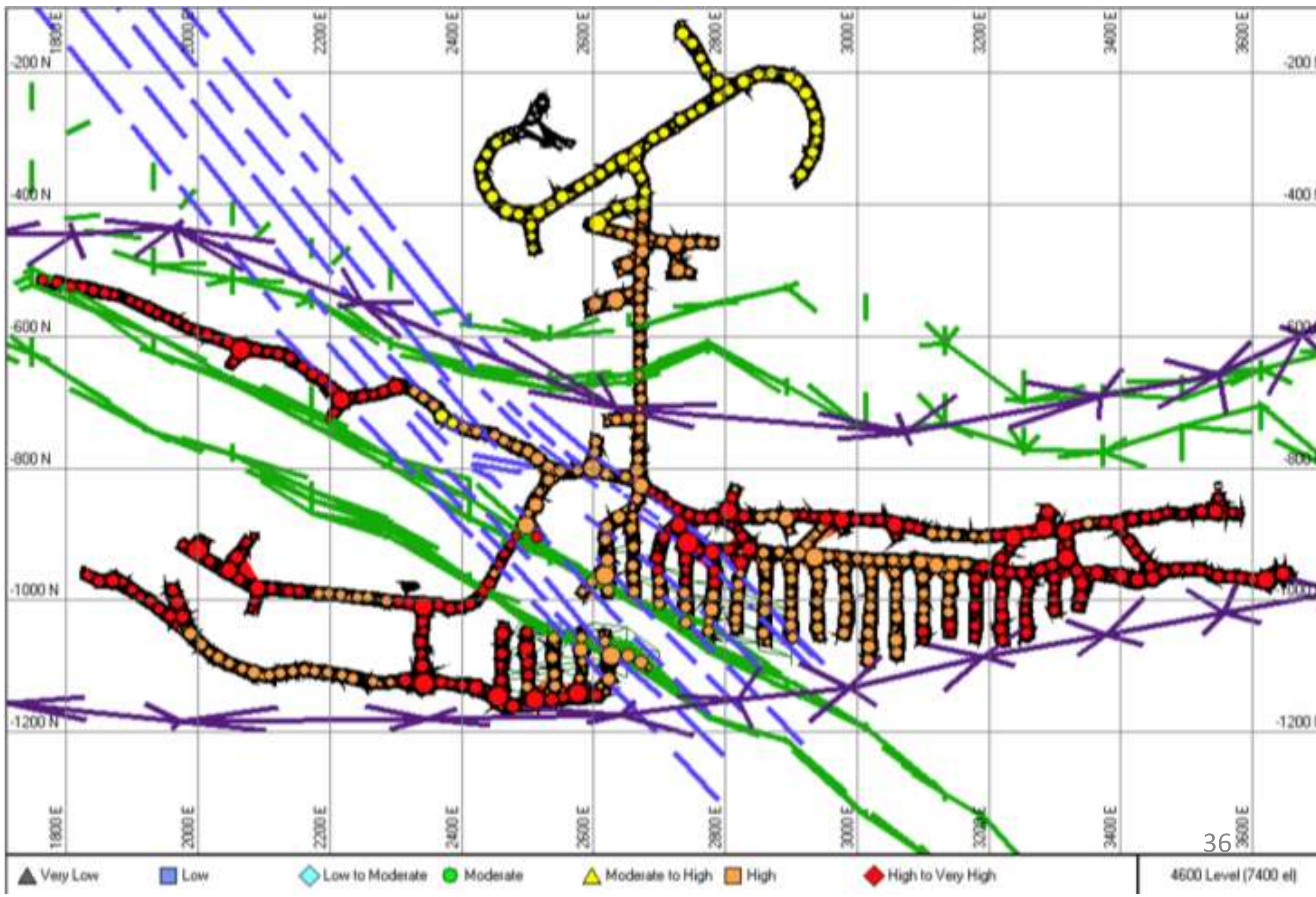
- <u>Applications</u>: re-entry protocols
  - It restricts access to affected areas following an event (e.g., rockburst)



- Microseismic activity increases after an event
- It decays to background levels in a few hours

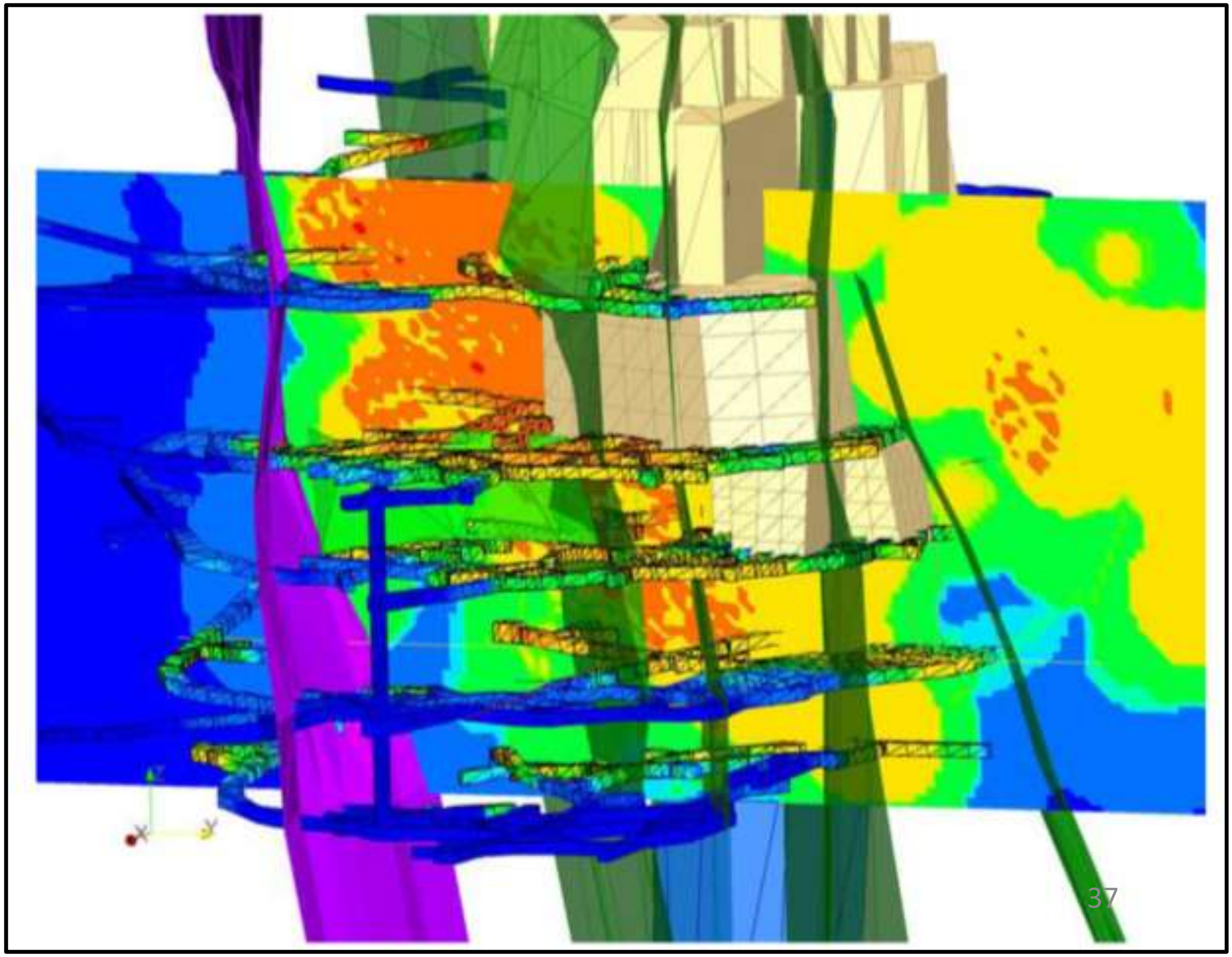
Microseismic monitoring

- Applications: 2D hazard maps



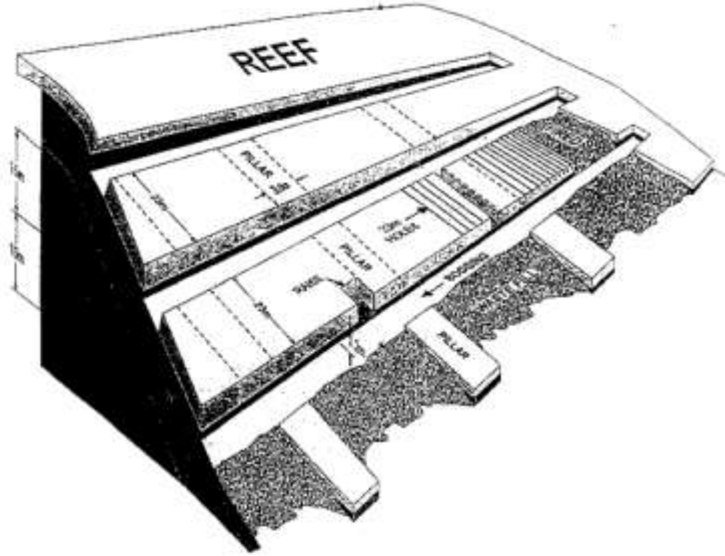
Microseismic monitoring

- Applications: 3D hazard maps



Vasak and Dasys 2009

Rockburst control



- Destress blasting
  - Historical background
    - It was first used in South Africa in the 1950s
      - It had been a cooperation between industry and government
      - Preconditioning: term for destress blasting in South Africa
    - Principle: increase the depth of fracture zone at face
      - This would reduce the occurrence and violence of rockbursts
      - It would act like a cushion between massive rock and face
      - Results: rockburst occurrence per area decreased by 36%
      - It was researched once again in the later 1980s
        - » Objective: to understand the fracture mechanics involved in destress blasting so as to design optimum blast patterns

Rockburst control

- Destress blasting
  - Experimental work was conducted in several mines
    - Different sizes and orientations of blastholes were used
      - Instrumentation was used to monitor various parameters

Toper et al 2003

» Blast monitoring
» Stress measurements
» Fracture mapping
» Numerical modelling
» Ground penetrating radar
» Rock testing (RQD and UCS)

Rockburst control

- Destress blasting
  - Experimental work was conducted in several mines
    - The following findings were reported from the test sites
      - Blast-induced fracture patterns are controlled by:
        - » Stress field (magnitude + orientation of principal stresses)
        - » Amount of blast pressure
        - » Rockmass properties
        - » Pre-existing fractures

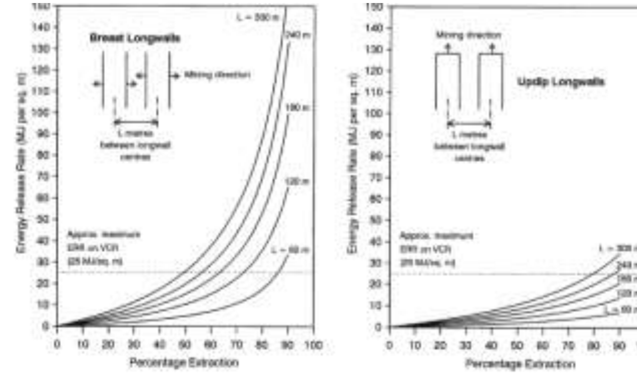


Figure 3—Comparison of energy release rate vs percentage extraction between several adjacent breast and updip mining longwalls (after Cook *et al.*[2])

Handley et al 2000

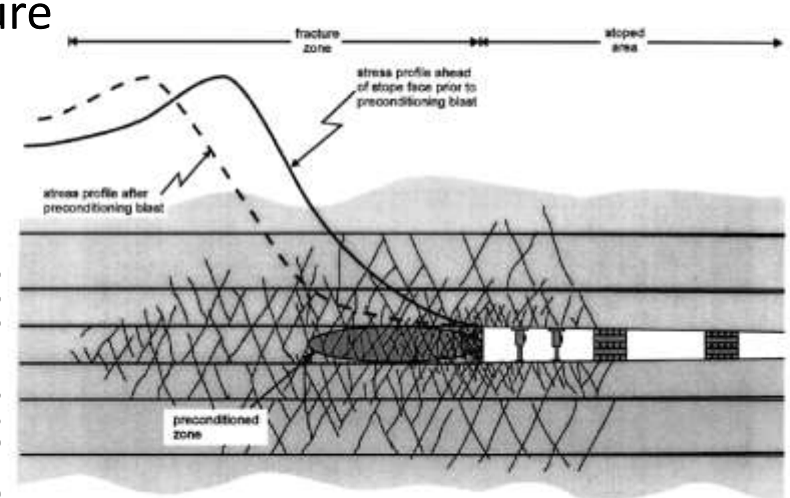
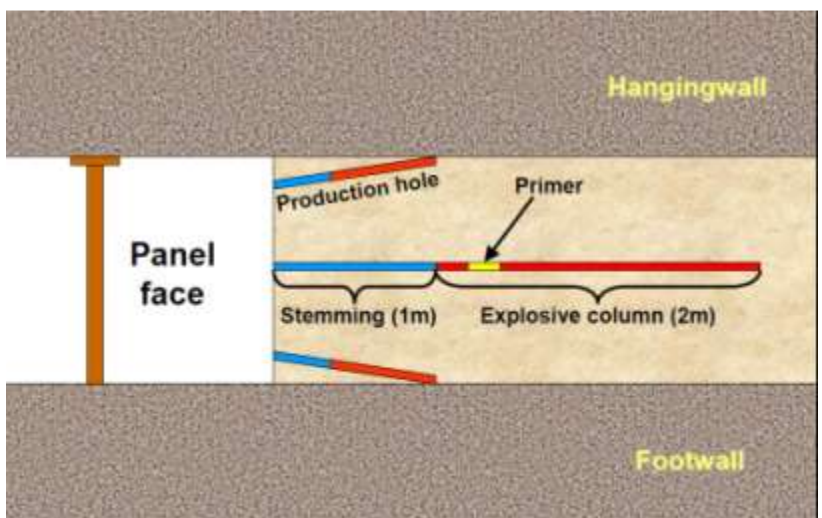


Figure 1—Stress redistribution due to preconditioning

Toper et al 2000

Rockburst control

- Destress blasting
  - Experimental work was conducted in several mines
    - The following findings were reported from the test sites
      - After blasting, the major principal stress (σ_1) increased
      - The minor principal stress (σ_3) decreased
      - Their orientation changed by almost 90°



Toper et al 2003

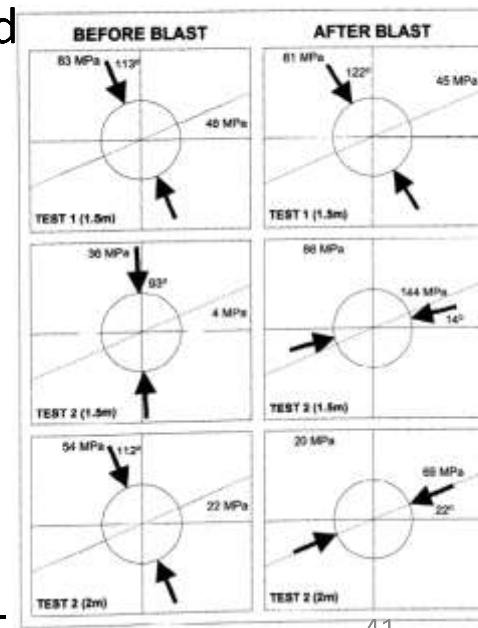
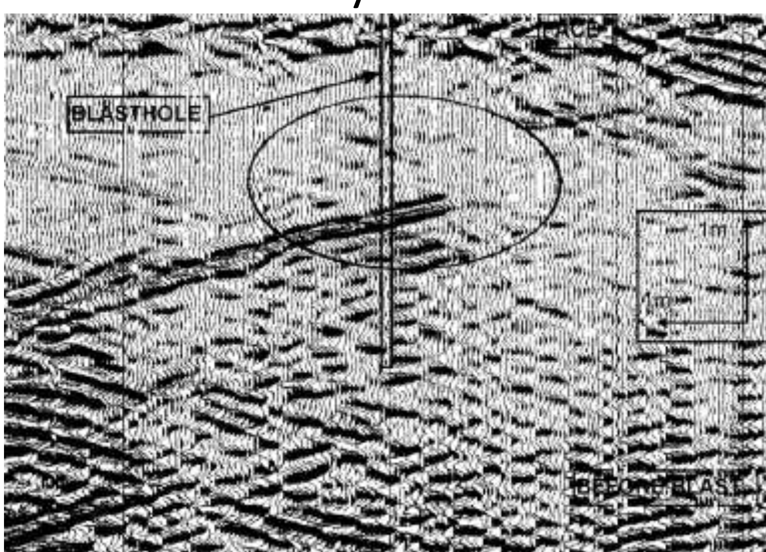


Figure 3.8.15 Orientation of principal stresses before and after test blasts 1 & 2

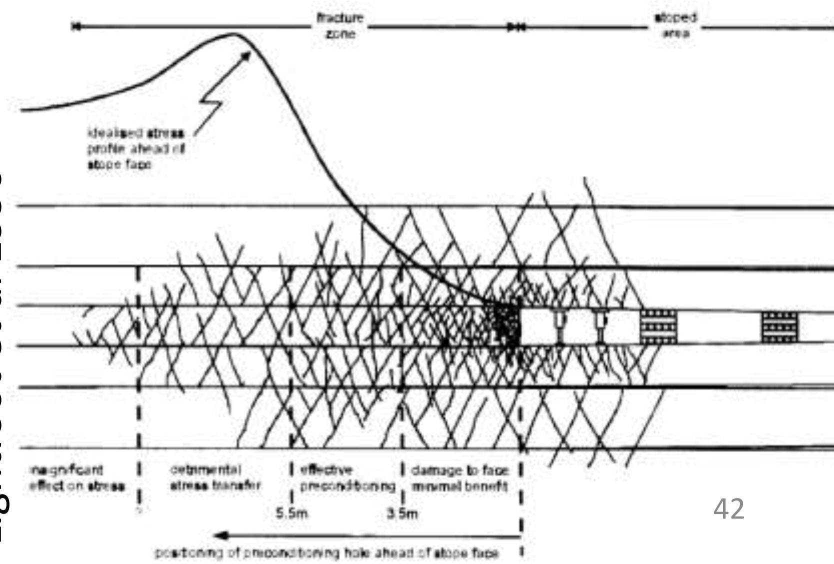
Toper et al 2003

Rockburst control

- Destress blasting
  - Two destress mechanisms impact the rockmass
    - A “shake-up” of the rockmass impacted by the blast
      - It allows shear slippage along pre-existing fractures
      - It also forces the breaking of any asperities along the fractures
      - Any stored strain energy is therefore released

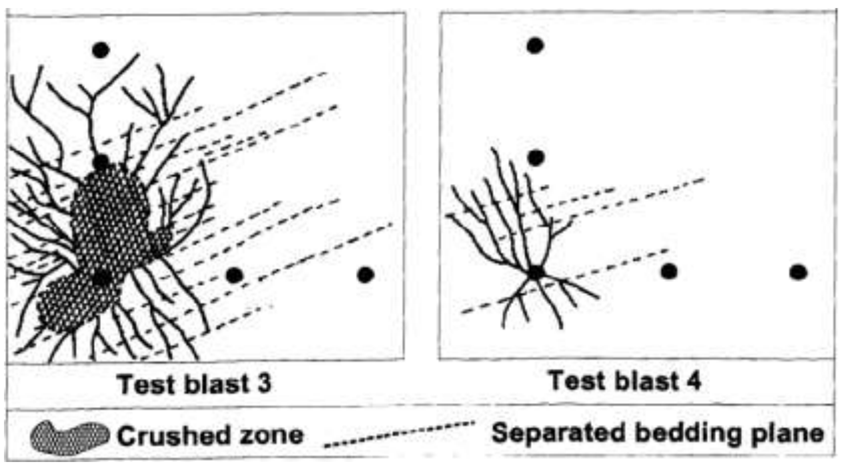


Lightfoot et al 1996

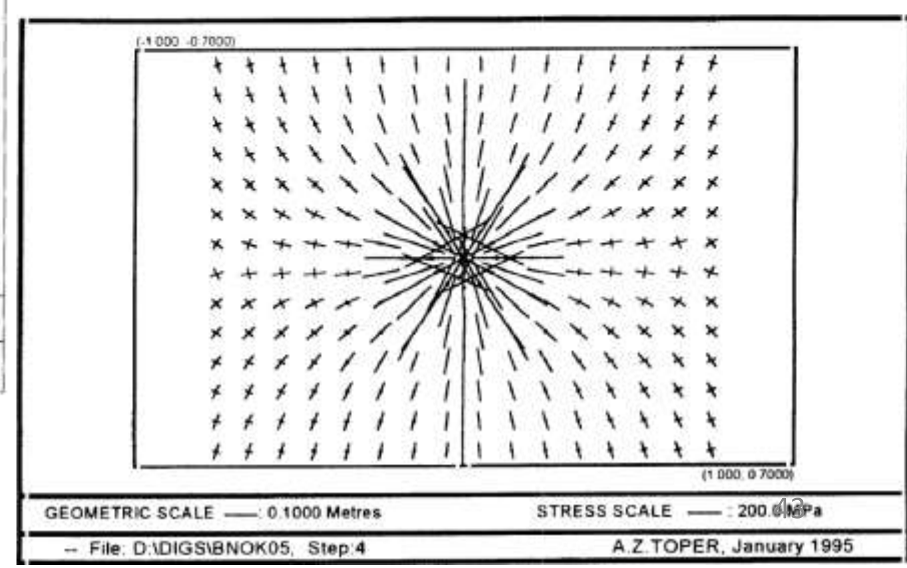


Rockburst control

- Destress blasting
  - Two destress mechanisms impact the rockmass
    - New fractures are created in the intact rockmass
      - They alter the rockmass properties and lower its strength
      - It will yield with the face advance and propagate the fractures



Toper 1995



Rockburst control

- Destress blasting
  - A system is required to evaluate its success
    - The Destressibility Index was developed for this purpose
      - Andrieux and Hadjigeorgiou (2006): 30 case studies
        - » It is based on the Rock Engineering System (RES) of Hudson (1992)
        - » It includes 8 parameters rated 0, 1, or 2
        - » These are multiplied by weight of parameter (cause)
        - » Final sum is divided by maximum total of 252

Rockburst control

- Destress blasting
  – A system is required to evaluate its success
    - The Destressibility Index was developed for this purpose

Parameter	Description	Associated measurable properties
P_1	Stiffness of the rock mass	$E_{\text{Laboratory}}$, RMR
P_2	Brittleness of the rock mass	B_1 (defined as $\sigma_{c\ \text{Rock mass}}/\sigma_{T\ \text{Rock mass}}$)
P_3	Degree of fracturing of the rock mass	RMR
P_4	Proximity to failure of the rock mass	$\sigma_{1\ \text{actual}}$, $\sigma_{3\ \text{actual}}$, Hoek–Brown failure criterion (at the rock mass scale)
P_5	Orientation of the destress blast	$\sigma_{1\ \text{actual}}$, azimuth of the destress blast
P_6	Width of the destress blast	Burden, blasthole diameter and number of blasthole rings used
P_7	Unit explosive energy	Explosive density, AWS, blasthole length and diameter, collar length, burden and spacing, charge coupling ratios
P_8	Confinement of the explosive charges	Toe breakthrough, collar and toe lengths, collar and toe stemming
P_9	Result of the destress blast	Stress level reduction, based upon instrumentation and measurements

Rockburst control

Overall normalised score	Destressability index
From 0.00 to 0.40	Low (likelihood of success for the destress blast considered)
From 0.40 to 0.70	Medium (likelihood of success for the destress blast considered)
From 0.70 to 0.85	Good (likelihood of success for the destress blast considered)
From 0.85 to 1.00	Excellent (likelihood of success for the destress blast considered)

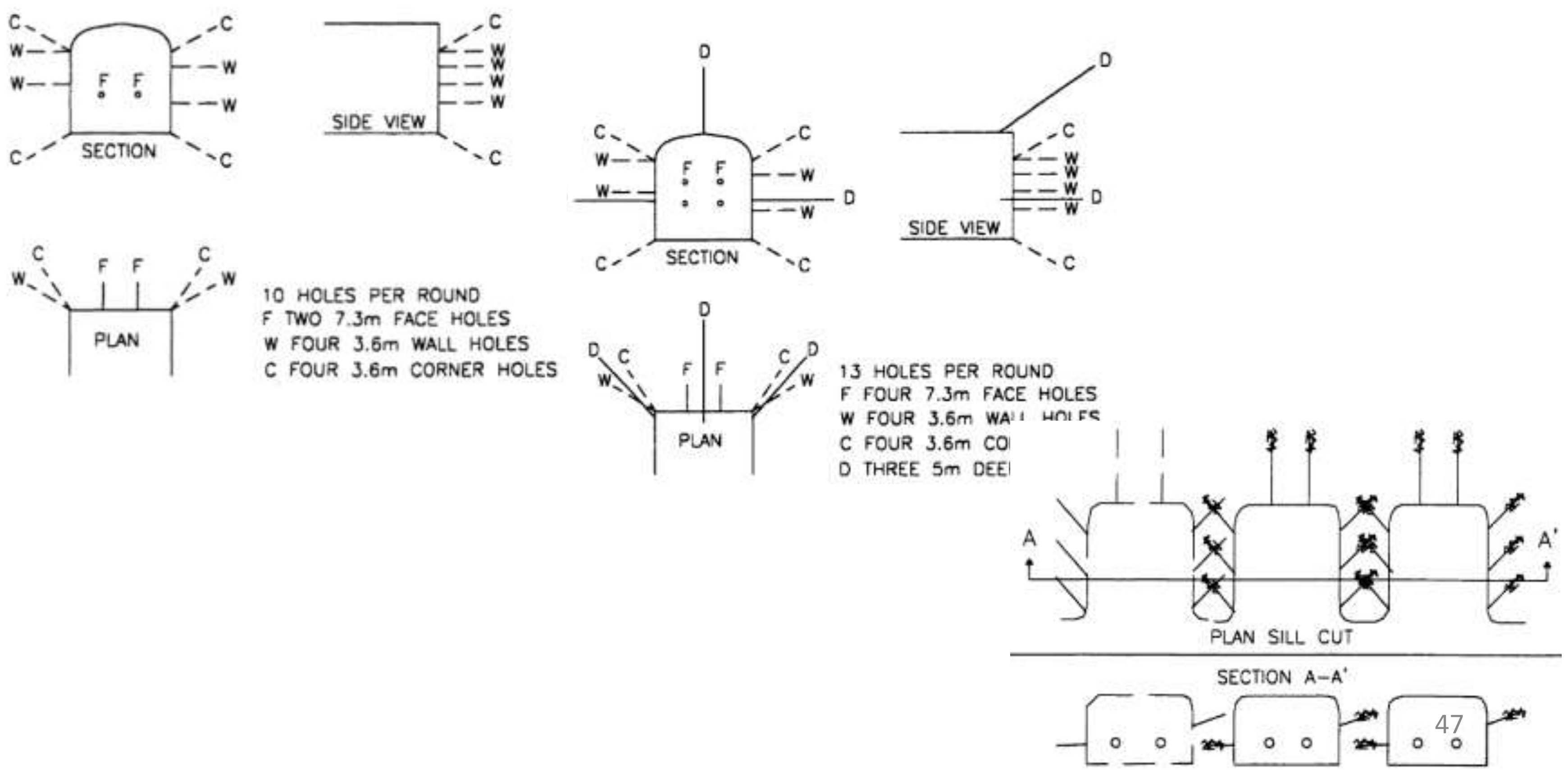
- Destress blasting
  - A system is required to evaluate its success
    - The Destressibility Index was developed for this purpose

Parameter	Property	Range of property values	Rating	Cause	Score	Maximum score
P_1 (stiffness of the rock mass)	Young's modulus (GPa)	Below 25	0	13	0	
		Between 25 and 50	1		13	26
		Over 50	2		26	
P_2 (brittleness of the rock mass)	B_1 ratio	Below 10.0	0	13	0	
		Between 10.0 and 18.0	1		13	26
		Over 18.0	2		26	
P_3 (degree of fracturing of the rock)	RMR	Between 0 and 60	0	14	0	
		Between 60 and 80	1		14	28
		Between 80 and 100	2		28	
P_4 (proximity to failure of the rock)	Proximity to H–B envelope (%)	Between 0 and 33	0	14	0	
		Between 33 and 70	1		14	28
		Between 70 and 100	2		28	
P_5 (destress blast orientation)	Angle θ from blast axis to σ_1 (°)	Between 0 and 30	0	13	0	
		Between 30 and 60	1		13	26
		Between 60 and 90	2		26	
P_6 (width of the target zone)	Number of blast rings	Below 2	0	18	0	
		Between 2 and 4	1		18	36
		Above 4	2		36	
P_7 (unit explosive energy)	Energy per unit mass (cal/kg)	Between 0 and 200	0	24	0	
		Between 200 and 350	1		24	48
		Between 350 and 500	2		48	
P_8 (confinement of the charges)	Blasthole diameter ratio	Between 0 and 25	0	17	0	
		Between 25 and 45	1		17	34
		Over 45	2		34	

Note: Proximity to failure is represented by $\sigma_1/\sigma_3 + [m\sigma_c\sigma_3 + s\sigma_c^2]^{0.5}$ and expressed in percentage, with parameters m and s expressed at the rock mass scale. Values of explosive energy per unit mass are expressed in calories of explosive energy per kilogram of rock.

Rockburst control

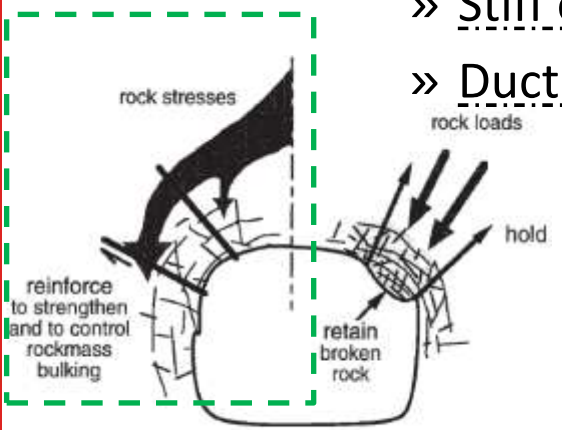
- Destress blasting
  - Destress blasting patterns in Canadian mines



Rockburst control

- <u>Dynamic support</u>: functions
  - Support system interactions are complex but…
    - ... 3 primary functions can be identified
      - Reinforcement of the rockmass
        - » It involves strengthening the rockmass to support itself
        - » This would raise the trigger limit for rockburst damage
        - » It restricts bulking, making use of rockmass **c** and ϕ
        - » Stiff elements: grouted rebars or dowels
        - » Ductile or yielding elements: Swellex and cone bolts

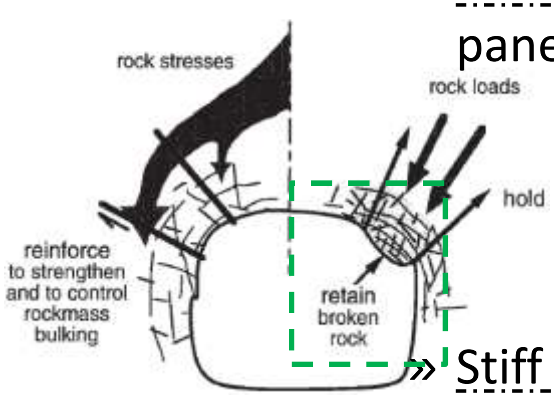
Kaiser et al 1996



Rockburst control

- Dynamic support: functions
  - Support system interactions are complex but…
    - ... 3 primary functions can be identified
      - Retention of broken rock
        - » It is required for safety reasons so as not to cause injuries
        - » It is needed to prevent progressive failure that goes deeper
        - » Stiff elements: cast concrete liner or shotcrete membrane
        - » Yielding elements: chain-link, welded-wire mesh, shotcrete panel
        - » Stiff to ductile: mesh-reinforced shotcrete

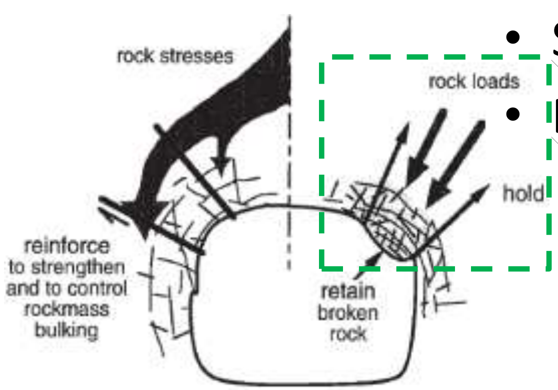
Kaiser et al 1996



Rockburst control

- Dynamic support: functions
  - Support system interactions are complex but…
    - ... 3 primary functions can be identified
      - Holding and tying element to stable rockmass
        - » It prevents gravity-driven rockfalls
        - » It can be provided by high-strength anchorage deep into rockmass
        - » With large displacements, a yielding element is required
          - Sliding mechanism: cone bolt or Split Set
          - Ductile mechanism: yielding Swellex

Kaiser et al 1996



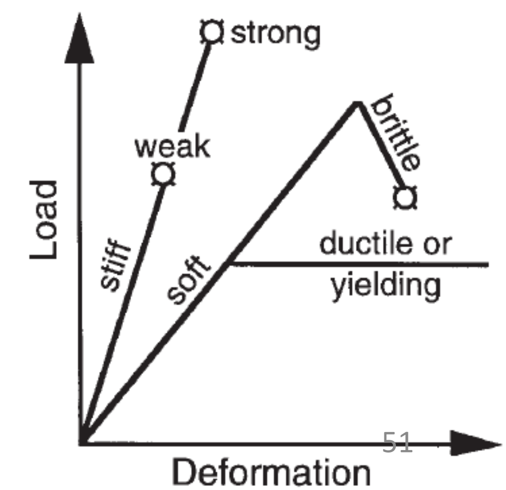
Rockburst control

- <u>Dynamic support</u>: element properties
  - Load-displacement curves: 3 comparisons (total 6)
    - Stiff vs. soft
    - Strong vs. weak
    - Brittle vs. ductile (yielding)
    - These 6 characteristics are coupled with the 3 functions

Table 1. Six characteristics of support elements with examples for three support functions

	Reinforcing	Retaining	Holding
stiff	grouted rebar	shotcrete	grouted rebar
soft	—	mesh	long mechanical bolt
strong	cable bolt	mesh-reinforced shotcrete	cable bolt
weak	thin rebar	#9 gauge mesh	Split Set bolt
brittle	grouted rebar	plain shotcrete	grouted rebar
ductile	Cone bolt	chain-link mesh; lacing	yielding Swellex bolt

Kaiser et al 1996



Rockburst control

- Dynamic support: element properties
  - Load-displacement curves: 3 comparisons (total 6)
    - Desired system properties depend on expected damage
      - No major damage: stiff and strong support reinforces rockmass and prevents loosening or weakening
      - Severe rockburst: support must be ductile and able to yield
    - Design rationale requires knowledge of these curves
      - These are based on lab tests
      - Field tests are also required

Kaiser et al 1996

Table 2. Load-displacement parameters of support elements

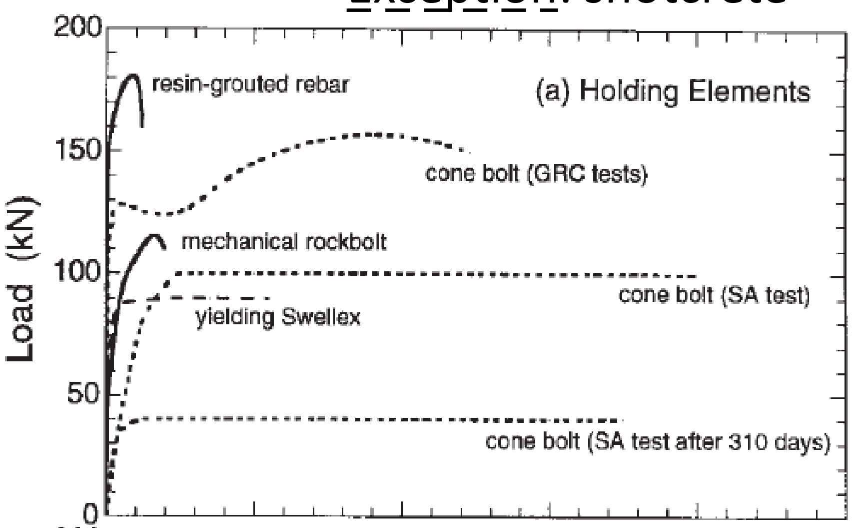
Description	Peak Load (kN)	Displace Limit (mm)	Energy Absorption (kJ)
19 mm resin-grouted rebar	100 — 170	10 — 30	1 — 4
16 mm cable bolt	160 — 240	20 — 40	2 — 6
16 mm, 2 m mechanical bolt	70 — 120	20 — 50	2 — 4
16 mm, 4 m debonded cable	160 — 240	30 — 50	4 — 8
16 mm grouted smooth bar	70 — 130	50 — 100	4 — 10
yielding Swellex bolt	80 — 90	100 — 150	8 — 12
yielding Super Swellex bolt	180 — 190	100 — 150	18 — 25
Split Set bolt	50 — 100	80 — 200	5 — 15
16 mm cone bolt	90 — 150	100 — 200	10 — 25
#6 gauge welded-wire mesh	20 — 30	100 — 200	1.5 — 2.5/m_2
#4 gauge welded-wire mesh	30 — 45	150 — 200	2.5 — 4 /m_2
#9 gauge chain-link mesh	30 — 35	350 — 450	3 — 4 /m_2
Shotcrete and welded-wire mesh	2 x mesh	< mesh	3 to 5 x mesh

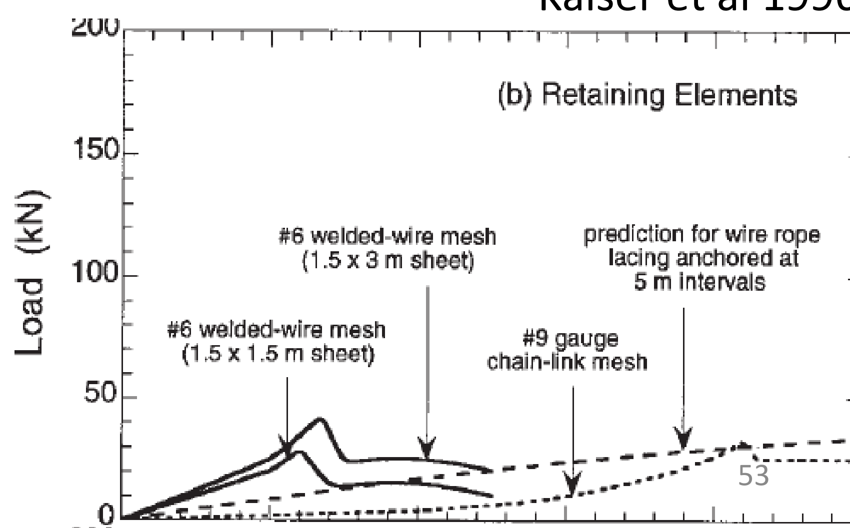
The displacement limit and energy absorption are taken at the point of failure for rock bolts and at peak load for mesh or shotcrete

Rockburst control

- Dynamic support: element properties
  - Load-displacement capacity of elements: results
    - Holding ones are stronger and stiffer than retaining ones
      - Exception: specifically-designed yielding bolts (50 to 100 mm)
    - Most retaining elements are both soft and weak
      - Exception: shotcrete

Kaiser et al 1996

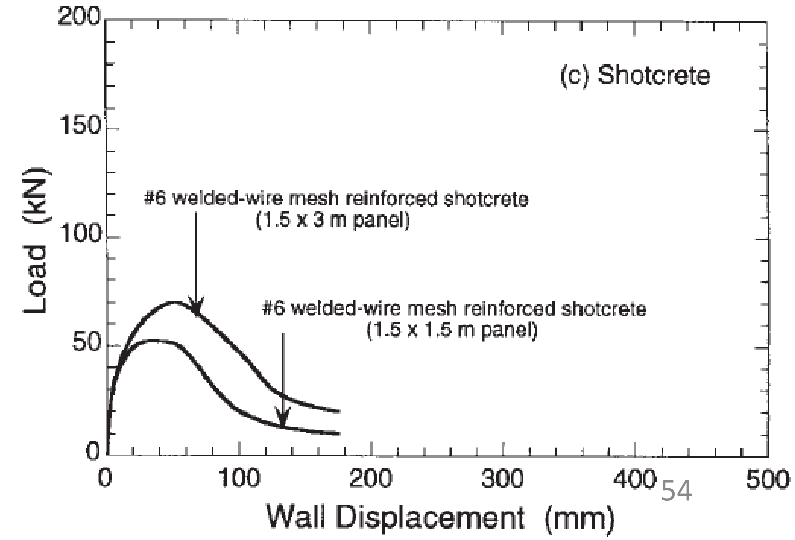




Rockburst control

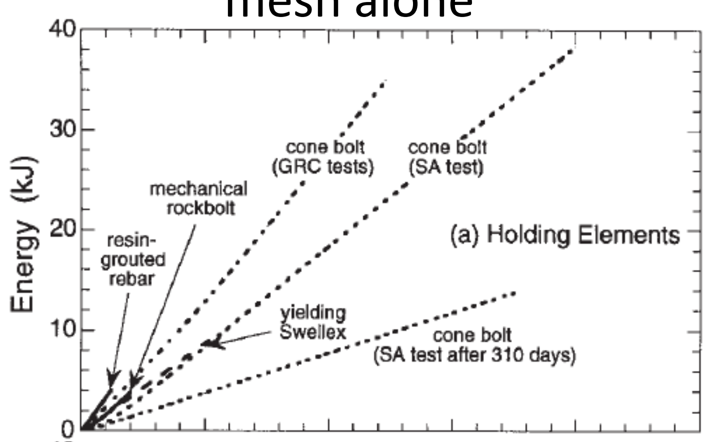
- Dynamic support: element properties
  - Load-displacement capacity of elements
    - There is a system that is initially stiff but later yields
      - "Supermesh": mesh-reinforced shotcrete
        - » It has better load-bearing capacity at small deformations
        - » At large deformations, it fractures but provides retaining capacity

Kaiser et al 1996

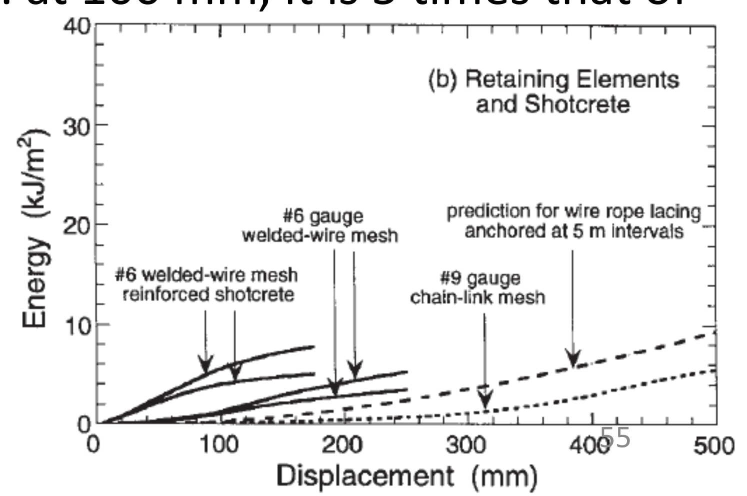


Rockburst control

- Dynamic support: element properties
  - Energy dissipation capacity of elements
    - It varies over a wide range based on the element type
      - 1 to 5 kJ: regular, non-yielding bolts
      - Up to 30 kJ: specialized yielding bolts
      - Mesh has a low dissipation capacity at < 200 mm deformation
        - » Mesh-reinforced concrete: at 100 mm, it is 5 times that of mesh alone



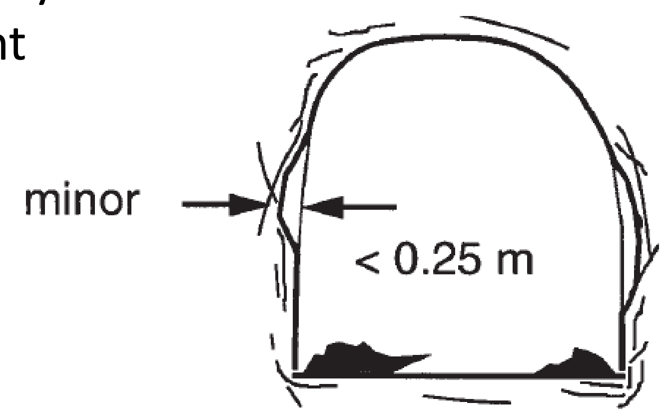
Kaiser et al 1996



Rockburst control

- Dynamic support: selection
  - An assessment of the expected damage is required
    - Three categories have been suggested (Kaiser et al 1996)
      - Minor: it involves a shallow rock skin < 0.25 m
        - » Example: spitting, spalling, shallow slabbing
        - » It occurs primarily during drift development or…
        - » … in highly-stressed, moderately-fractured rockmass at a distance from a fault-slip event

Kaiser et al 1996



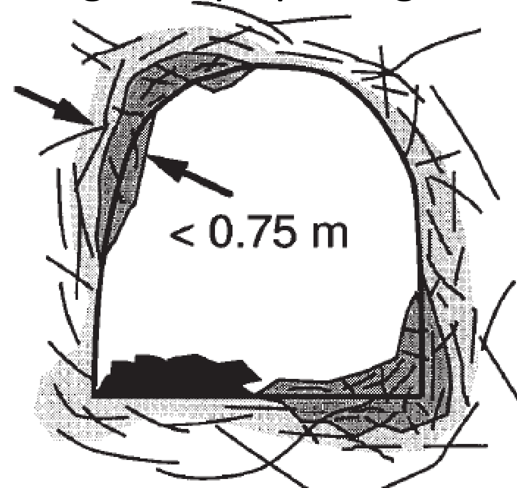
- » Total volume of displaced rock < 1 tonne/m of tunnel

Rockburst control

- Dynamic support: selection
  - An assessment of the expected damage is required
    - Three categories have been suggested (Kaiser et al 1996)
      - Moderate: it creates a fractured rock annulus between 0.25 and 0.75 m thickness
        - » Example: rock fracturing, onion skinning, deep spalling, loosening

Kaiser et al 1996

moderate

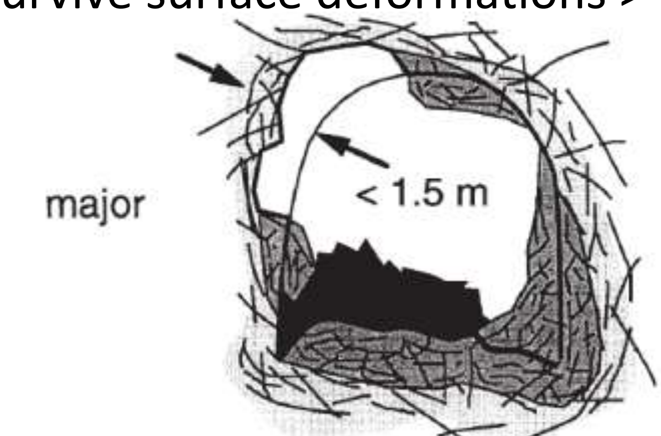


        - » Damaged opening is self-stabilizing
        - » Fracture process does not continue after the rockburst

Rockburst control

- Dynamic support: selection
  - An assessment of the expected damage is required
    - Three categories have been suggested (Kaiser et al 1996)
      - Major: it involves deep fracturing and significant rock bulking to a depth > 0.75 m or a violent ejection of large blocks
        - » Rockmass bulking cannot be prevented by regular support
        - » System must be designed to survive surface deformations > 0.1 m

Kaiser et al 1996



        - » If proper support is not used, the drift would be closed

Rockburst control

- <u>Dynamic support</u>: selection
  - An assessment of the expected damage is required
    - Damage severity can be estimated from empirical data
      - This has been summarized in the table below

Kaiser et al 1996

Table 3. Rockburst damage mechanisms and nature of the anticipated damage

Damage mechanism	Damage severity	Cause of rockburst damage	Thickness (m)	Weight (kN/m²)	Closure (mm)	v_e (m/s)	Energy (kJ/m²)
Bulking	minor	highly stressed rock	<0.25	<7	15	<1.5	not critical
without	moderate	with little excess	<0.75	<20	30	<1.5	not critical
ejection	major	stored strain energy	<1.5	<50	60	<1.5	not critical
Bulking	minor	highly stressed rock	<0.25	<7	50	1.5 to 3	not critical
causing	moderate	with significant	<0.75	<20	150	1.5 to 3	2 to 10
ejection	major	excess strain energy	<1.5	<50	300	1.5 to 3	5 to 25
	minor	jointed or broken rock	<0.25	<7	<150	>3	3 to 10
Ejection	moderate	with energy from	<0.75	<20	>300	>3	10 to 20
	major	remote seismic event	<1.5	<50	>300	>3	20 to 50
	minor	inadequate strength,	<0.25	<7g/(a+g)	na	na	na
	moderate	forces increased	<0.75	<20g/(a+g)	na	na	na
Rockfall	major	by seismic acceleration	<1.5	<50g/(a+g)	na	na	na

v_e is the velocity of displaced or ejected rock; a and g are seismic and gravitational accelerations

Rockburst control

- Dynamic support: selection
  - Design philosophy: it is based on the 2 factors
    - Load-displacement characteristics vs. expected failure
      - Tables 3 and 4 (Kaiser et al 1996)

Table 3. Rockburst damage mechanisms and nature of the anticipated damage

Damage mechanism	Damage severity	Cause of rockburst damage	Thickness (m)	Weight (kN/m²)	Closure (mm)	v_e (m/s)	Energy (kJ/m²)
Bulking	minor	highly stressed rock	<0.25	<7	15	<1.5	not critical
without	moderate	with little excess	<0.75	<20	30	<1.5	not critical
ejection	major	stored strain energy	<1.5	<50	60	<1.5	not critical
Bulking	minor	highly stressed rock	<0.25	<7	50	1.5 to 3	not critical
causing	moderate	with significant	<0.75	<20	150	1.5 to 3	2 to 10
ejection	major	excess strain energy	<1.5	<50	300	1.5 to 3	5 to 25
	minor	jointed or broken rock	<0.25	<7	<150	>3	3 to 10
Ejection	moderate	with energy from	<0.75	<20	>300	>3	10 to 20
	major	remote seismic event	<1.5	<50	>300	>3	20 to 50
	minor	inadequate strength,	<0.25	<7g/(a+g)	na	na	na
	moderate	forces increased	<0.75	<20g/(a+g)	na	na	na
Rockfall	major	by seismic acceleration	<1.5	<50g/(a+g)	na	na	na

v_e is the velocity of displaced or ejected rock; a and g are seismic and gravitational accelerations

Table 4. Role of support for different rockburst conditions

Mechanism	Severity	Role of support system
Bulking without ejection	minor	– tolerate minor damage or strengthen rockmass to prevent initiation of fracturing
	moderate	– reinforce rockmass to limit rockmass bulking and control rock displacements with support pressure
	major	– control rockmass bulking and survive large rock displacements
Bulking causing ejection	minor	– retain small volumes of ejected rock with a tough retaining system and limit rock displacements
	moderate	– retain small volumes of ejected rock with a tough retaining system and survive rock displacements
	major	– survive large rock displacements and absorb energy
Ejection	minor	– retain small volumes of ejected rock with a tough retaining system that absorbs energy
	moderate	– absorb energy and survive rock displacements and retain ejected rock
	major	– absorb energy and survive rock displacements and retain ejected rock
Rockfall	minor	– strengthen rockmass to prevent failure or unraveling
	moderate	– strengthen rockmass and hold broken rock
	major	– maintain rockmass integrity and hold broken rock in place

Rockburst control

- Dynamic support: selection
  - Design philosophy: it is based on the 2 factors
    - Load-displacement characteristics vs. expected failure
      - Tables 3 and 4 = Table 5 (Kaiser et al 1996)

Table 5. Support systems appropriate for burst-prone ground

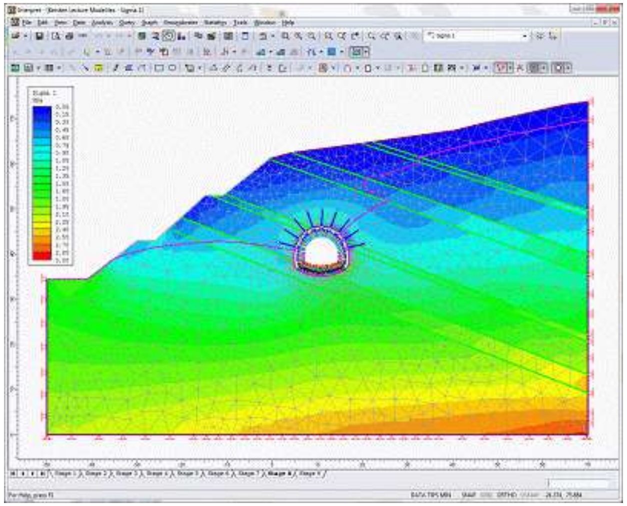
Mechanism	Damage severity	Support System Capacities: Load (kN/m²)	Displace (mm)	Energy (kJ/m²)	Examples of suggested support systems
Bulking without ejection	minor	50	30	not critical	– mesh with rockbolts or grouted rebars (and shotcrete)
	moderate	50	75	not critical	– mesh with rockbolts and grouted rebars (and shotcrete)
	major	100	150	not critical	– mesh and shotcrete panels with yielding bolts and grouted rebars
Bulking causing ejection	minor	50	100	not critical	– mesh with rockbolts and Split Set bolts (and Shotcrete)
	moderate	100	200	20	– mesh and shotcrete panels with rebars and yielding bolts
	major	150	>300	50	– mesh and shotcrete panels with strong yielding bolts and rebars (and lacing)
Ejection by remote seismic event	minor	100	150	10	– reinforced shotcrete with rockbolts or Split Set bolts
	moderate	150	300	30	– reinforced shotcrete panels with rockbolts and yielding bolts (and lacing)
	major	150	>300	>50	– reinforced shotcrete panels with strong yielding bolts and rebars and lacing
Rockfall	minor	100	na	na	– grouted rebars and shotcrete
	moderate	150	na	na	– grouted rebars and plated cablebolts with mesh and straps or mesh-reinforced shotcrete
	major	200	na	na	– as above plus higher density cable bolting
MPSL		200	300	50	– Maximum practical support limits

Notes:
Items in brackets are beneficial but optional.
Displacement capacity is dominated by the stiffer elements in the support system.
"Rockbolt" is used as a generic term referring to any holding or reinforcing element.
"Mesh" is used as a generic term for all mesh types.
"Shotcrete panels" refers to shotcrete applied such that displacement incompatibilities are avoided and over stressed shotcrete is minimized (e.g., flat walls, thin shotcrete in corners, arches with slots).

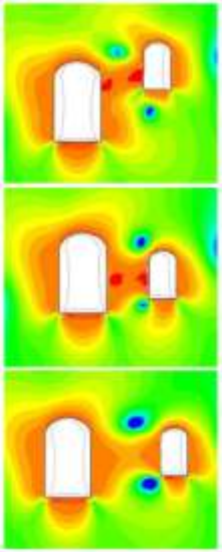
Numerical modelling

- What is numerical modelling?
  - It is a computer-based method for solving complex mathematical equations
  - It simulates field conditions with a computer code
    - Rock mechanics applications: civil, mining, petroleum engineering

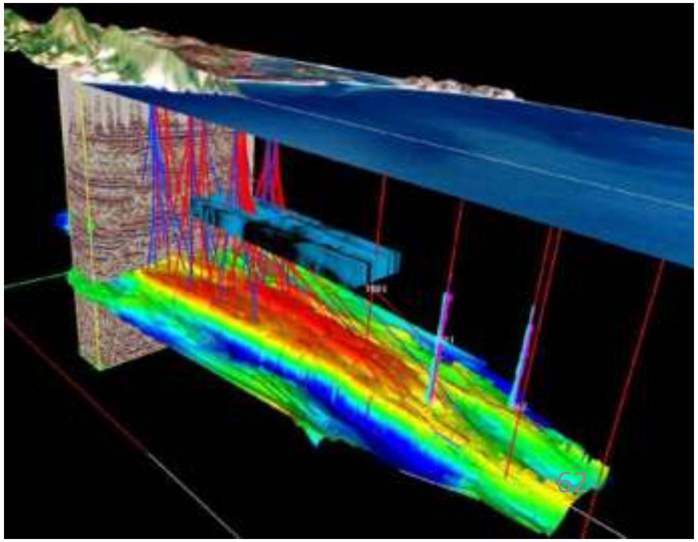
Rocscience



Hoek 2007

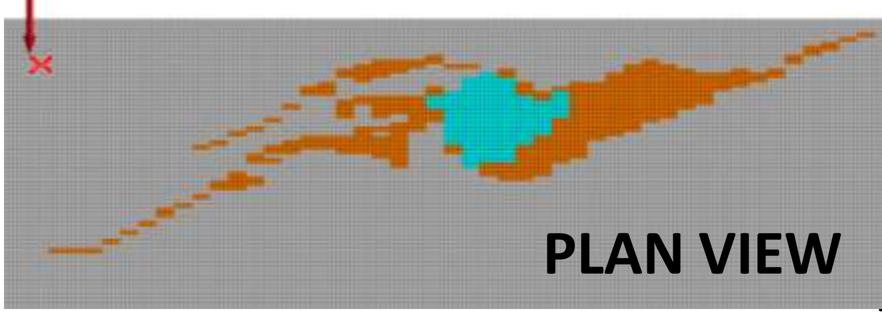


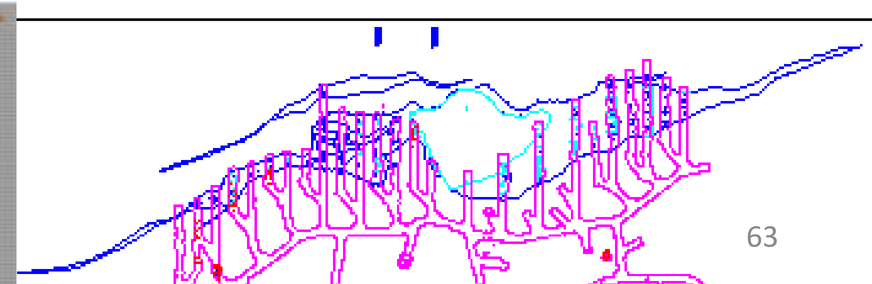
Imperial College



Numerical modelling

- What is numerical modelling?
  - Rockmass components are simulated in model
    - All geological units and structures are present
    - Replication of a unit's or structure's geometry is made
    - Rockmass and discontinuity properties are input
    - In-situ stress orientation and magnitude is generated
      - This is related to model boundary conditions
    - **The model must first be calibrated**

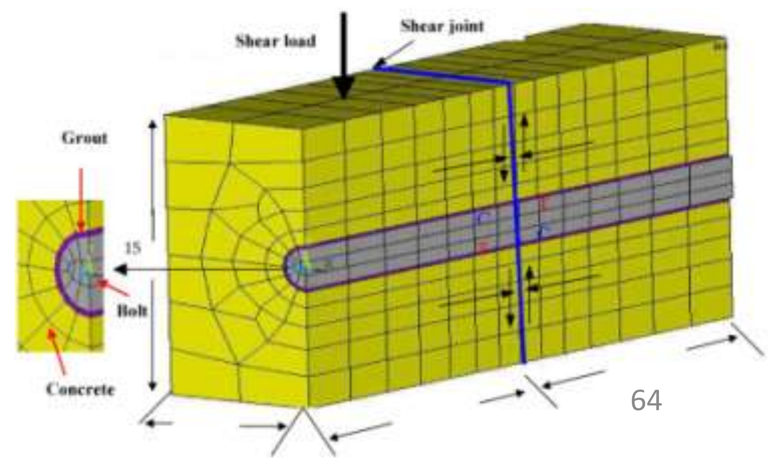




Numerical modelling

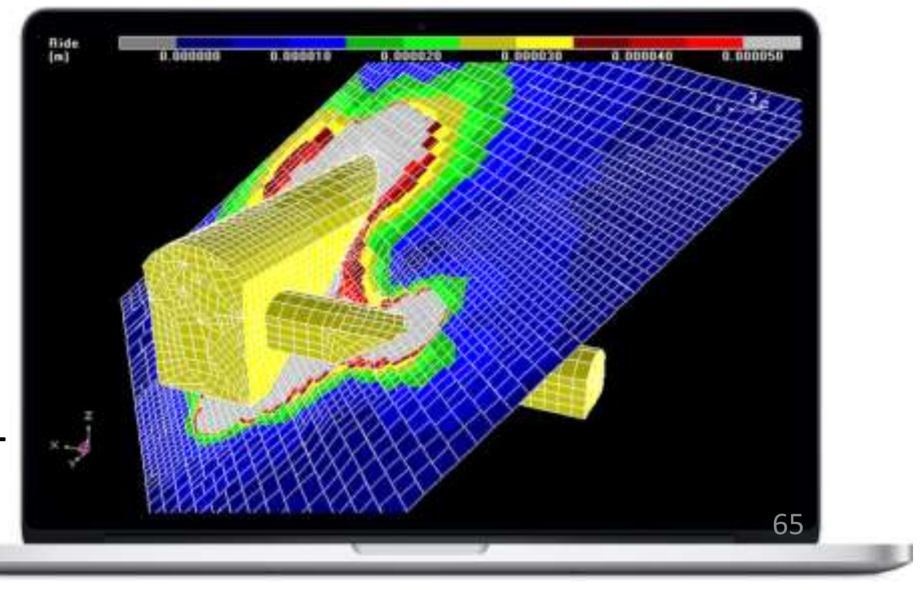
- What is numerical modelling?
  - The rockmass domain is subdivided into smaller elements
    - Solution: approximations are calculated with differential equations
    - Continuum vs. discrete components
      - It depends on problem scale and nature of discontinuities

Jalalifar and Aziz 2012



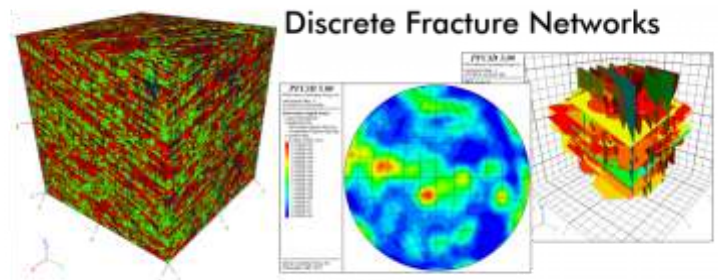
Numerical modelling

- Several methods and codes can be used
  - Continuum
    - **Finite difference method (FDM)** – FLAC, **FLAC^{3D}**
    - **Finite element method (FEM) – Phase^{2}**, Plaxis, ABAQUS
    - **Boundary element method (BEM)** – **Examine^{3D}**, Map^{3D}



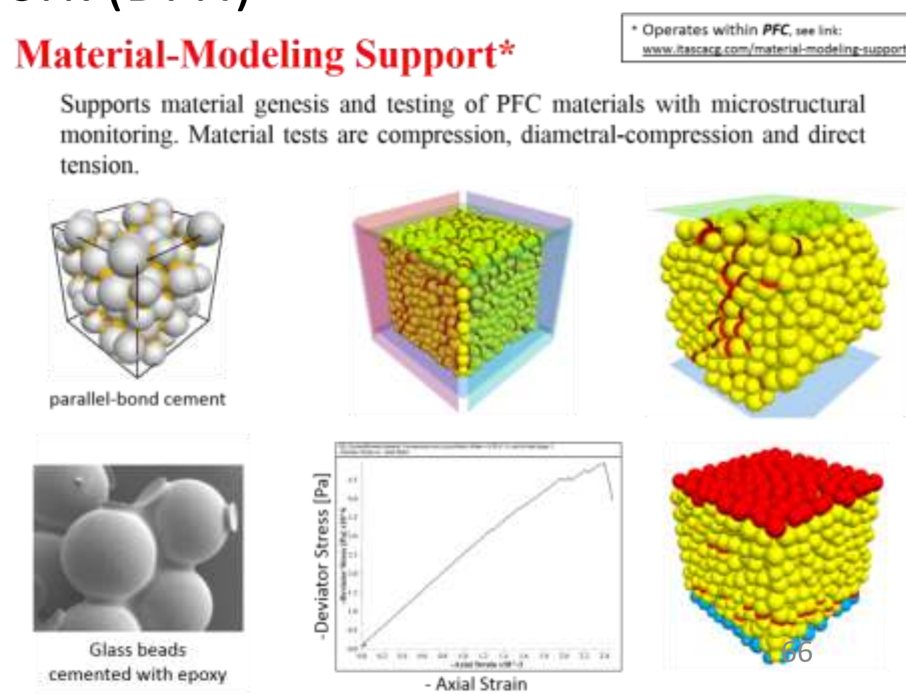
Map3D

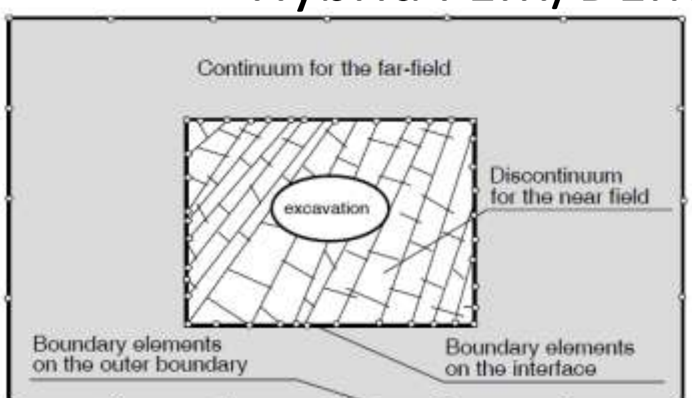
Numerical modelling



- Several methods and codes can be used
  - Discrete
    - **Discrete element method (DEM)** – UDEC, 3DEC, PFC
    - Discrete fracture network (DFN)
  - Hybrid
    - Hybrid FEM/BEM
    - Hybrid FEM/DEM

Itasca





Jing 2003

Numerical modelling

	Points								
	One round behind the drift face			Just behind the drift face			Just in front of the drift face		
β	A6	B6	C6	A7	B7	C7	A8	B8	C8
0.1	87.4	188.9	115.7	146.1	150.2	135.5	114.6	130.4	120.1
0.2	85.6	188.2	112.4	140.3	148.4	130.9	109.9	127.7	119.4
0.3	83.5	184.5	108.3	134.7	144.2	126.7	106.6	123.9	118
0.4	81.2	180.8	104.4	128.7	140.5	122.5	103.6	119.7	116.5
0.5	78.9	174.4	99.3	122.5	134.8	118.5	100.7	115.8	114.5
0.6	76.4	173.3	96.2	115.8	134.5	114.2	98.1	110.5	113
0.8	70.7	164	87.2	101	129	105.1	93.8	99.2	108.6
1.0	65.9	159.8	81.9	87.7	129.2	97.7	87.7	88.5	104.4

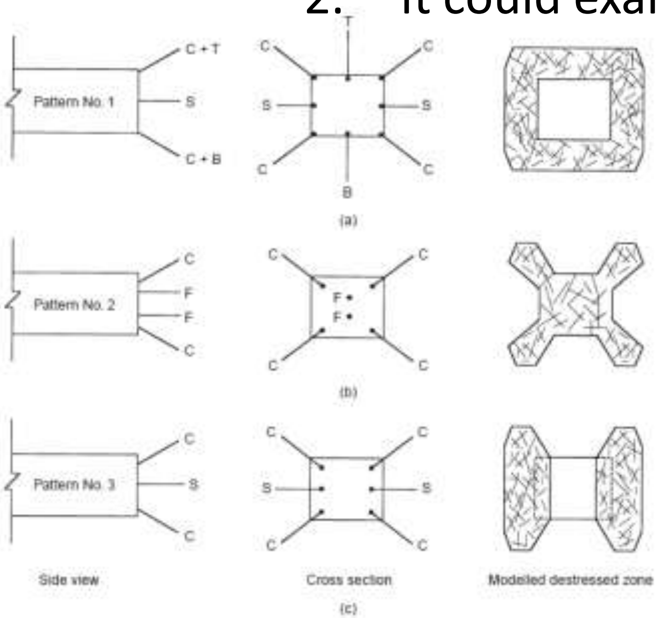
- Destress blasting
  - Numerical modelling can be used for assessment
    - Several considerations need to be accounted for
      - Numerical model should replicate field effects of destressing
        - » Destressed area must carry less stress than before
        - » Higher stresses should be transferred to rockmass behind
      - Tang (2000) developed two new factors (range from 0 to 1)
        - » α: rock fragmentation factor
        - » β: stress reduction factor

Tang 2000

	Feature points σ_1(MPa)								
	One round behind the drift face			Just behind the drift face			Just in front of the drift face		
α	A6	B6	C6	A7	B7	C7	A8	B8	C8
0.05	50.6	127	79.3	108	106.4	106.8	85.7	110	95.9
0.1	50.8	133	80.7	113	106	111.4	91	109	97.8
0.2	53.7	160	89.7	120	121.7	116.7	97	115	107.3
0.4	56.9	194	99.5	128	140.5	122.5	103.6	120	116.5
0.5	58	205	102	132	146	124.4	105.6	121	119.1
0.6	60.3	230	108	140	157.2	128.2	109.6	122	123.6
0.8	60.5	232	109	141	159.3	128.8	109.2	123	123.9
1	61.5	244	111	145	164.4	130.5	111	123	125.6

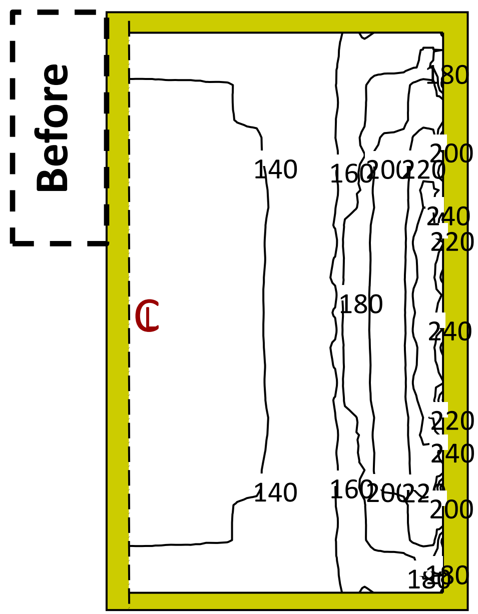
Numerical modelling

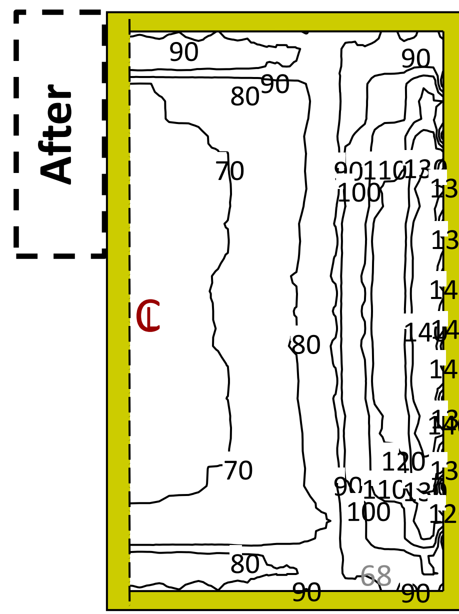
- Destress blasting
  - – Numerical modelling can be used for assessment
    - Two important contributions can be made
      1. It could indicate if blast was successful or not (less stress)
      2. It could examine different blast designs for optimum results



F = face, S = side wall, T = roof, B = floor, C = corner

Tang and Mitri 2001

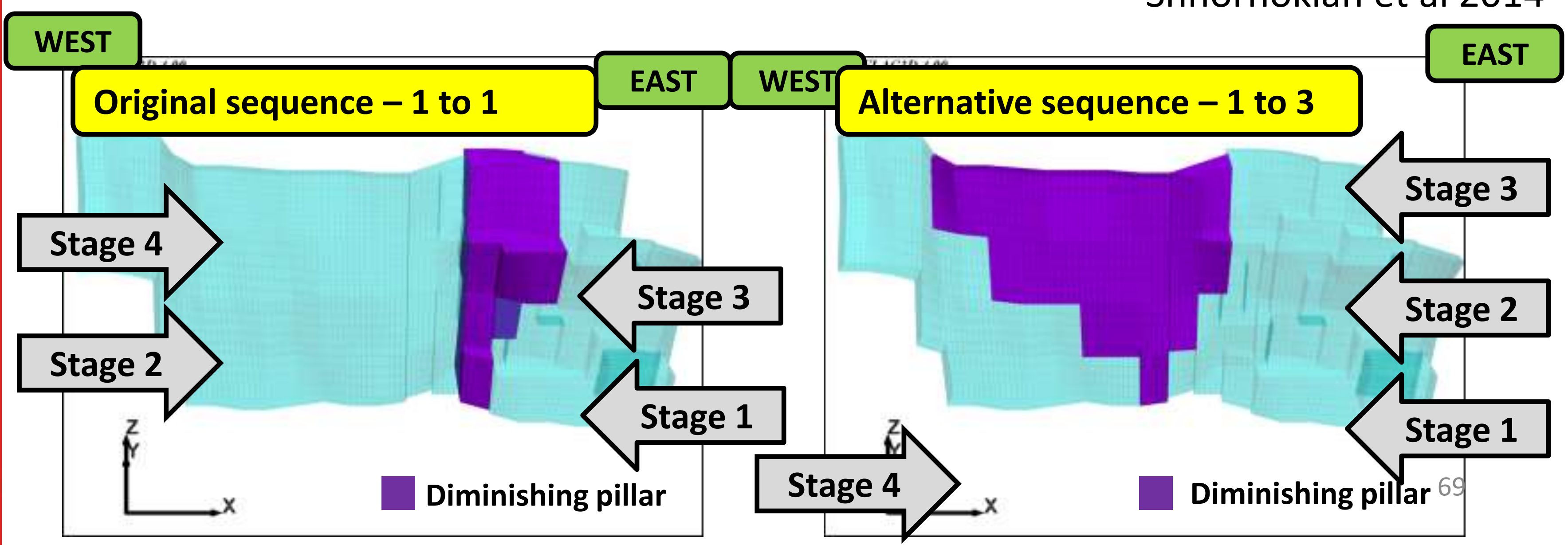




Numerical modelling

- Stope sequencing
  - It is the remaining option if destress blasting and dynamic support are not enough
    - Different sequences redistribute induced stresses more favourably

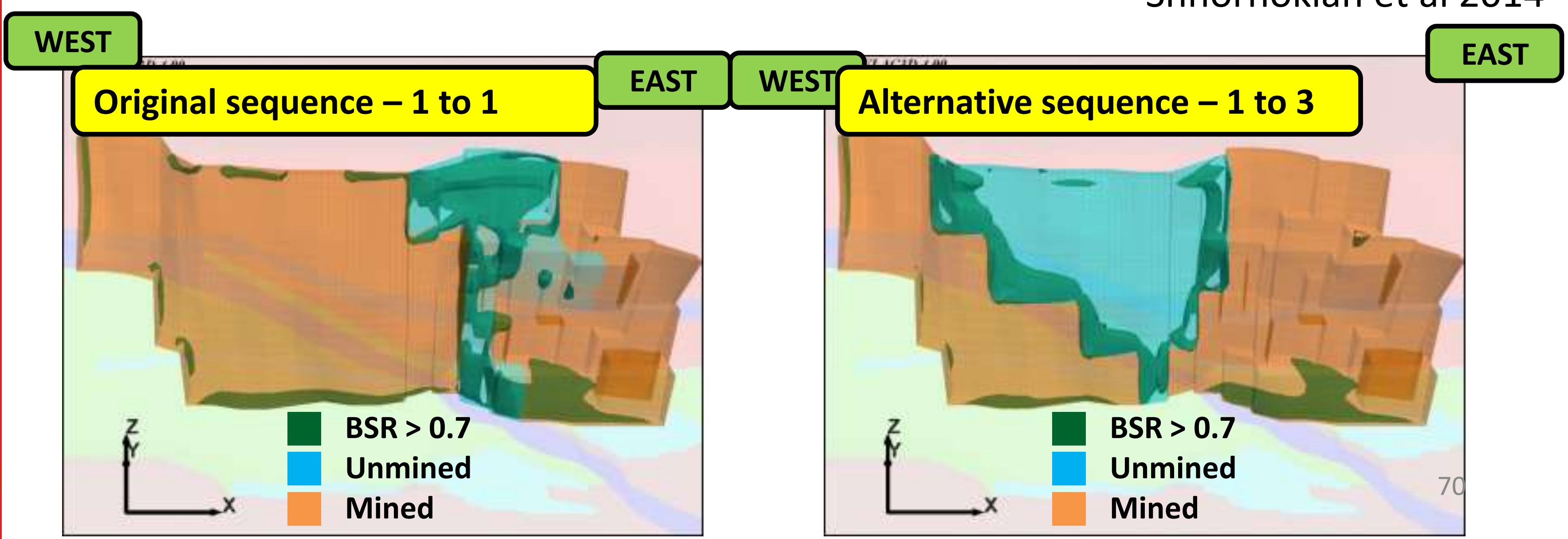
Shnorhokian et al 2014



Numerical modelling

- Stope sequencing
  - It is the remaining option if destress blasting and dynamic support are not enough
    - This is best done by using numerical modelling tools

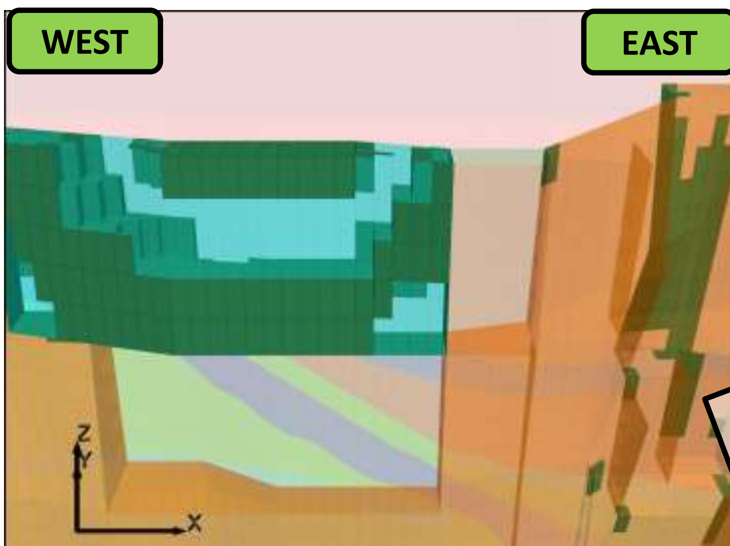
Shnorhokian et al 2014

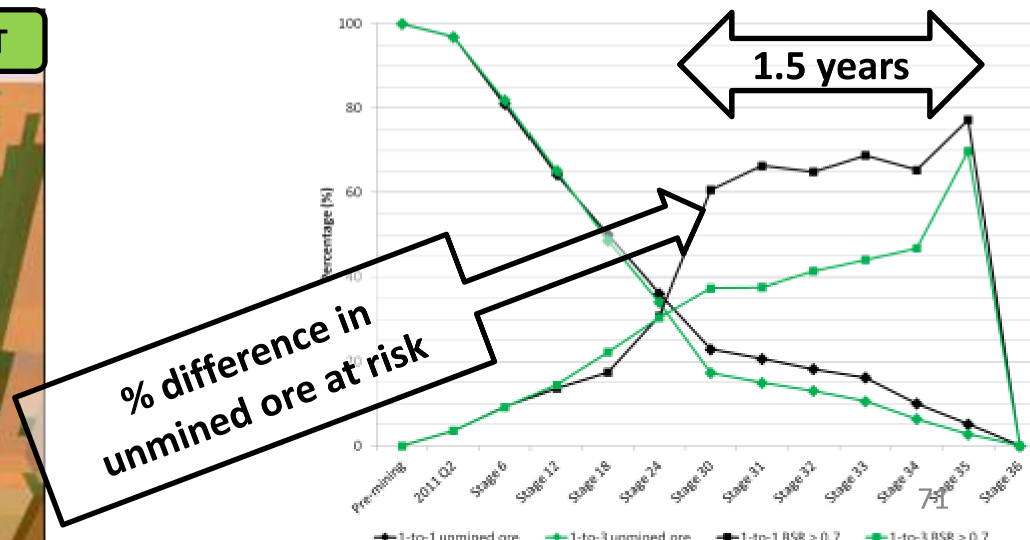


Numerical modelling

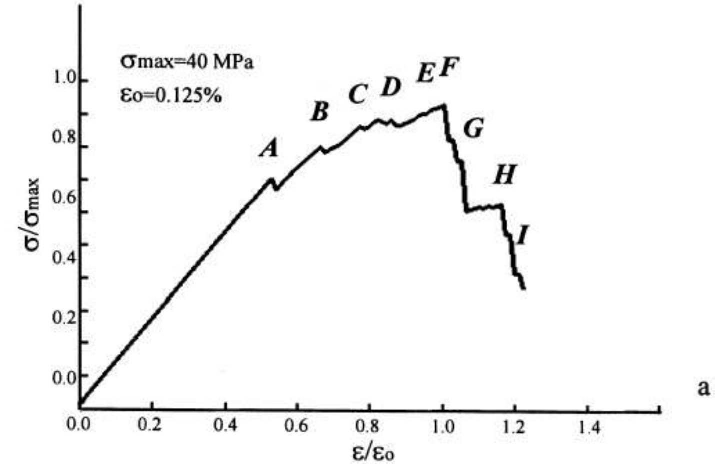
- Stope sequencing
  - It is the remaining option if destress blasting and dynamic support are not enough
    - It can be combined with different failure criteria and also provide the volume of expected instability

Shnorhokian et al 2014





Numerical modelling



- Stope sequencing
  - It is the remaining option if destress blasting and dynamic support are not enough
    - Energy accumulation and storage can also be used as potentials for instability

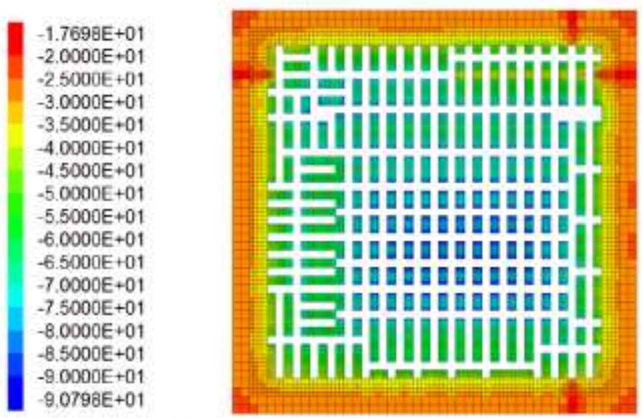
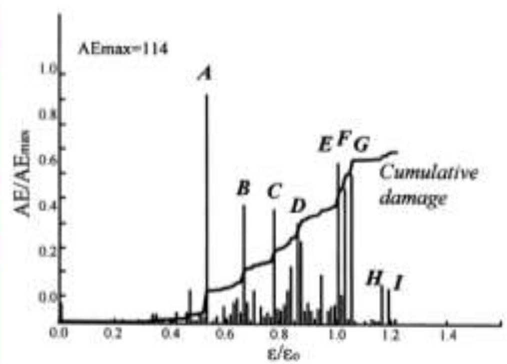


Figure 6: Vertical stress (MPa) at the end of mining sequence with FLAC-3D.

Lafont et al 2013



Tang and Kaiser 1998

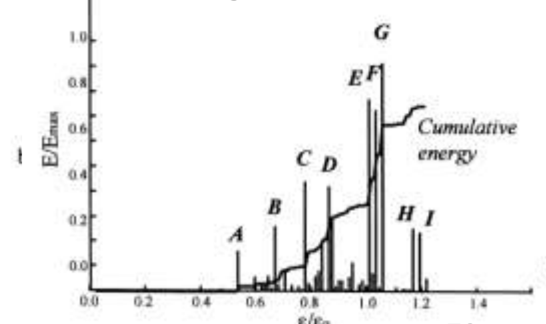


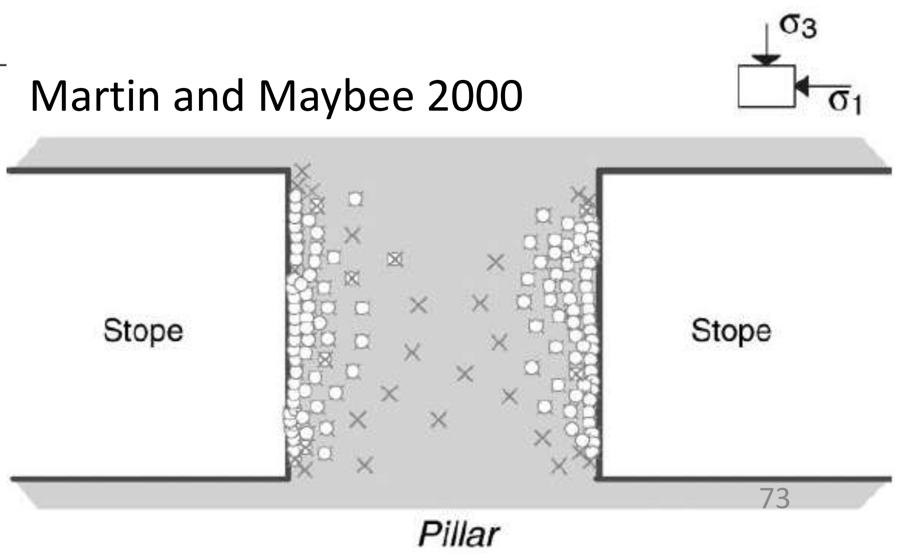
Fig. 7. Stress-strain, AE counts and Energy release for sample with weak zones.

Numerical modelling

- Pillar stability
  - Elliot Lake uranium orebody in Ontario
    - Numerical modelling was conducted using Phase^2
      - Analytical methods provide only a single value for a pillar
      - Numerical methods indicate stress distributions within a pillar
      - If a zone fails, stresses are redistributed in the remaining ones

Parameter	Description/value
Rock-type	Quartzite, Conglomerate
Insitu stress	$\sigma_1 = 2\sigma_3$ and $\sigma_2 = 1.66\sigma_3$
	$\sigma_3 = 0.028$ MPa/m
Intact rock strength	$\sigma_{ci} = 230$ MPa
Geological Strength Index	$GSI = 80$
Hoek−Brown constants	$m_i = 22$
	$m_b = 10.7$
	$s = 0.108$
	$m_r = 1$
	$s_r = 0.001$

Martin and Maybee 2000

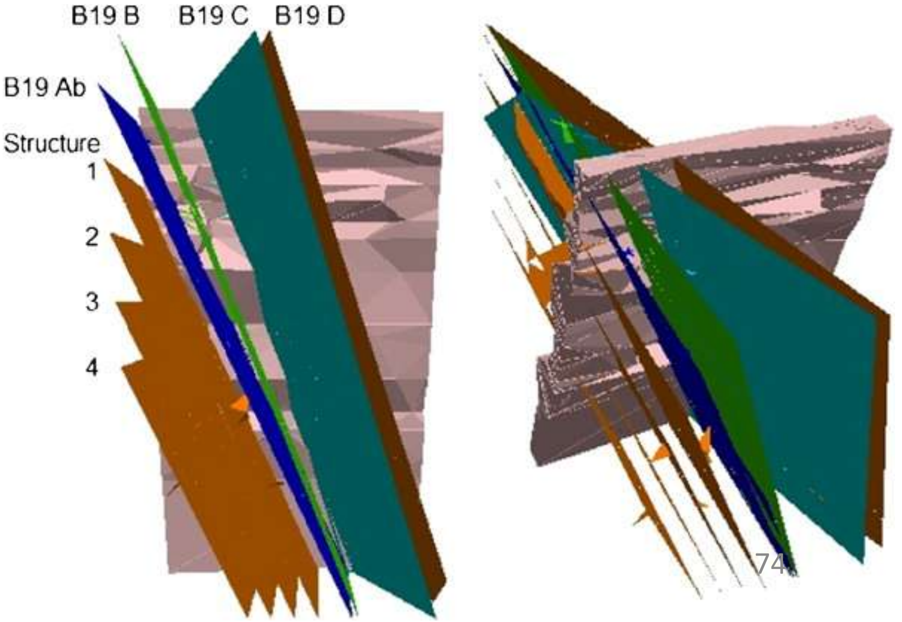


x shear failure
o tensile failure

Numerical modelling

- Fault movement
  - There are a number of studies that examine the expected displacements along faults
    - However, this is very difficult to do numerically since the calibration process requires data from the fault region

Sjoberg et al 2012



Thank you, **IIMP**!

- Questions?