Challenges and Innovations in Site investigation, Ground Behaviour Prediction and Risk Assessment for Deep Hard Rock Tunnels

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Challenges with Deep Tunnelling

- Pre-Construction Investigation
- In Situ Stress Determination
- Rock Stability Prediction
- Rockbursting
  - Fracture and Burst Potential
  - Effect of Geo-Structure
  - Rockburst Support
  - TBM and DB Safety
- RQD, Q, RMR, GSI don’t mean much at depth

Challenges with Deep Tunnelling

- RQD, Q, RMR were once invaluable but we need to move on…
- In addition, classification and GSI don’t mean much for hard rock at depth

1966

1970

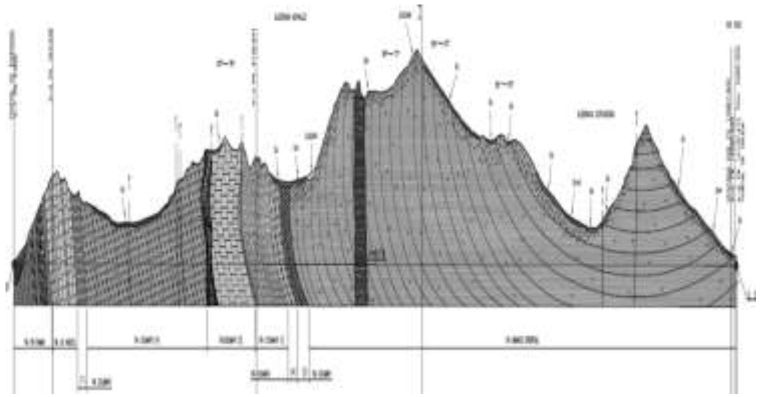
Site Investigation Access

- Sampling of Rock through Drilling is Practical
  - If depths permit
  - If strata is sub-horizontal
  - If topographic relief is low
  - If access is possible

- Sampling of Rock is often not done at all:
  - If depths are significant
  - If strata is inclined or subvertical and variable
  - If topography is prohibitive
  - If ground above is inaccessible

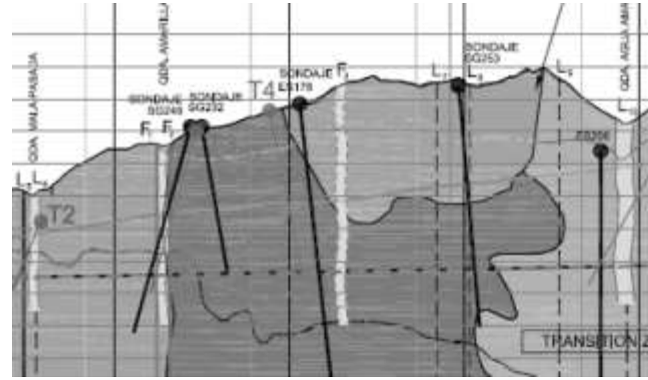
Tunnel Investigation often stuck on vertical

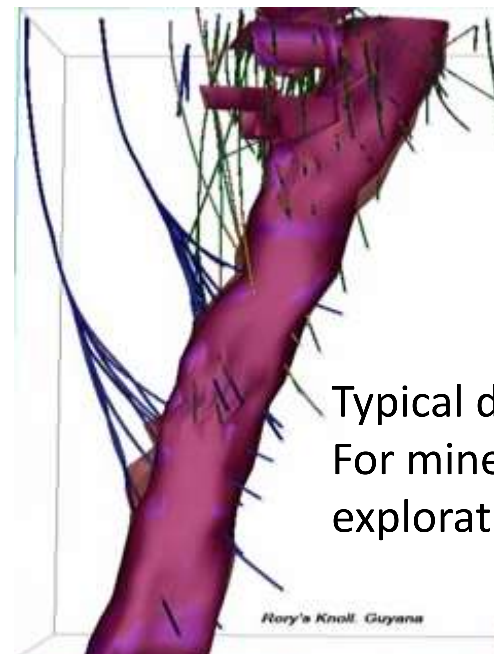
- Tunnel investigations are often based on sub-vertical holes.
- Provide little information for sub-vertical strata variations
- This limits campaign according to access and cost
- Surface sampling not representative of rock at depth >>



Fan Drilling, Curved Drilling, Horizontal Drilling

- Many holes can be drilled from one location (where access permits)
- Fan drilling to optimize access
- Geological model construction is essential (folding, faulting, distortion)
- Horizontal drilling from a tunnel niche hundreds of metres ahead to confirm models and detect risks





Typical drilling
For mineral
exploration

Continuous rock core:

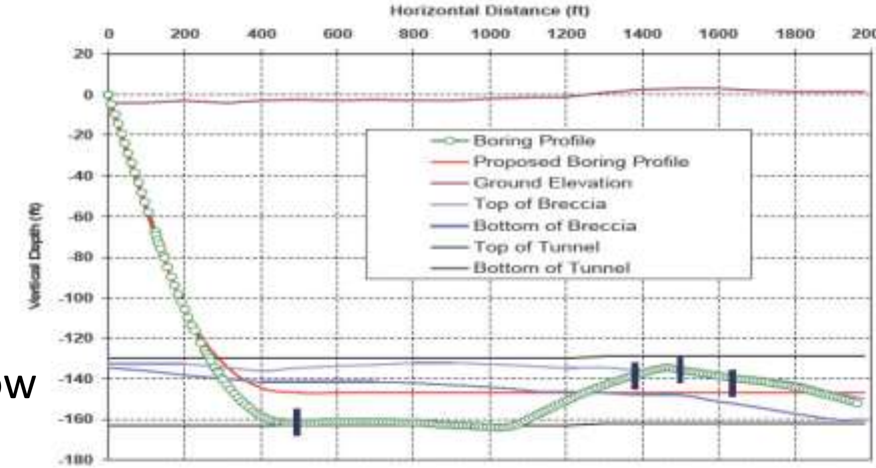
Fault zones, Fractures, Lithology

Rock mechanical properties

Smooth hole at tunnel axis:

Geophysical Analysis, Water Press/Flow

Stress analysis (frac)



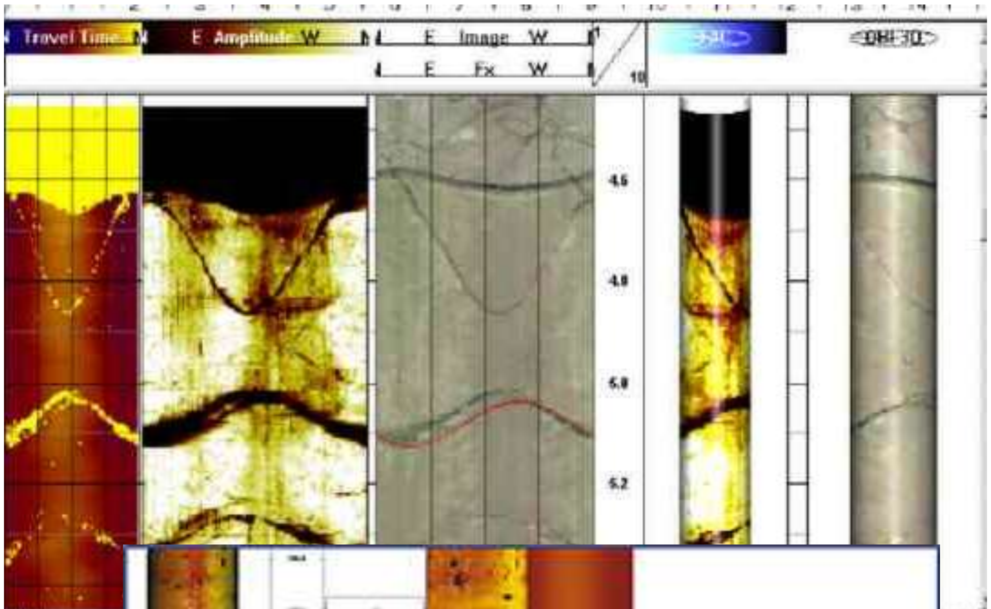
"Directional drilling techniques are now available to drill from ground level to great depth and then along a horizontal alignment. This method does not require provision of working space at the tunnel level and can be very useful in investigations for deep tunnels."

HK government specs

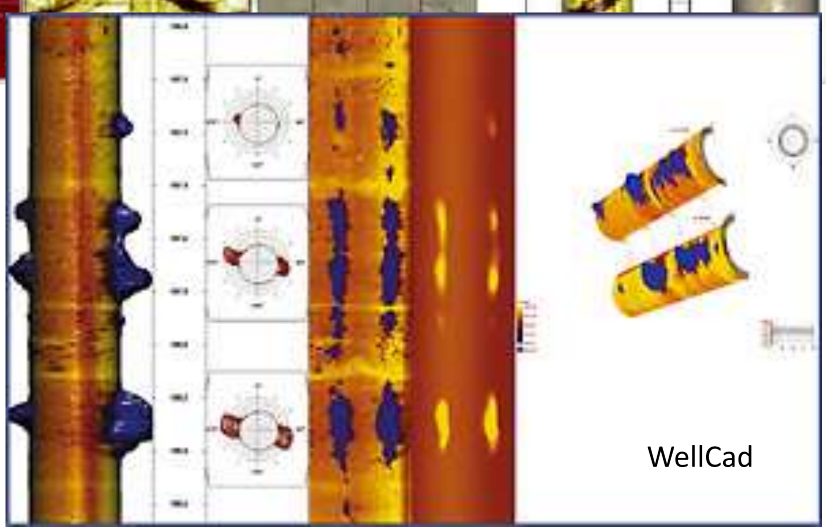
Courtesy
Devico

Getting more our of our boreholes

Acoustic and Optical Televiewers, Improved Logging

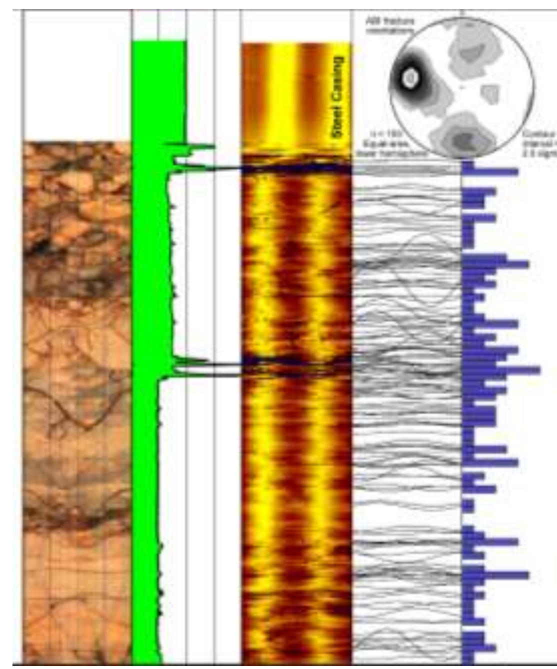


Terraplus



WellCad

D. Garroux Current Queen's PhD
N. Blacklock Current Queen's MSc
J. Day current Queen's PhD

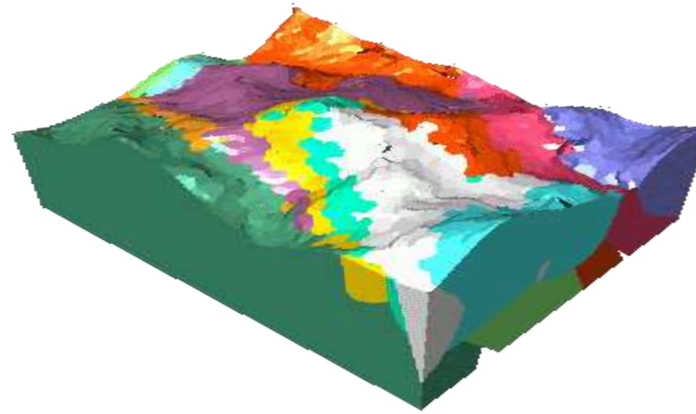


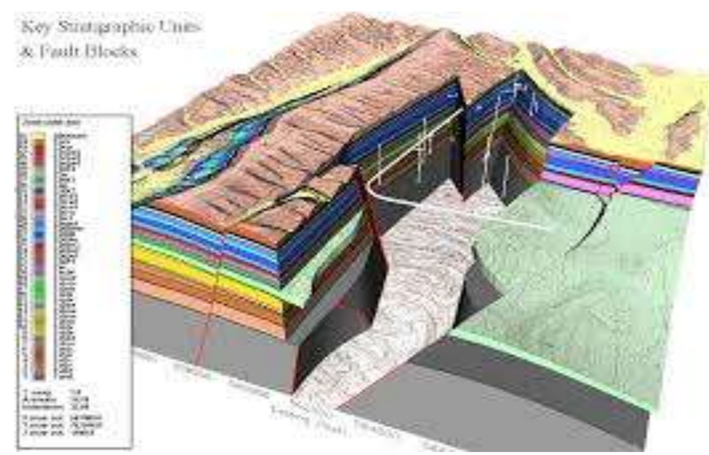
USGS

Surface geology is not tunnel geology
Better 3D visualization is needed
…and is available!

- Project geology is often communicated using surface maps.
- Actual geology at the tunnel must be modelled and presented
- Decisions made based on vertical geology projection are dangerous

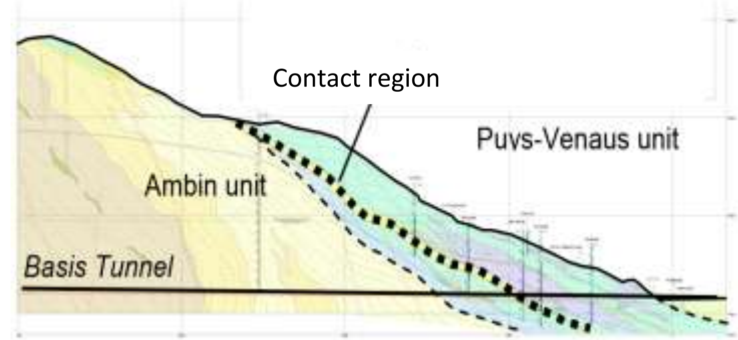
- NEED a new approach to the updating of geology actual and for contract purposes during a project

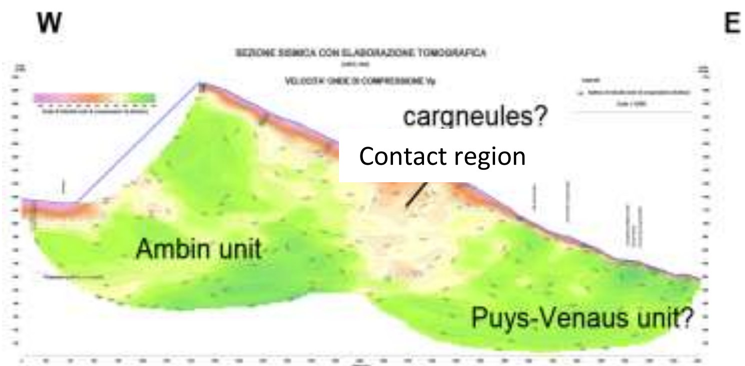




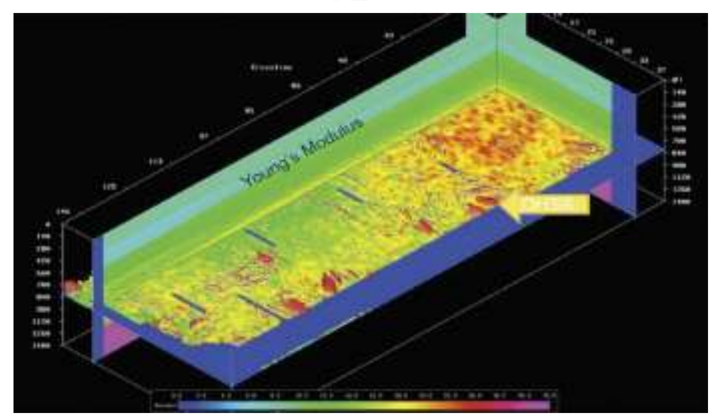
Geophysics can help with subsurface prediction

- Deep Seismic Refraction can detect the depth of the weathered zone



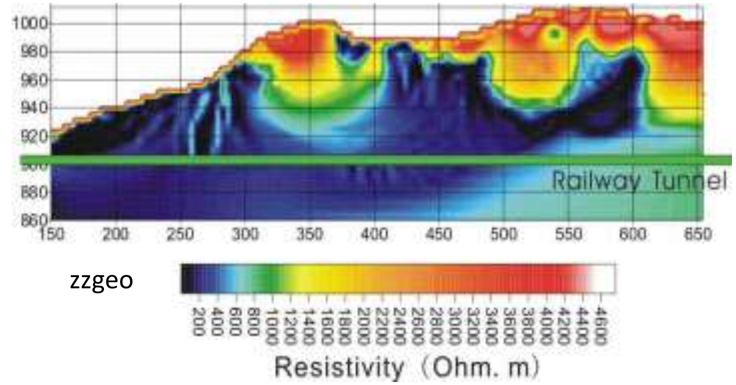


- Seismic Reflection has been used in gently dipping/folded terrain to confirm strata model
- Seismic Tomography can reveal differences in mechanical properties (and rockburst potential) but $$$$



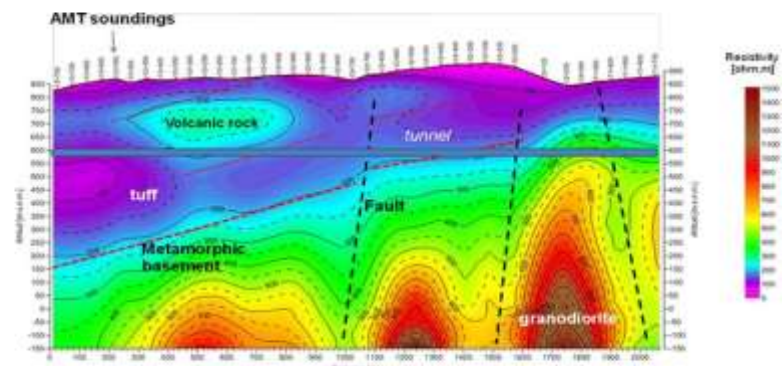
Geophysics can help with subsurface prediction

- Resistivity surveys can reveal high water zones and can show variations in competence
- Resistivity surveys can differentiate between lithologies
- Resistivity shows where rock fracturing is dominant
- Borehole geophysics can quantify rock properties

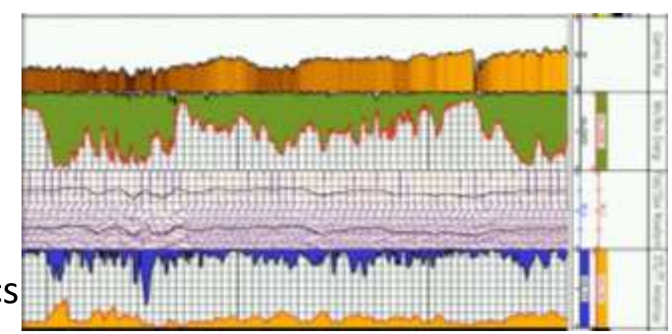


Conventional electrode resistivity

Phoenix Geosystems



Audio-frequency magnetotellurics



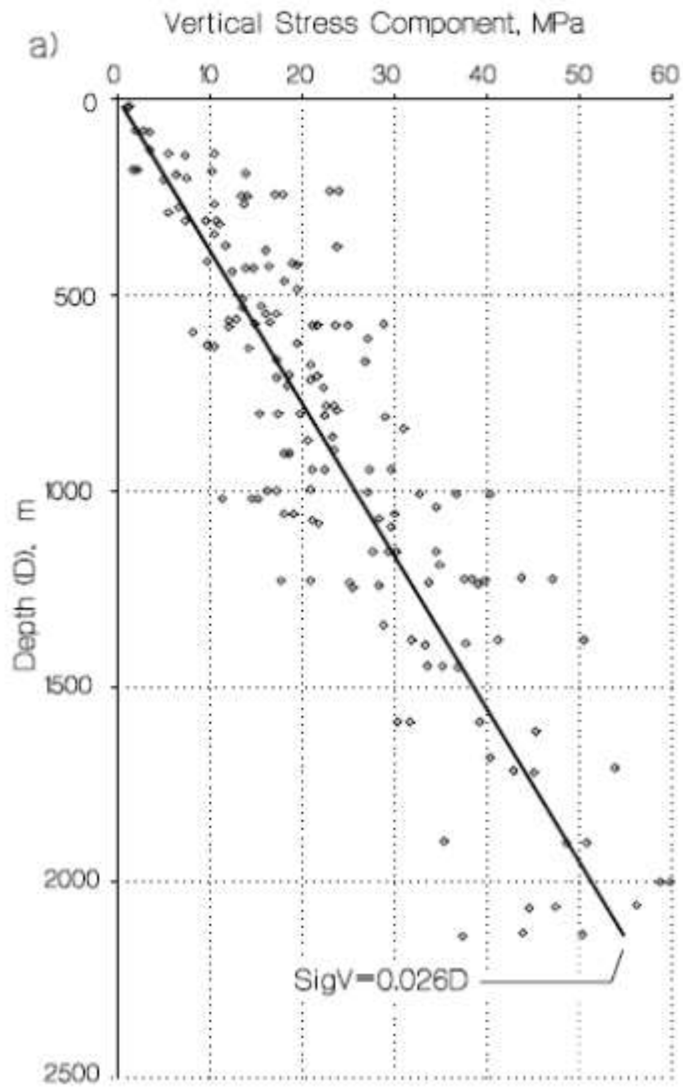
Borehole Geophysics

In Situ Stress

- Every major tunnelling dispute in my 15 years of consulting (>> $1B in claims and losses) has involved questions of

  In Situ Stress

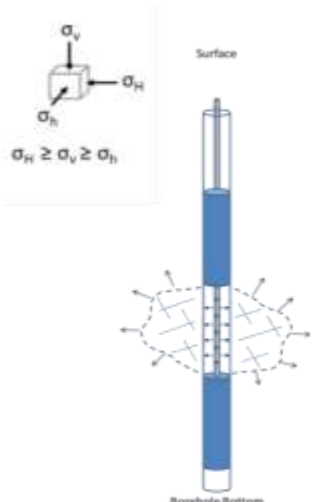
- Stress measurement at depth is difficult if K>>1
- Stress measurement at tunnel depth during construction can help confirm
- Local tests have low reliability

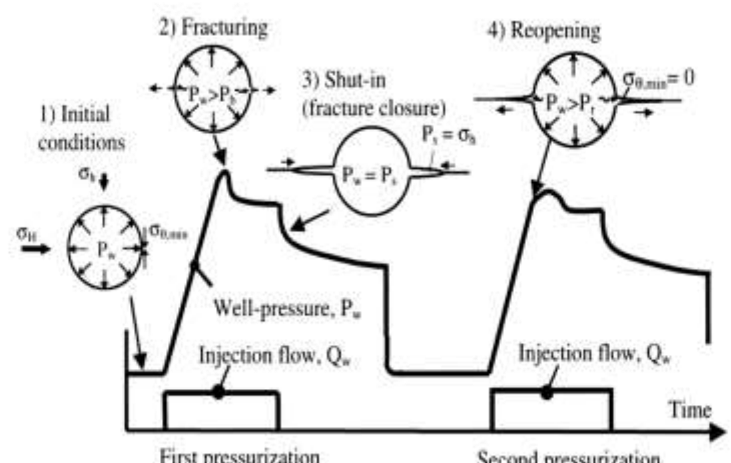


- Overcoring Methods
  - Doorstopper
  - USBM Gauges
  - Triaxial strain cell (CSIRO)

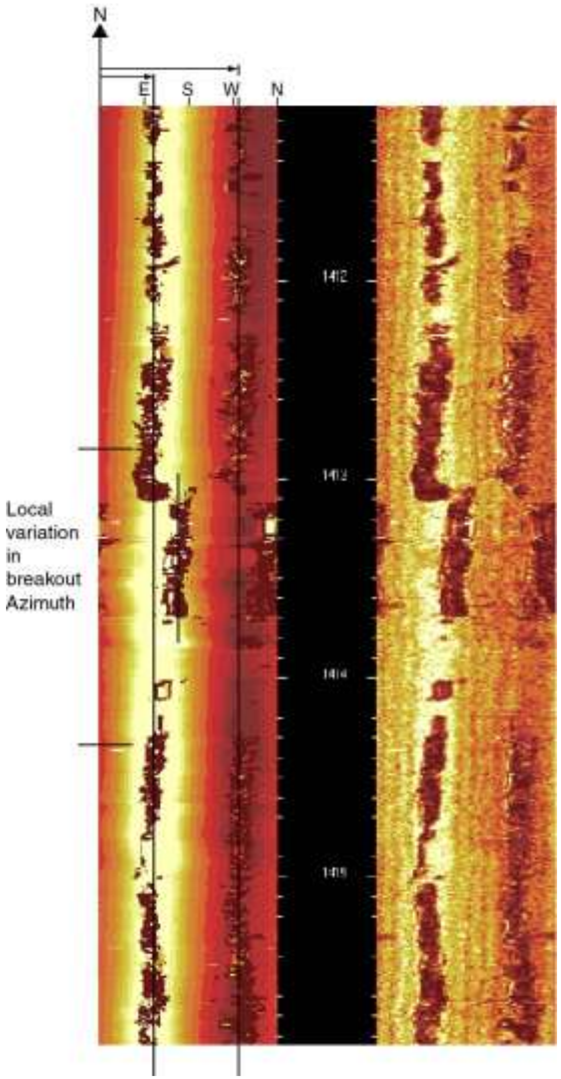
- Hydraulic Methods
  - Hydraulic fracturing
  - Hydraulic testing of pre-existing fractures

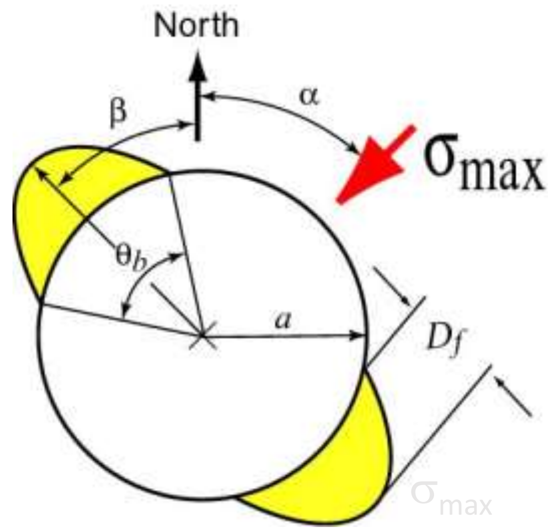
Suitable for use in deep, water-filled boreholes but unreliable when k>>1

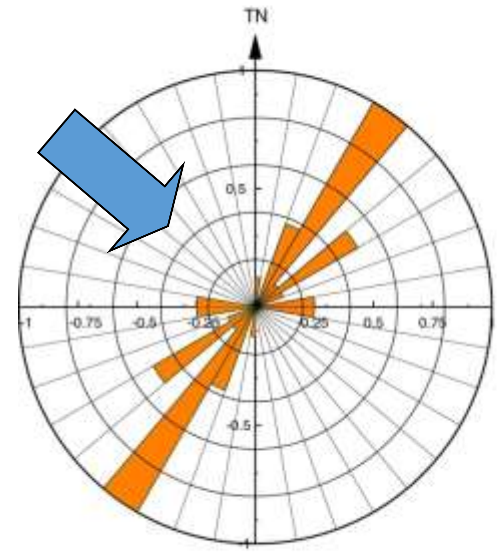


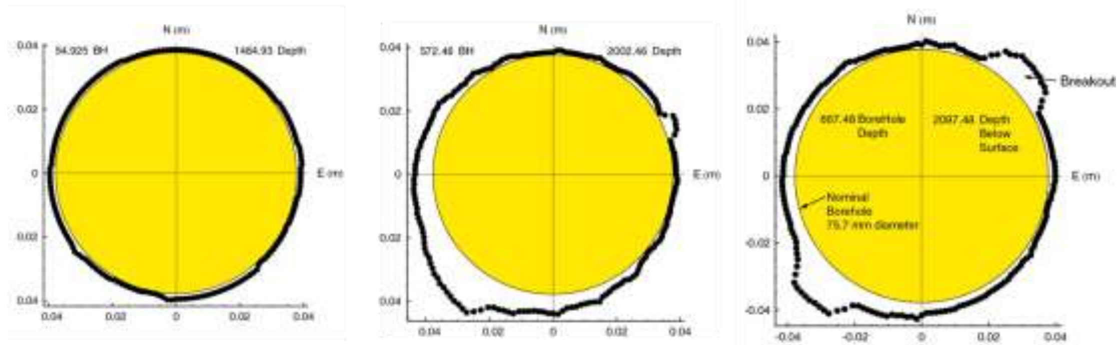


Constrain through Borehole Breakouts and Deformation









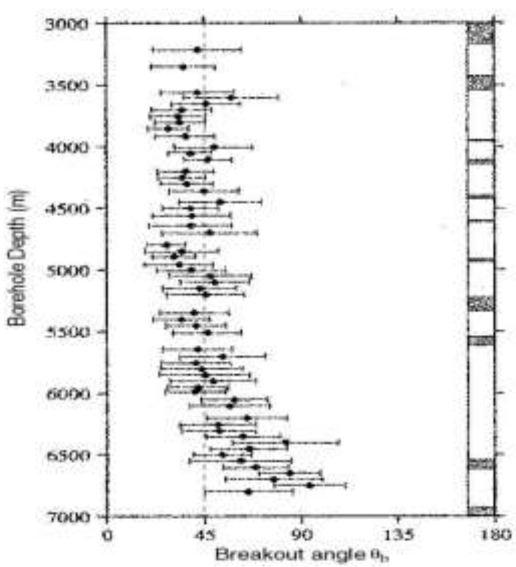
No Breakout *Irregular Breakout* *Classic Breakout*

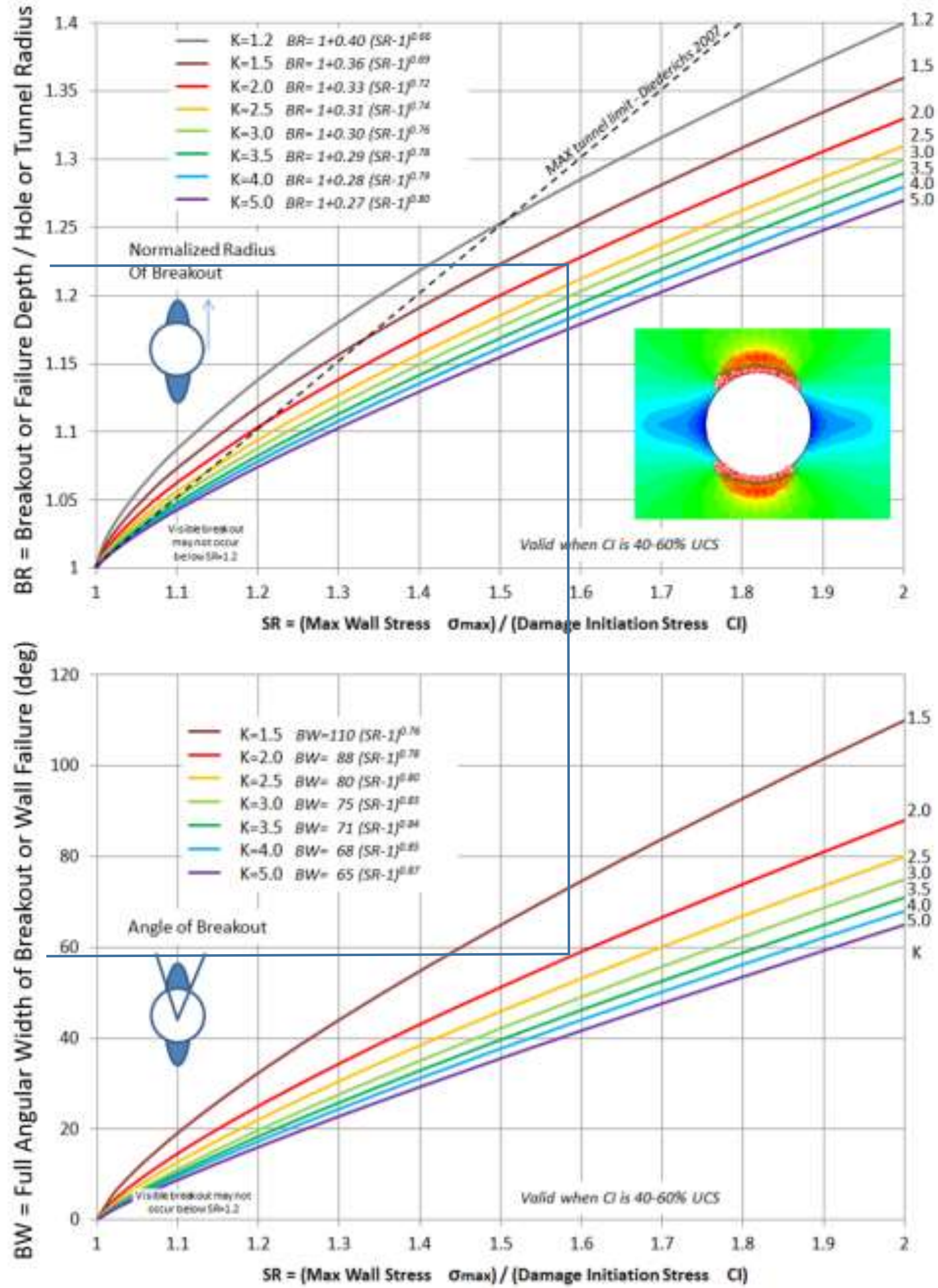
A. Leriche Current Queen's MSc

Possible to estimate Stress Magnitude Ratio andOrientation from borehole breakout observations

G. Walton Queen’s PhD 2014

Need OTV or ATV data



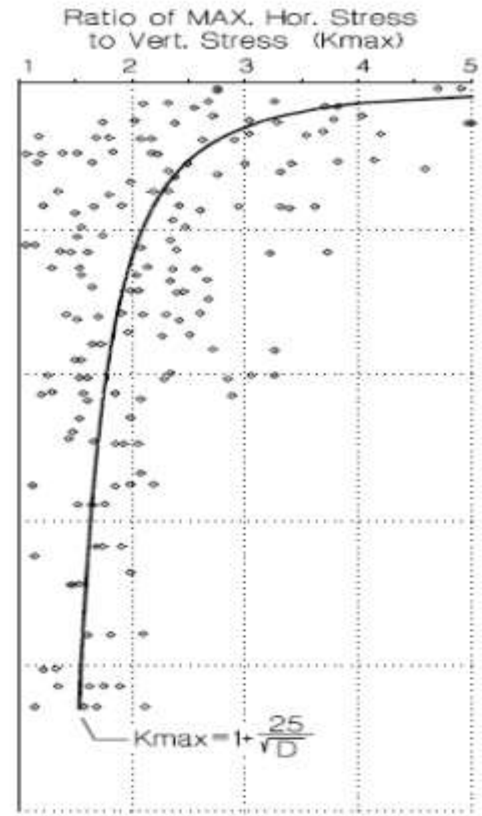


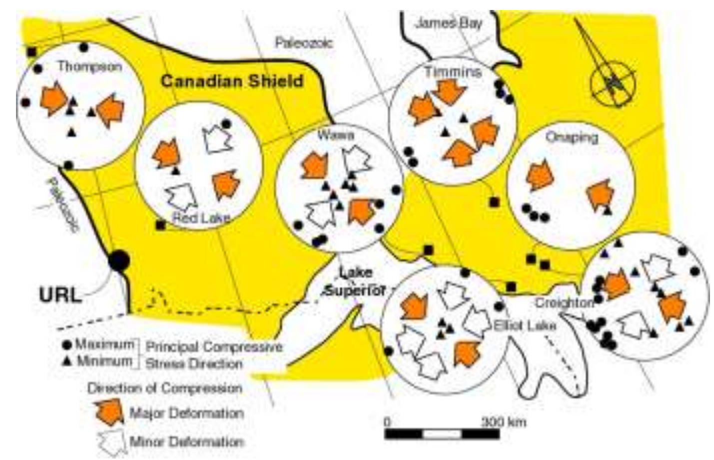
In Situ Stress

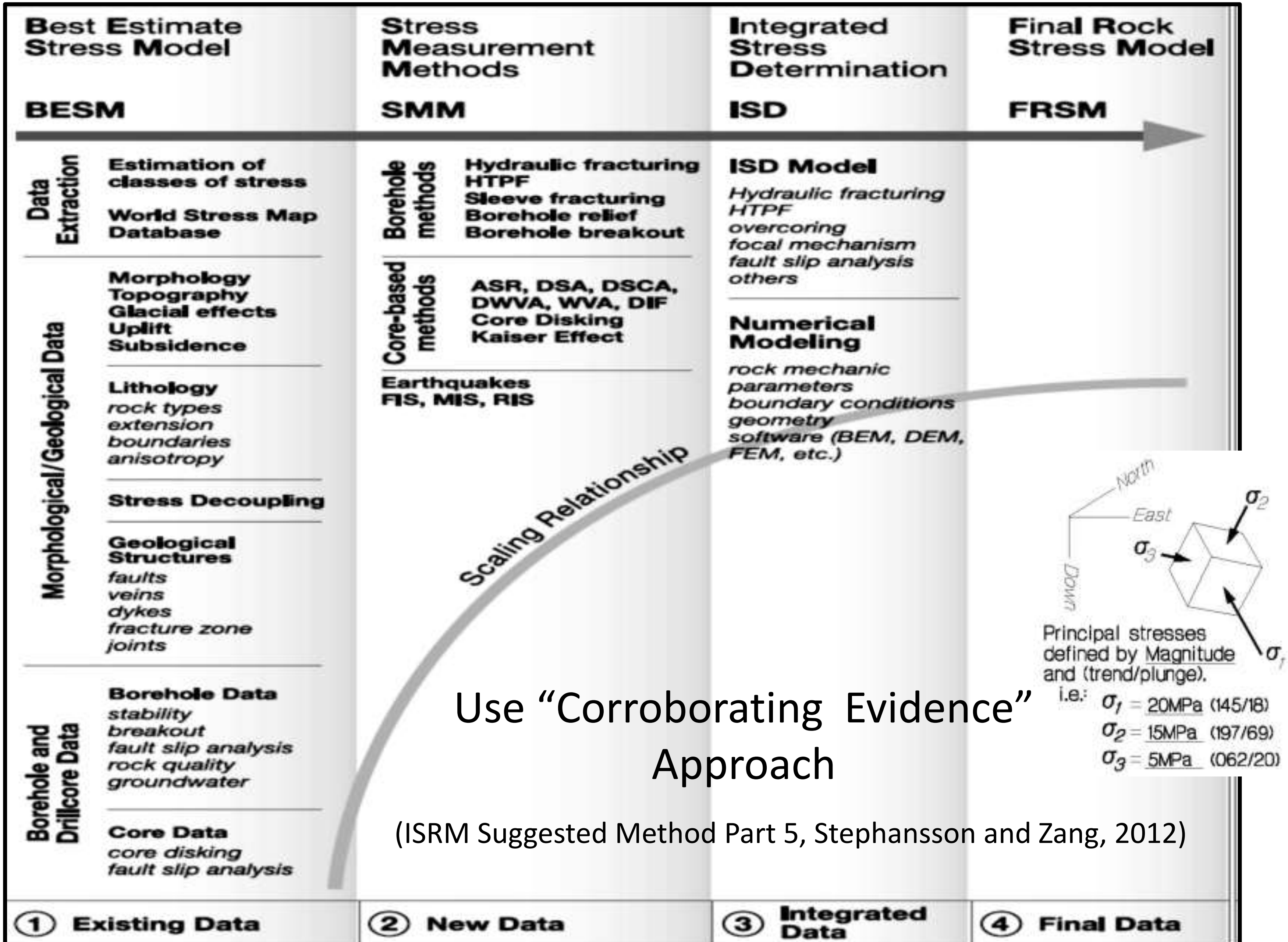
- Good geological considerations are the best tool.
- The horizontal stress ratio is ALMOST NEVER 1:1 for deep rock tunnels in competent rock

  There are a few exceptions

- Don’t ignore stress in a GBR
  - It will ALWAYS end in tears!





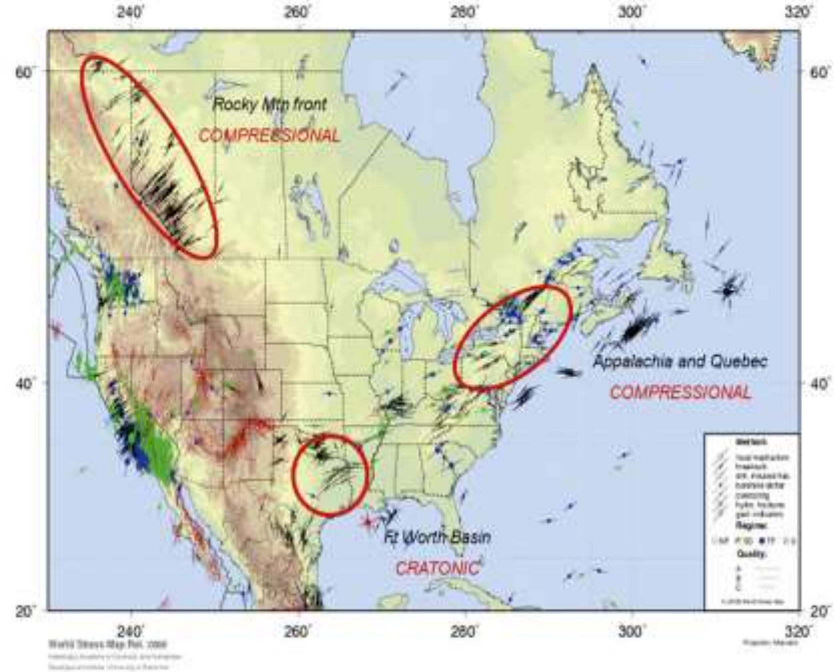


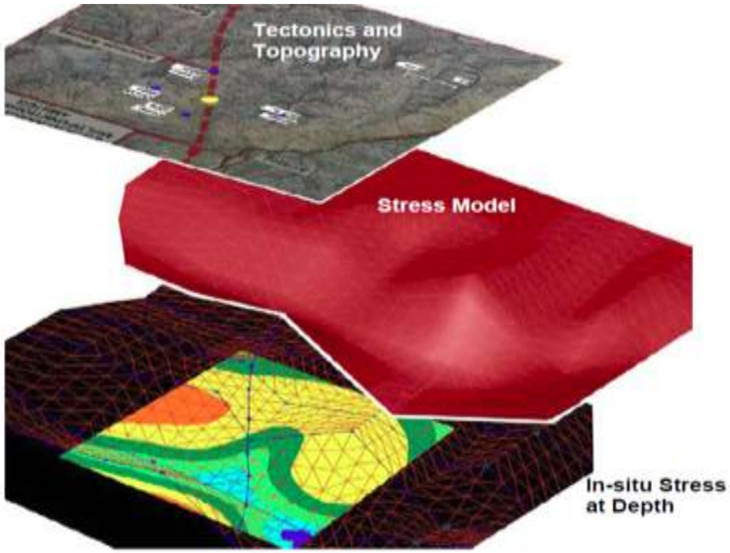
Use "Corroborating Evidence" Approach

(ISRM Suggested Method Part 5, Stephansson and Zang, 2012)

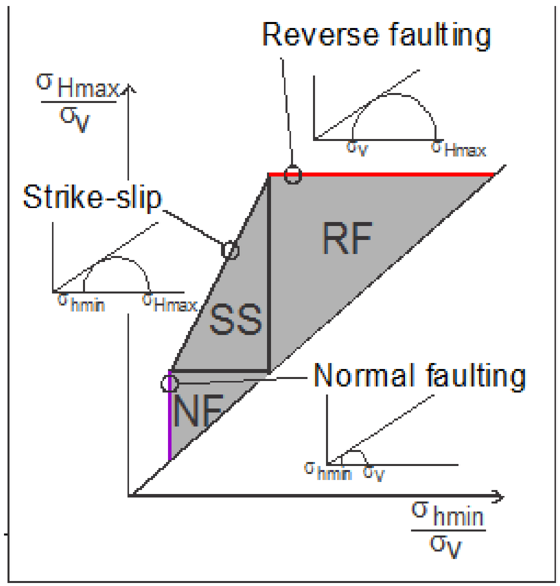
In Situ Stress

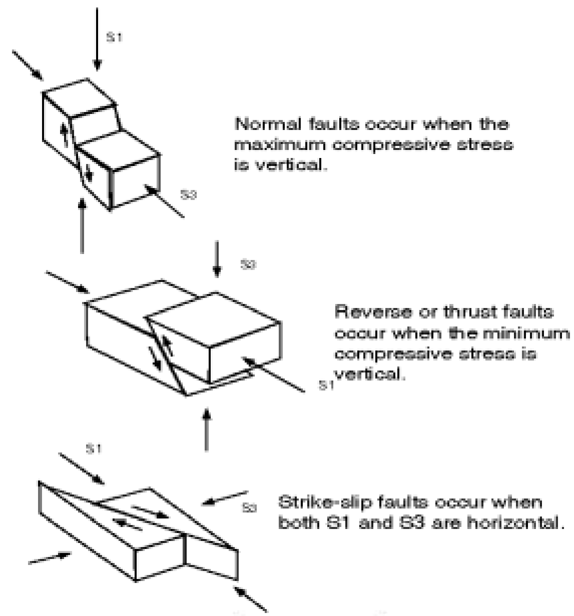
- Prediction based on regional data, tectonic interpretation
- Modelling can be used to combine tectonics with topography
- Local tests from within tunnel should be specified as soon as target ground is encountered

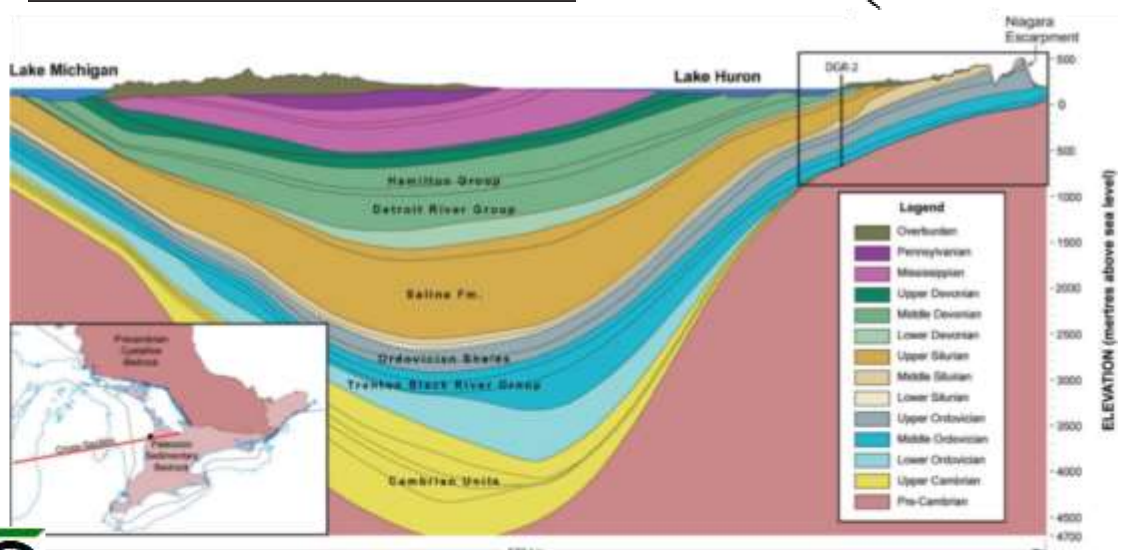


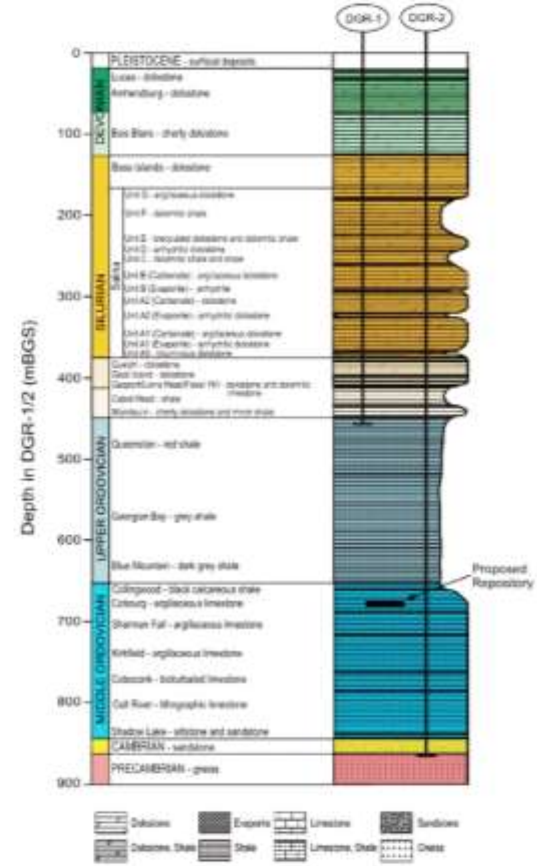


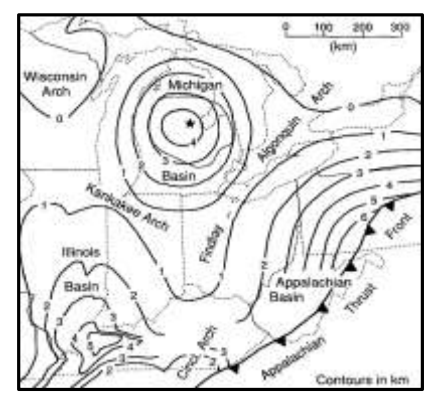
Consider geological setting



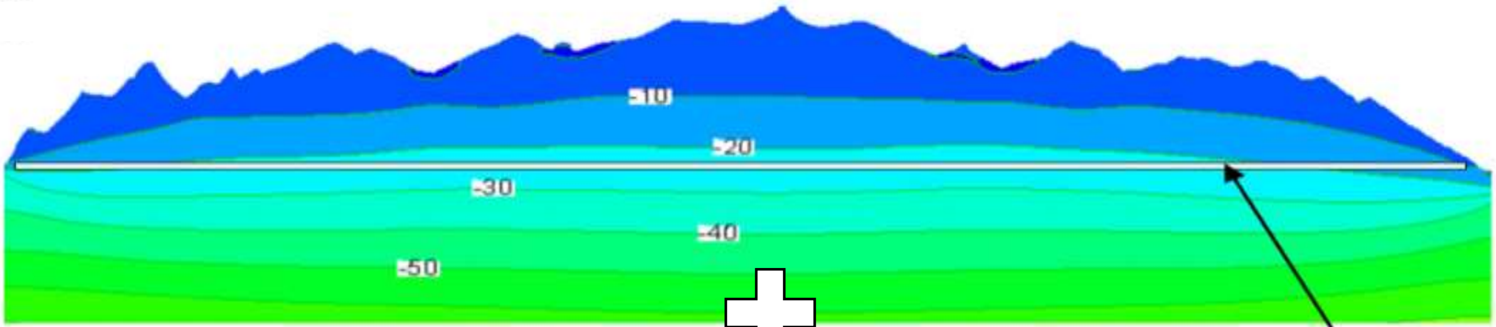




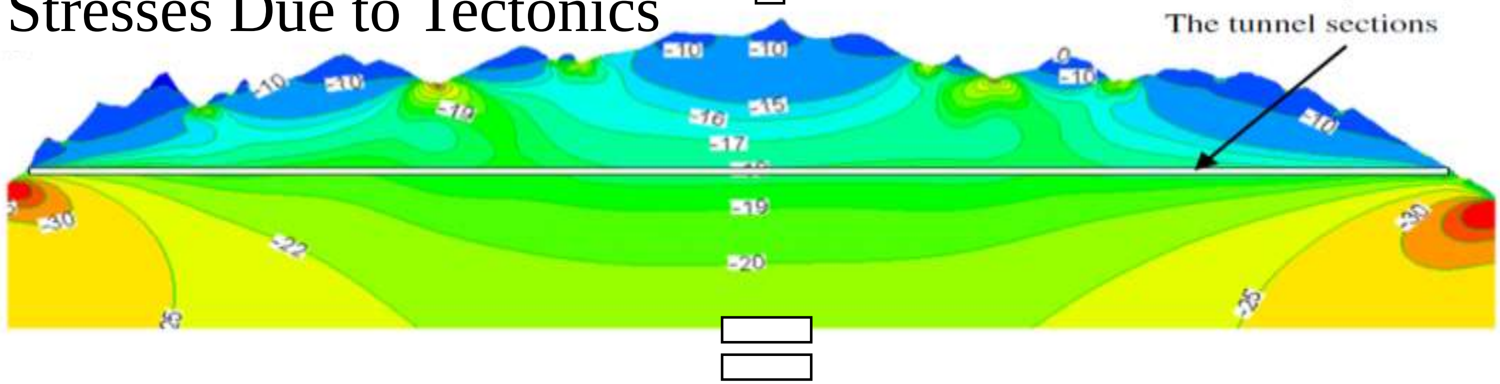


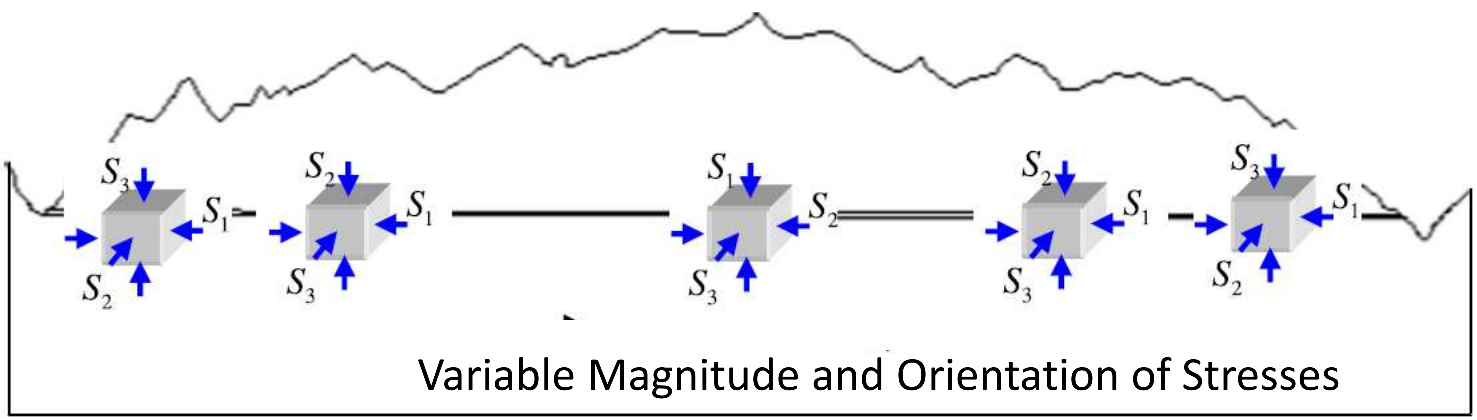


Horizontal Stresses Due to Gravity and Topography



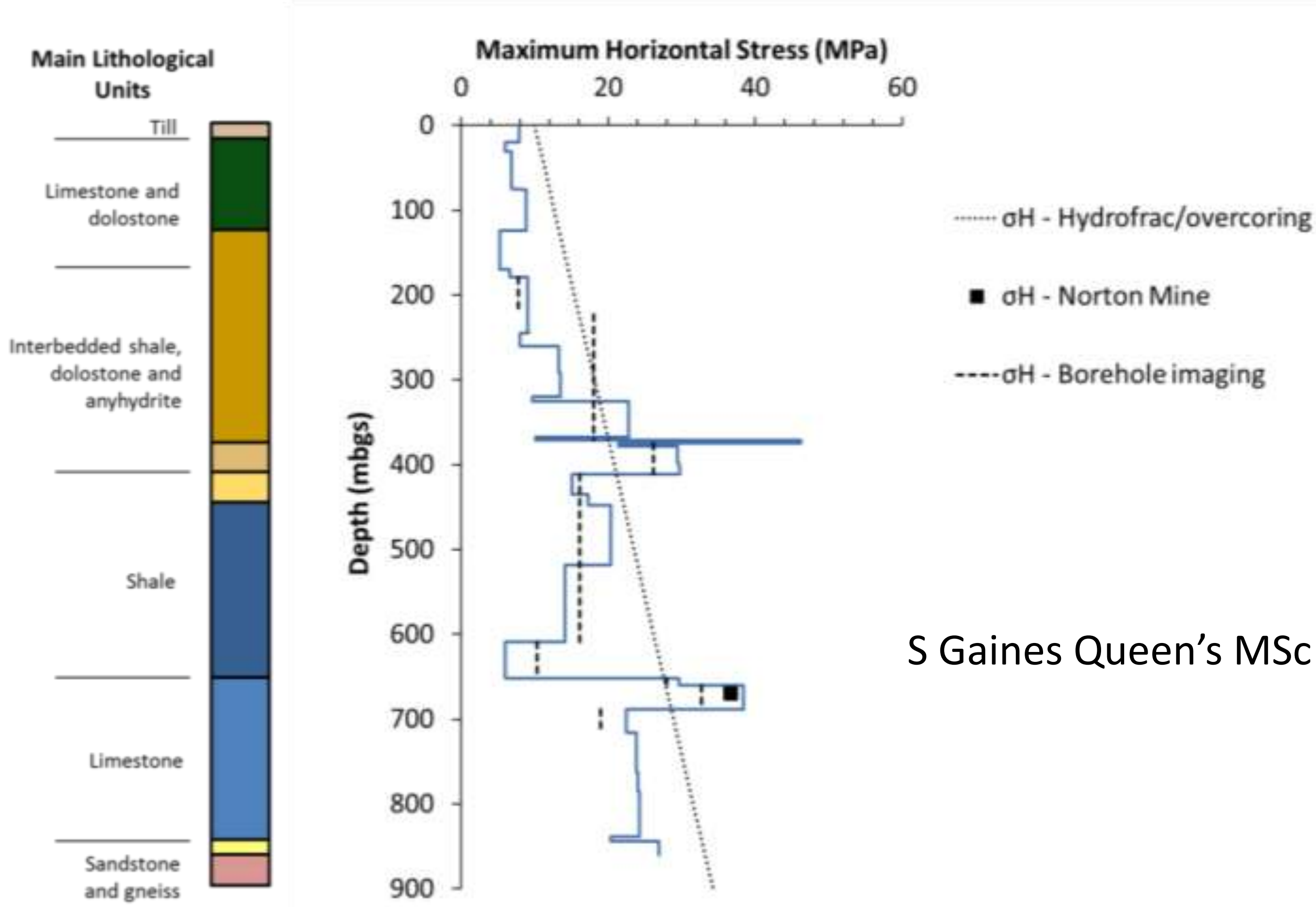
Stresses Due to Tectonics





Variable Magnitude and Orientation of Stresses

Calibrate Model to Known Point Data and Regional Data



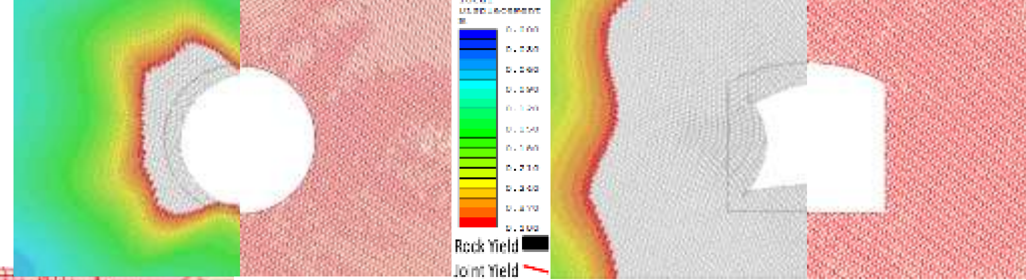
S Gaines Queen's MSc 2013

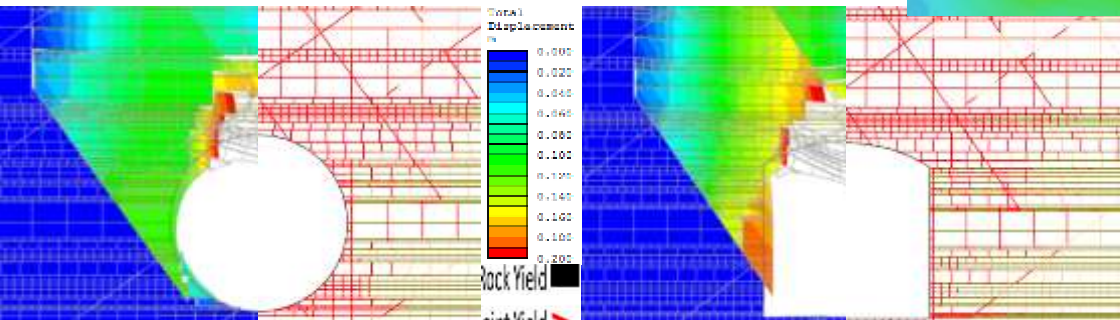
Rock Stability Prediction

- Need to consider possible failure modes not just propoerties
- Indicate in GBR/GRR
- Given site conditions, likelihood of different failure modes can be determined from basic case modelling

Case 1: Squeezing

Failure Modes

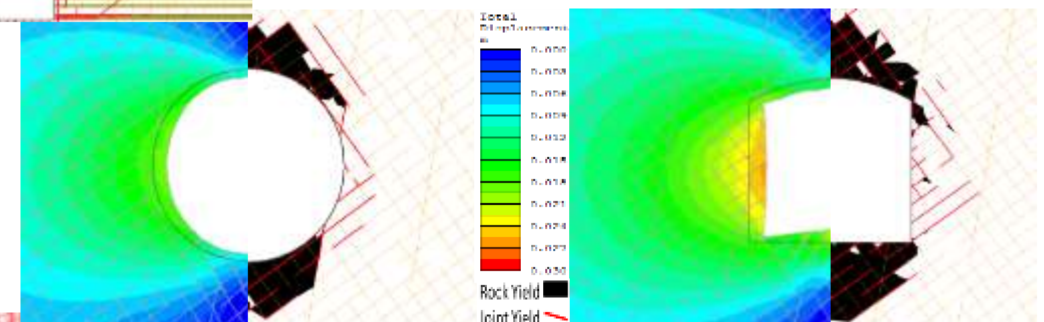


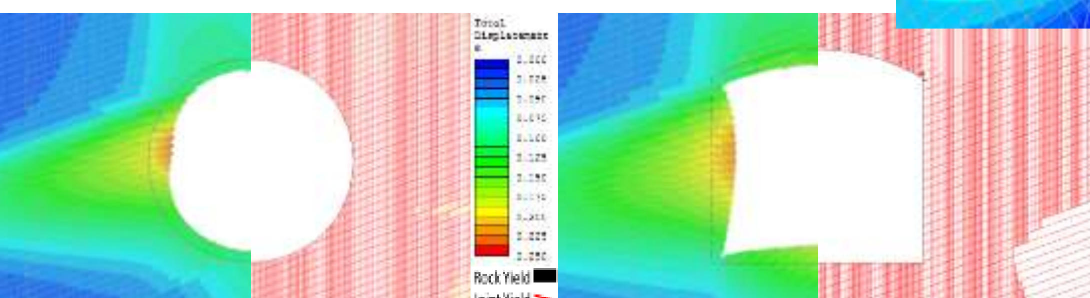


Case 2: Stratified Structure

SAME Q !

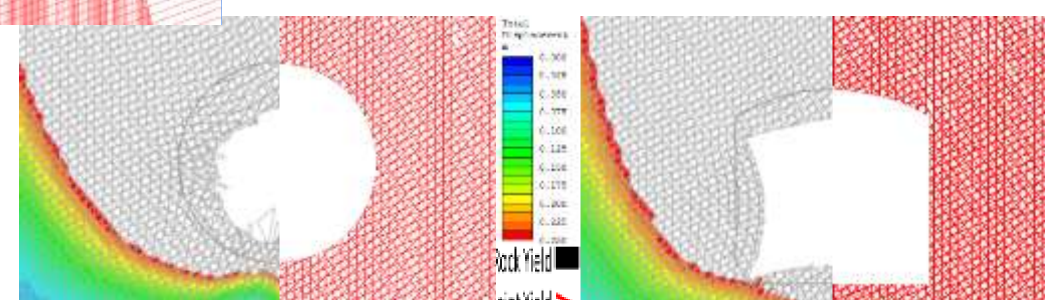
Case 3: Spalling





Case 4: Metamorphic Structure

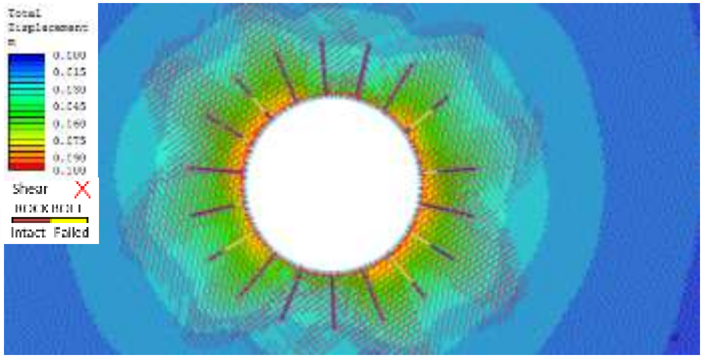
Case 5: Raveling



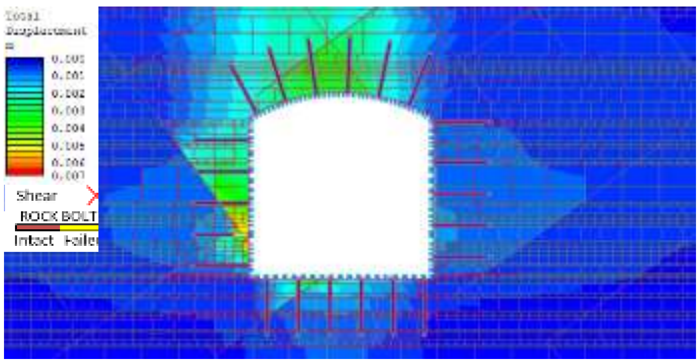
M. VdP Kraan   Queen's MSc 2014

Supported Results

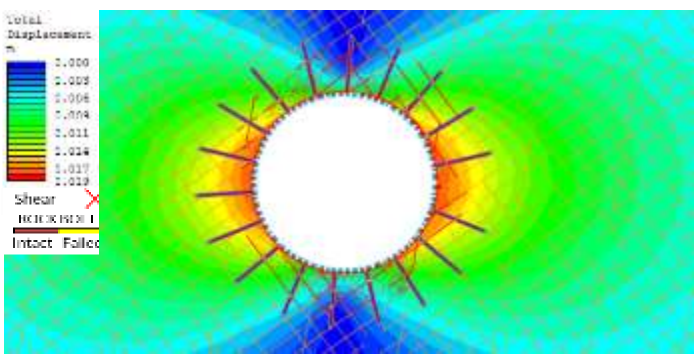
Case 1
Squeezing



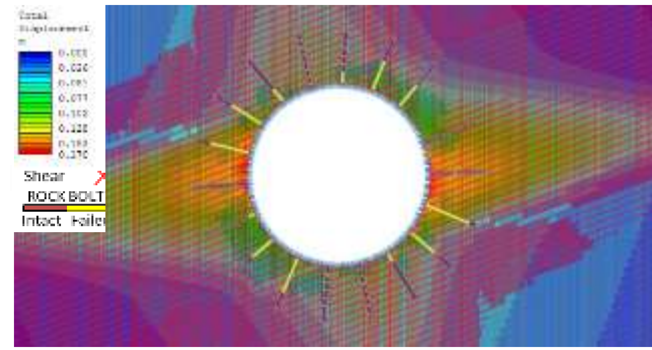
Case 2
Sedimentary
Structure



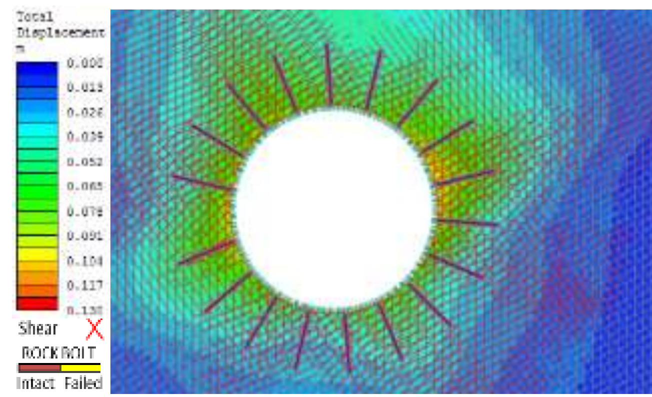
Case 3
Spalling



Case 4
Metamorphic
Structure



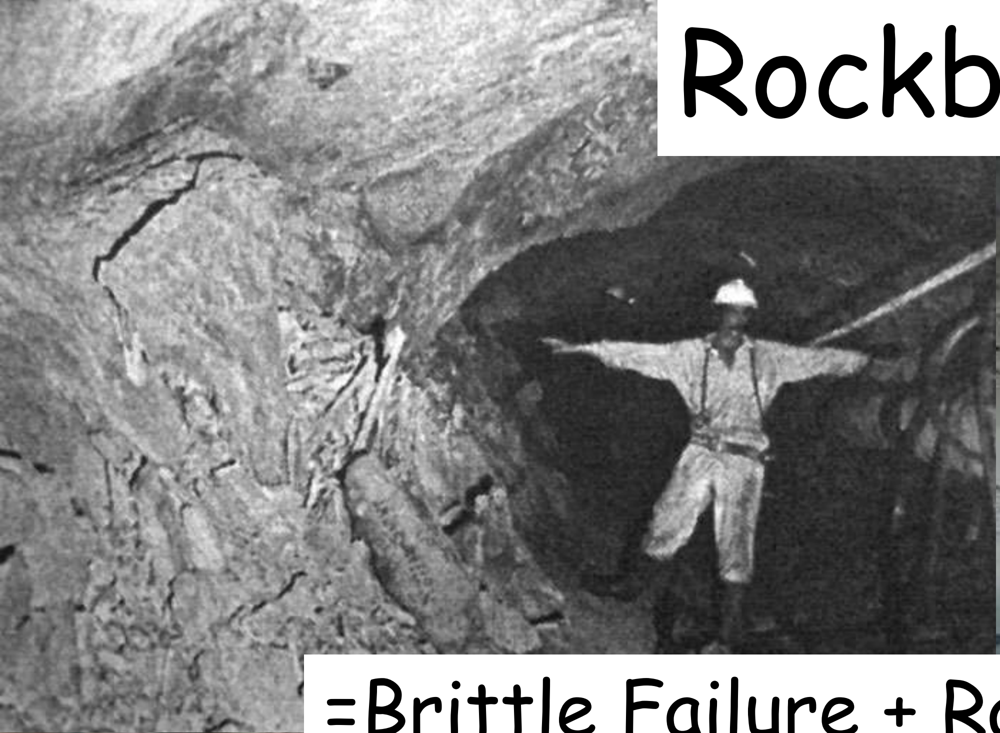
Case 5
Raveling



SAME Q !

MAJOR CHALLENGES IN DEEP TUNNELS

Rockbursts



=Brittle Failure + Rapid Energy Release

A Major Rockburst 8m/s

Main Issue with Deep Tunnelling

- Highly unlikely that standard risk sharing or risk shedding models will be effective in managing geological variability and risk.

- In modern tunnelling and with zero risk culture:

ROCKBURSTS ARE A PROJECT KILLER

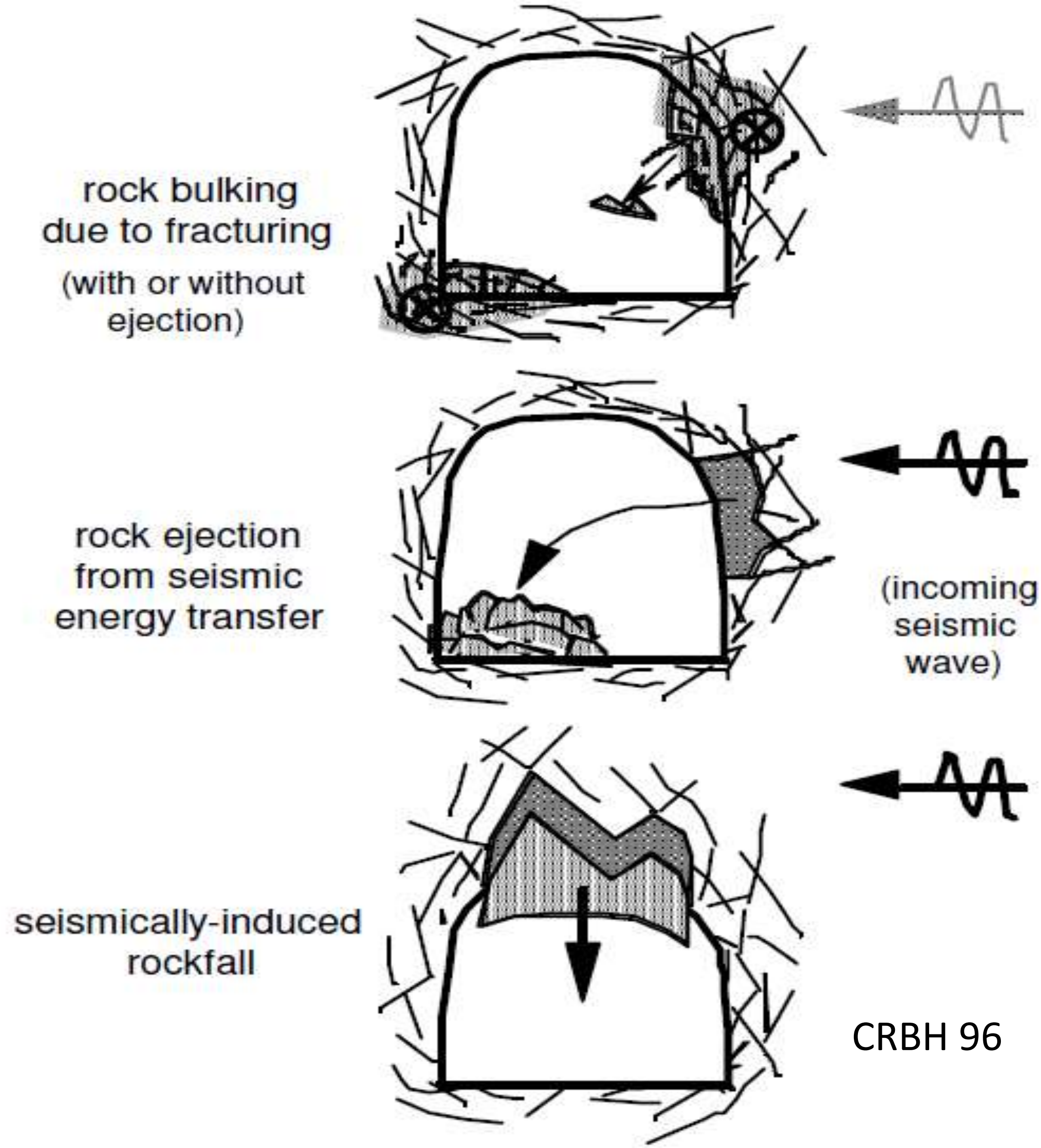
Owners and Contractors Beware:

There is no way to pass the buck on this one!

This is everyone's problem.

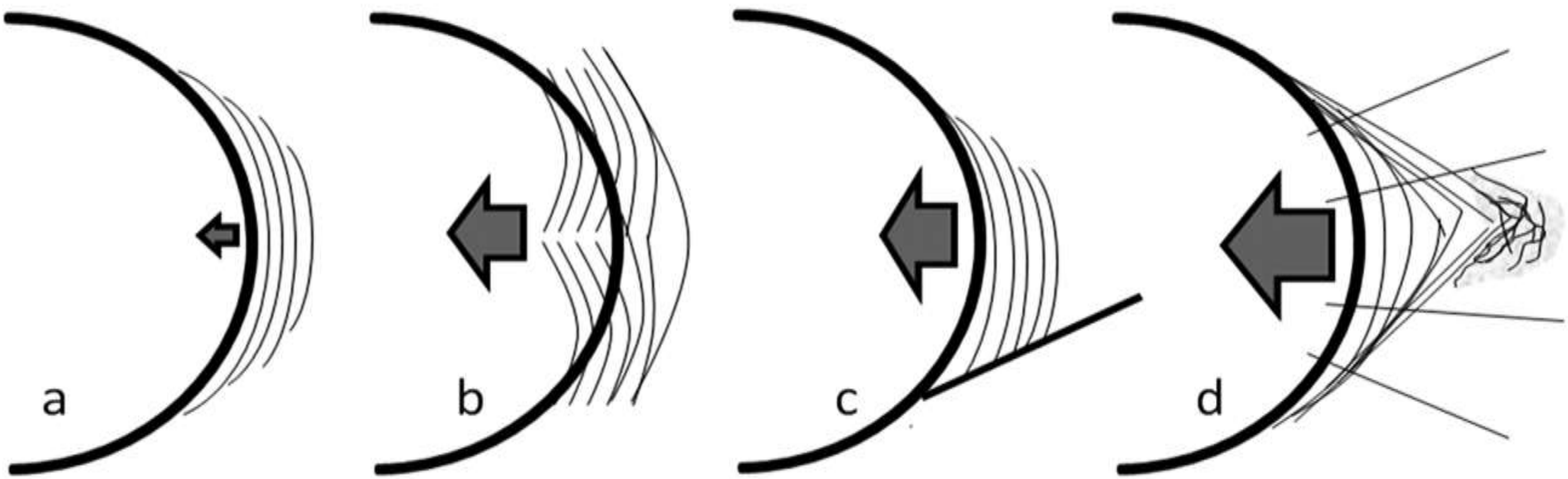
Rockburst damage due to a remotely triggered event

Most common in Mining



CRBH 96

Auto-seismic Event (Strainburst) Most common in Tunnelling



What is a Rockburst?

An explosive failure of rock which occur when very high stress concentrations are induced around underground openings
(Hoek 2006)

A sudden and often violent breaking of a mass of rock from the walls of a tunnel…caused by failure of highly stressed rock and the rapid or instantaneous release of accumulated strain energy.
(US Bureau of Mines)

Damage to an excavation that occurs in a sudden or violent manner and is associated with a seismic event
(Canadian Rockburst Handbook, 1996)

Loss of continuity of the production process of the mining operation, caused by the rupture and instant projection of the rock mass, associated with a seismic event."
(Codelco (2008)

Mild Bursting Behind Shield

Floor Heave (Bursting after Shield)

Local Bursting

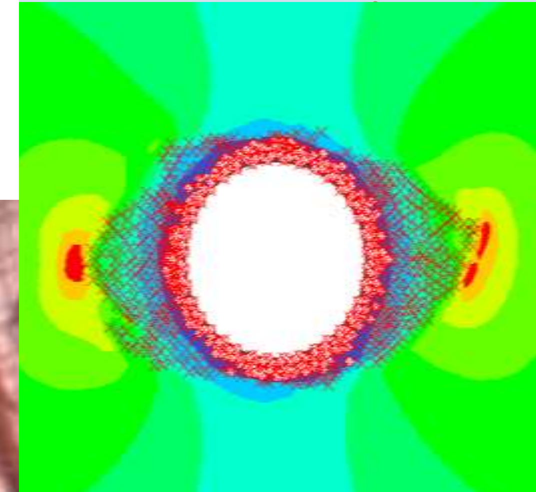
Strong Bursting

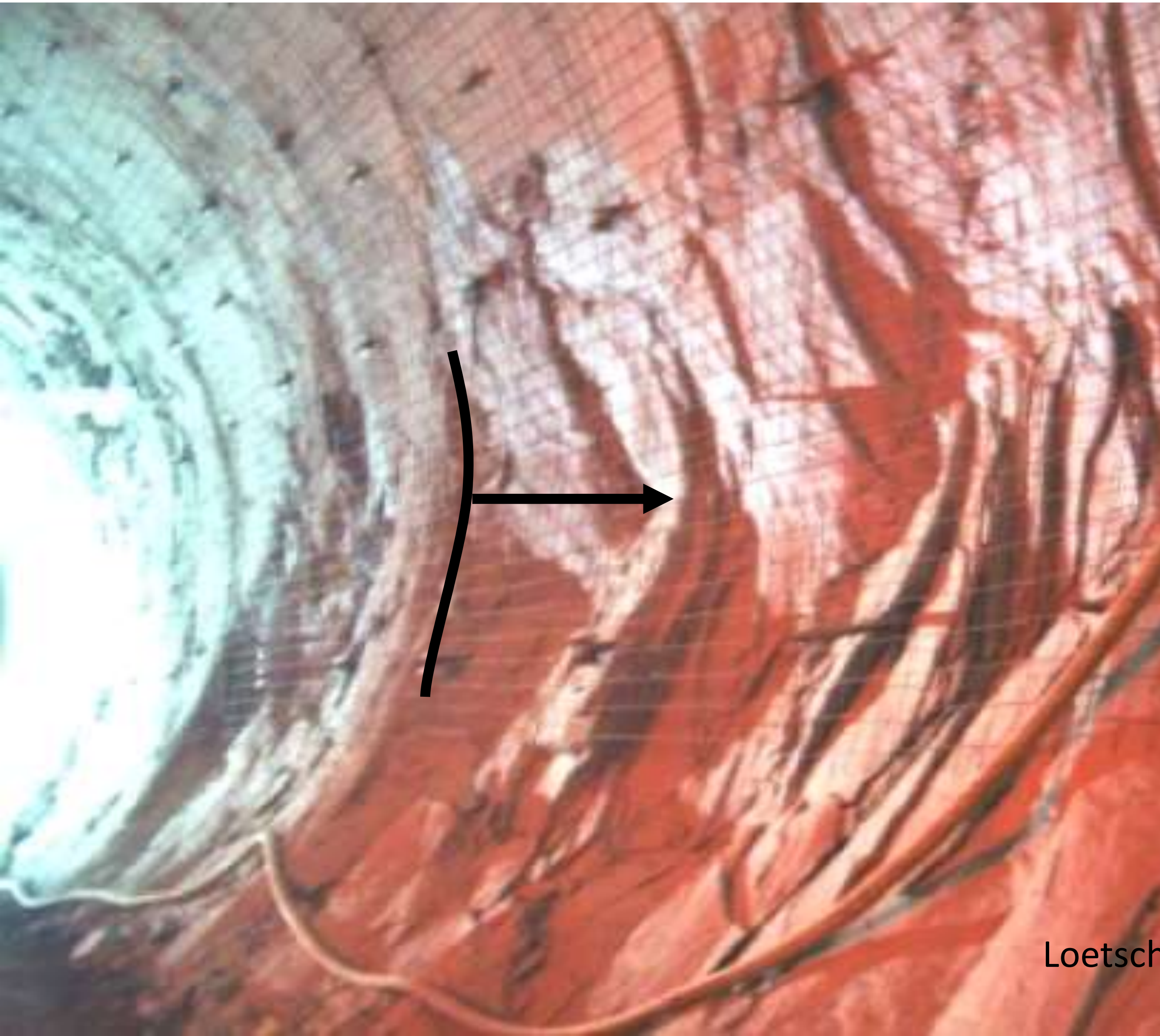
Bursting at the Face

Rockburst Components

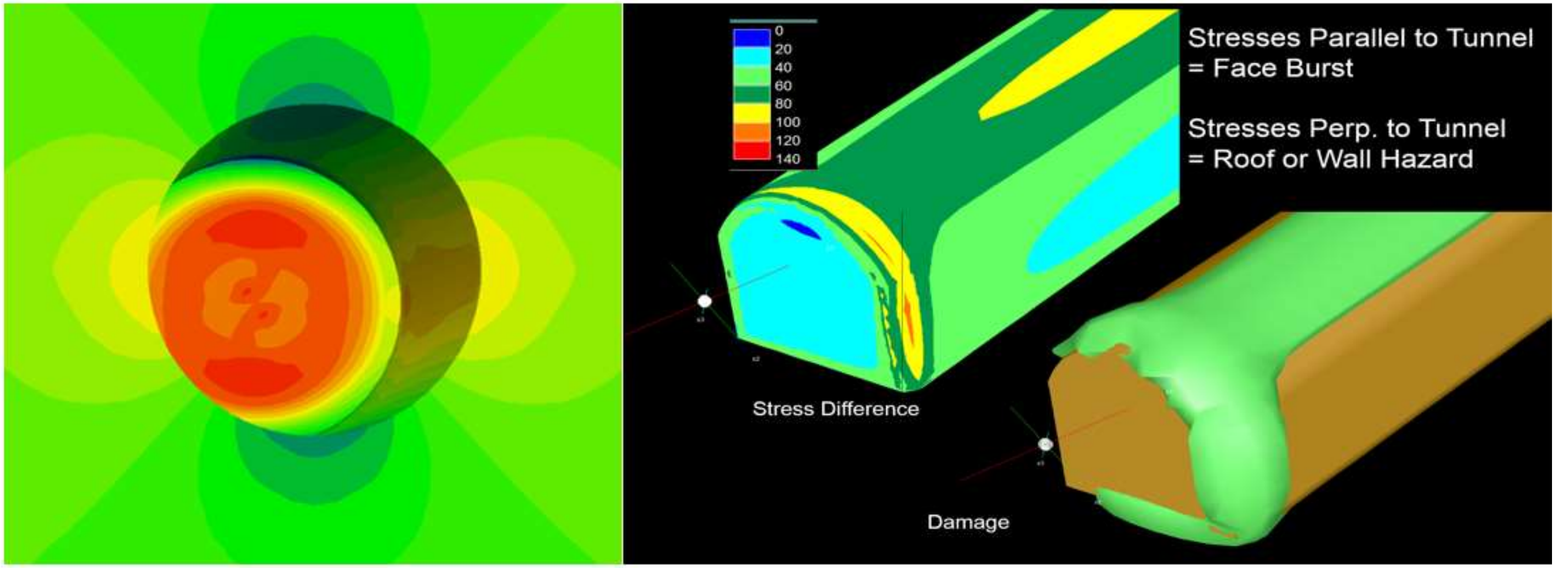
- Stress Concentration (geometry, geology)
- Brittle Failure (brittle rockmass)
- Energy Capacity (high strength capacity)
- Energy Storage (stress path, geometry)
- Rapid Release (stiff rock or soft surroundings)
- Failure Volume (Instantaneous Yield via Geometry or Structure)

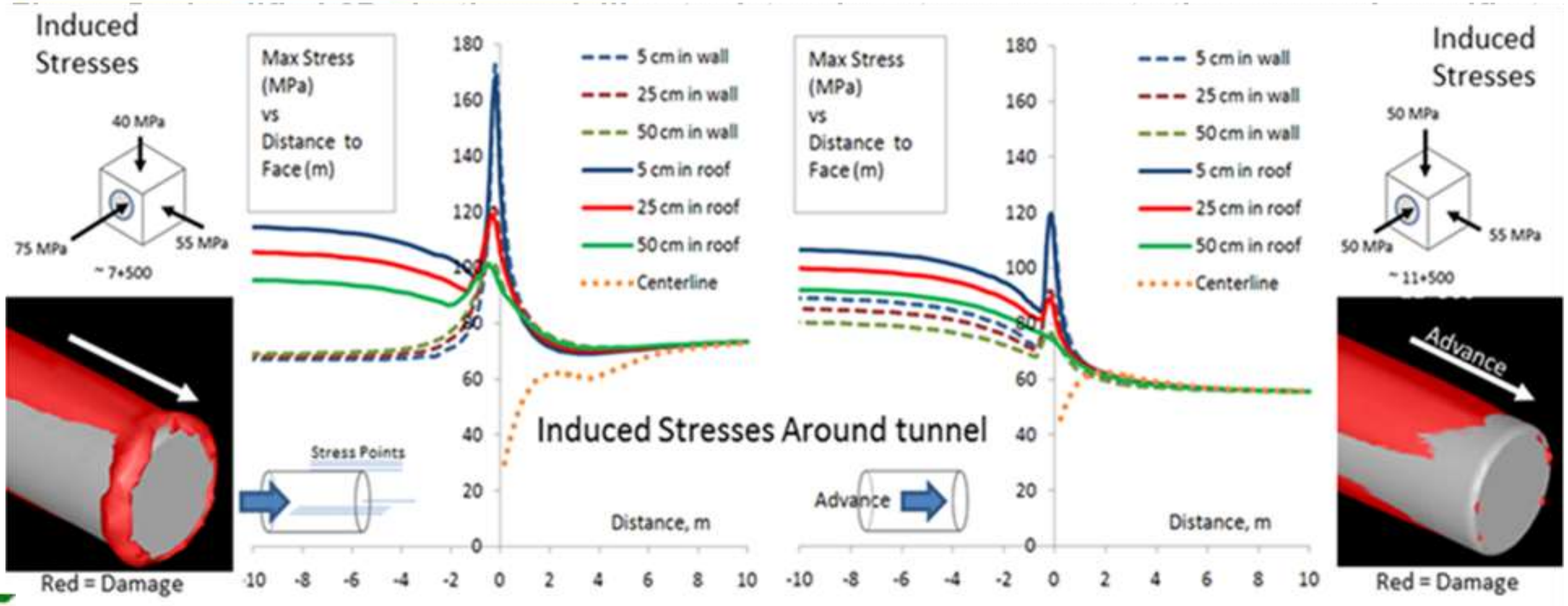
Spalling can lead to Bursting



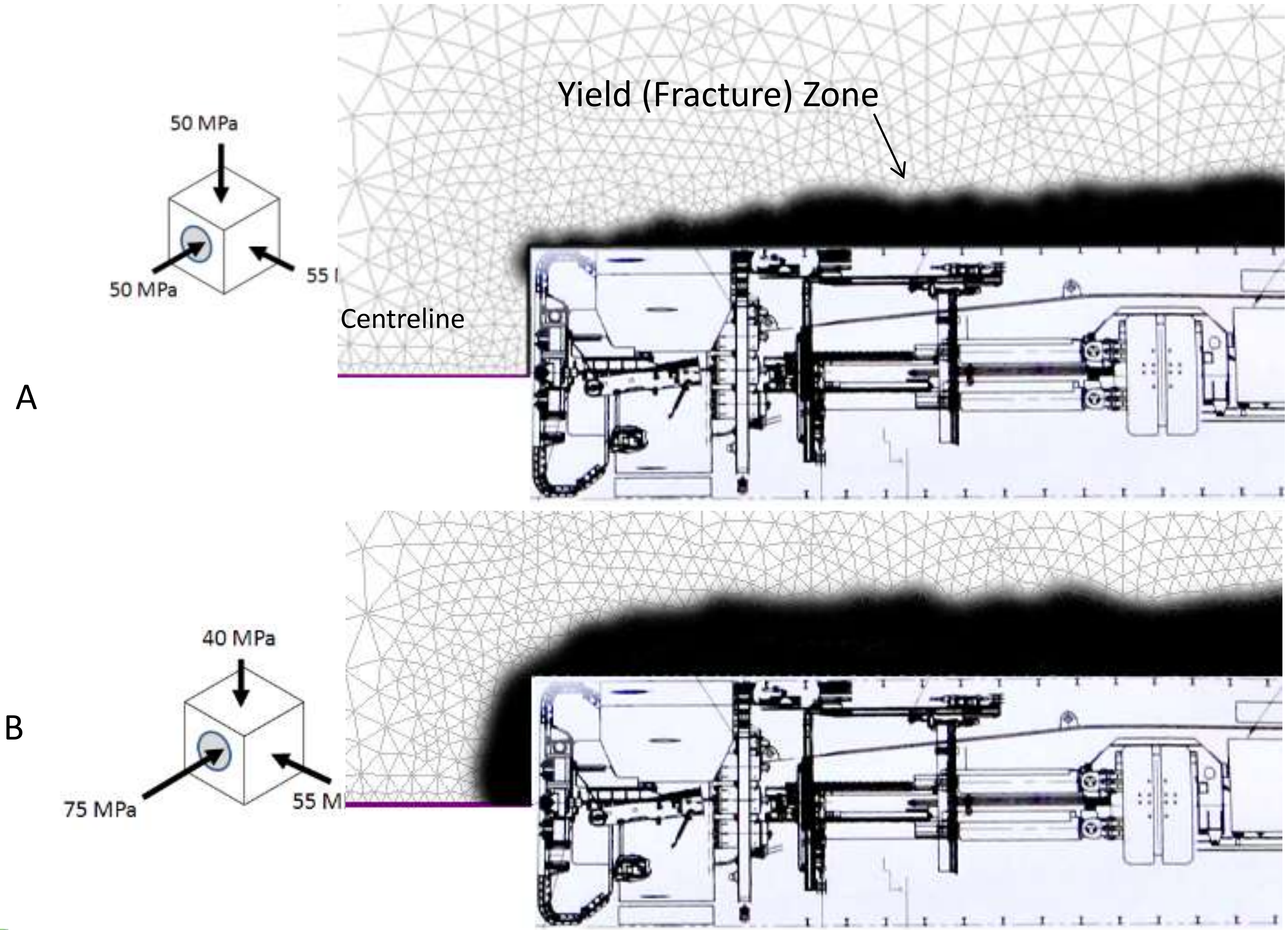


Simple Models to Predict Overstress (Burst) Hazard

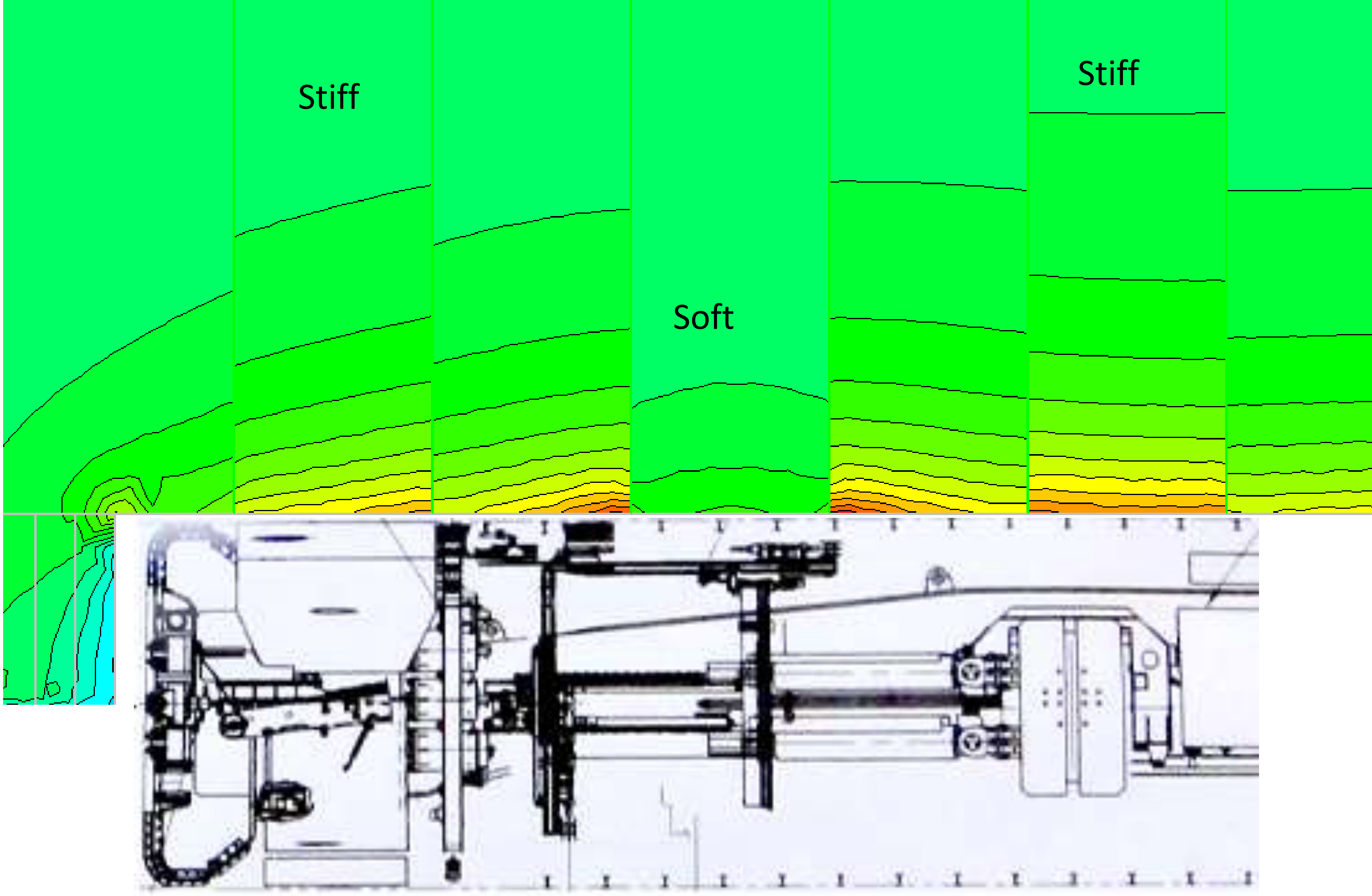




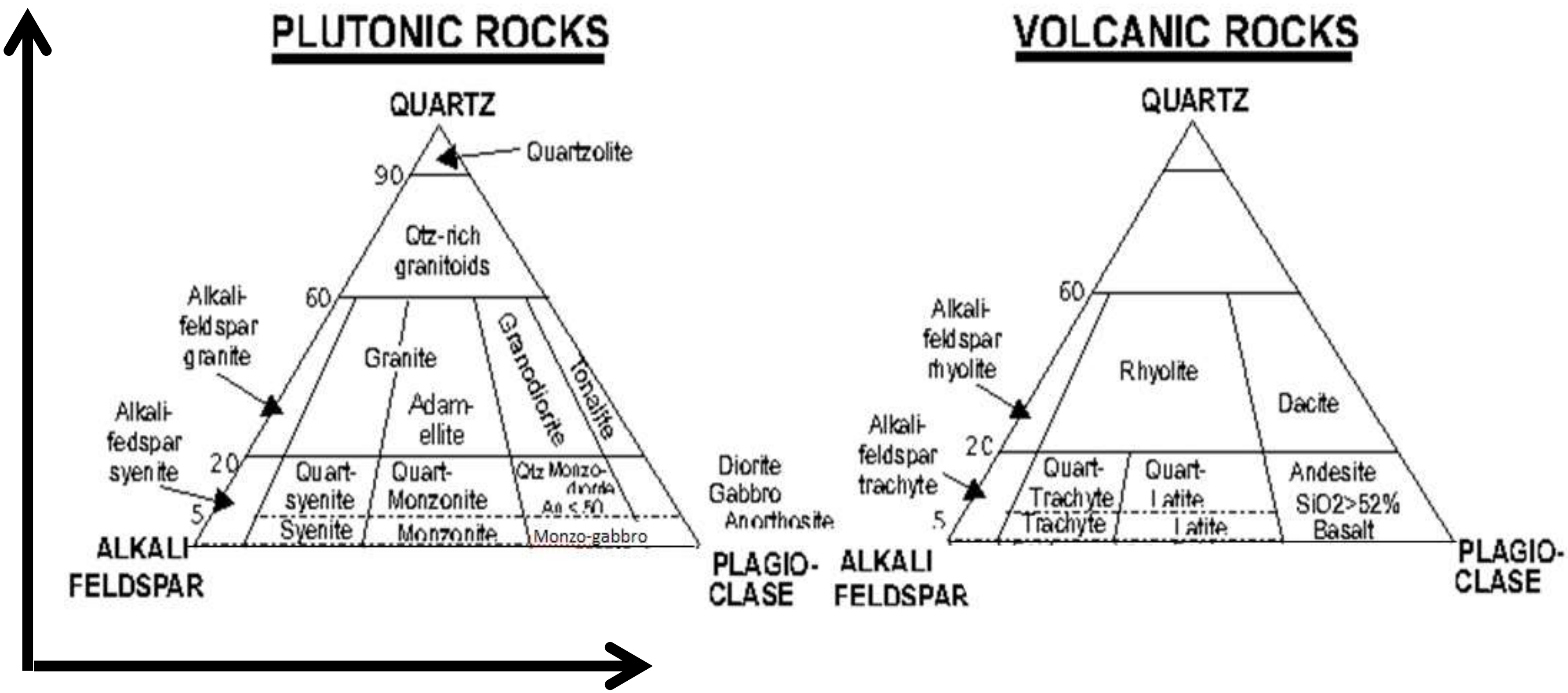
Simple Modelling can Demonstrate the Nature of the Hazard



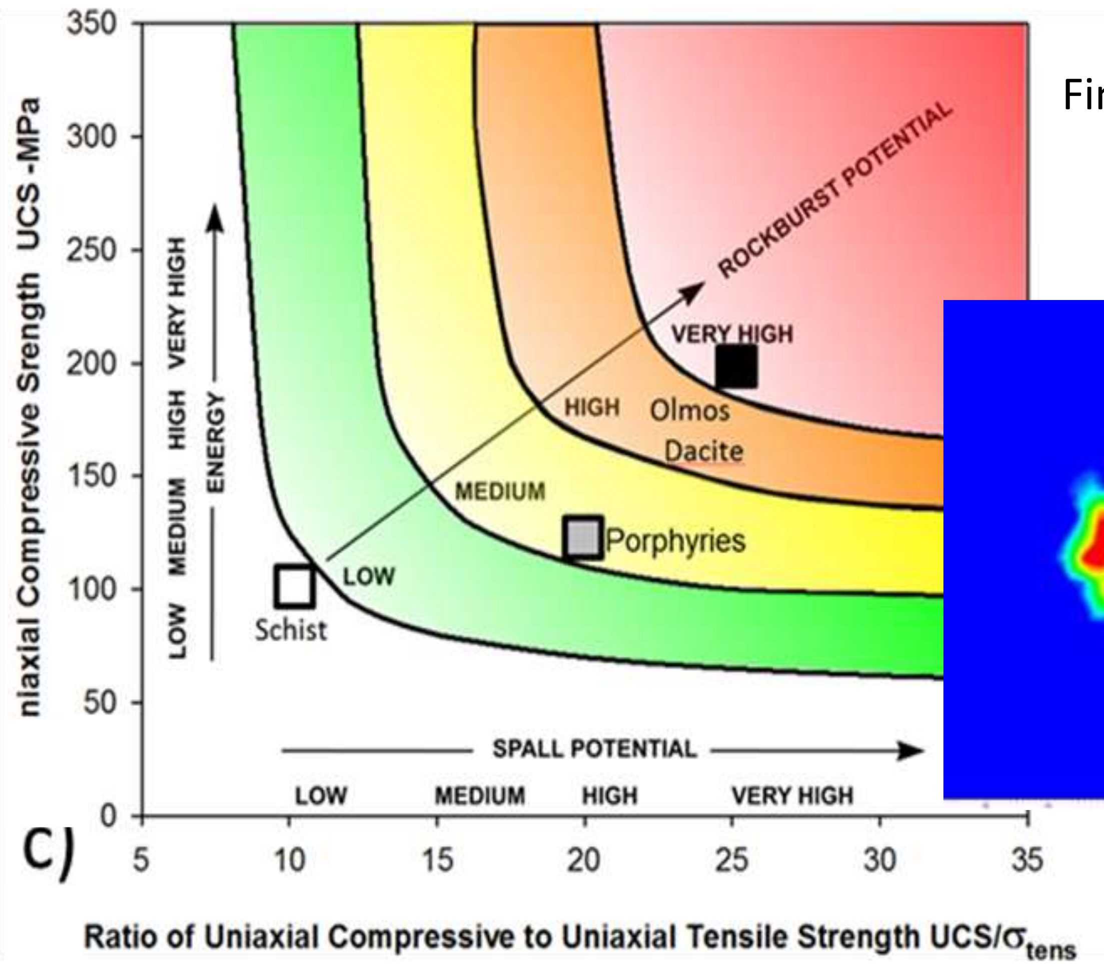
Simple Modelling with Geological Section Detail Shows Stiffness Contrasts That Can Increase Stress Concentrations

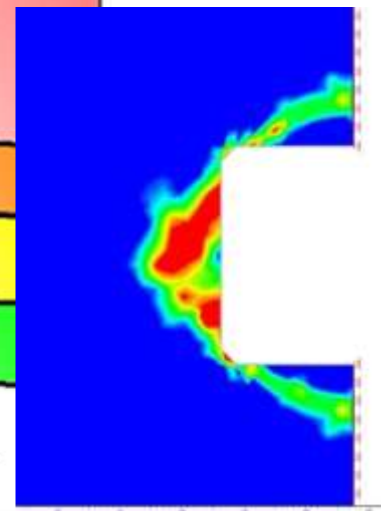


Brittleness and Burst Potential - Think Geology: Rock types prone to brittle failure

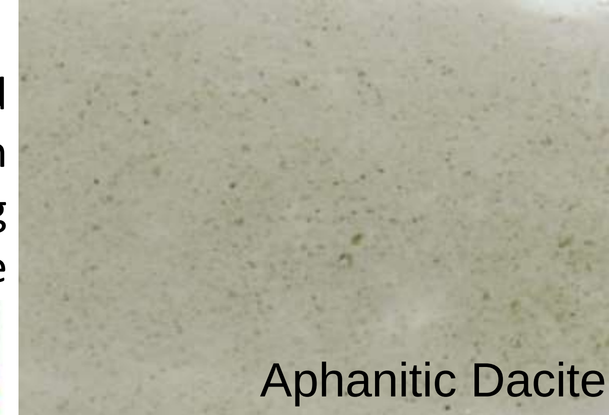


More Brittle





Fine grained
Uniform
Strong
Brittle



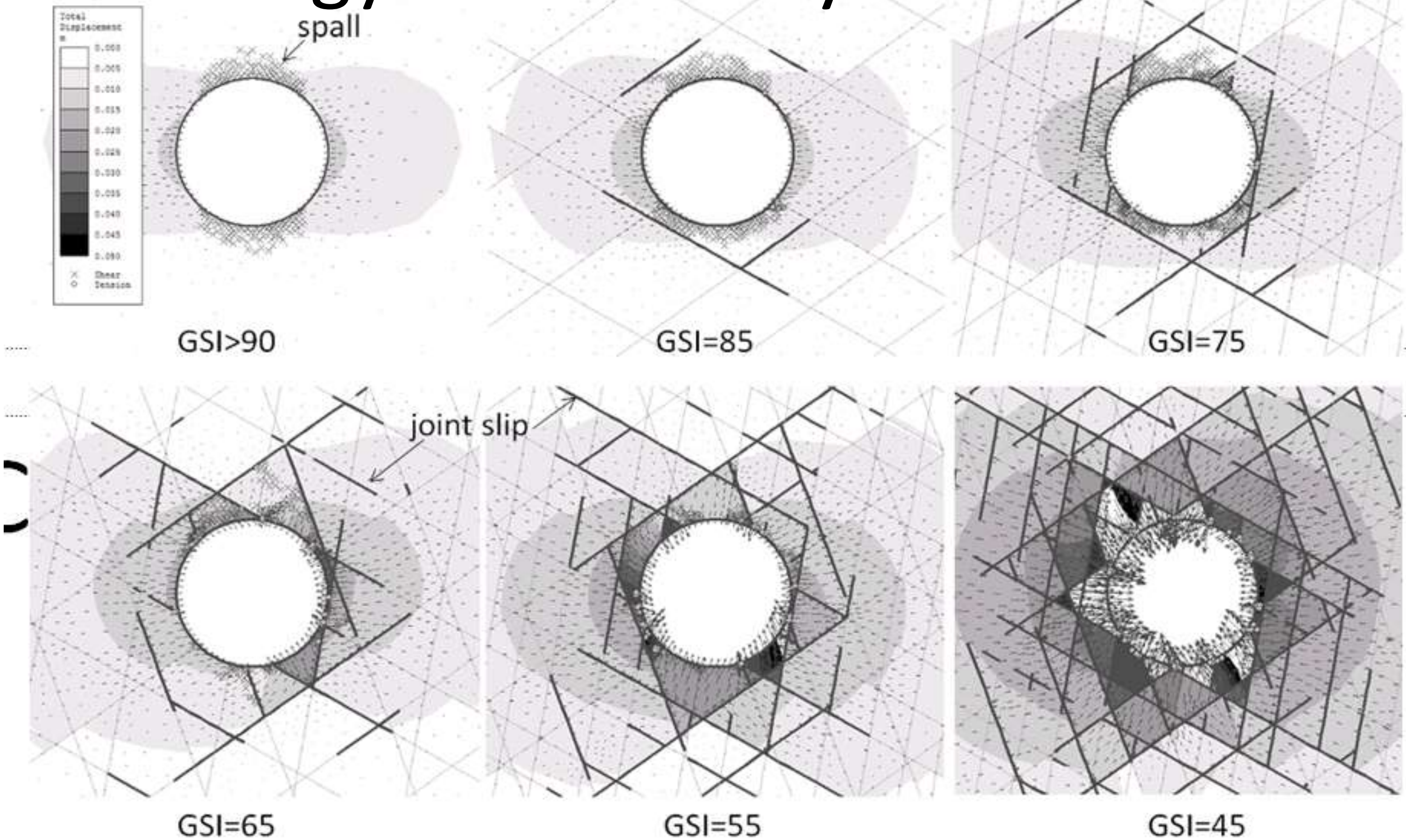
Aphanitic Dacite

Andesite
Porphyry/Breccia

Course grained
Heterogenous
Less Strong
Less Brittle

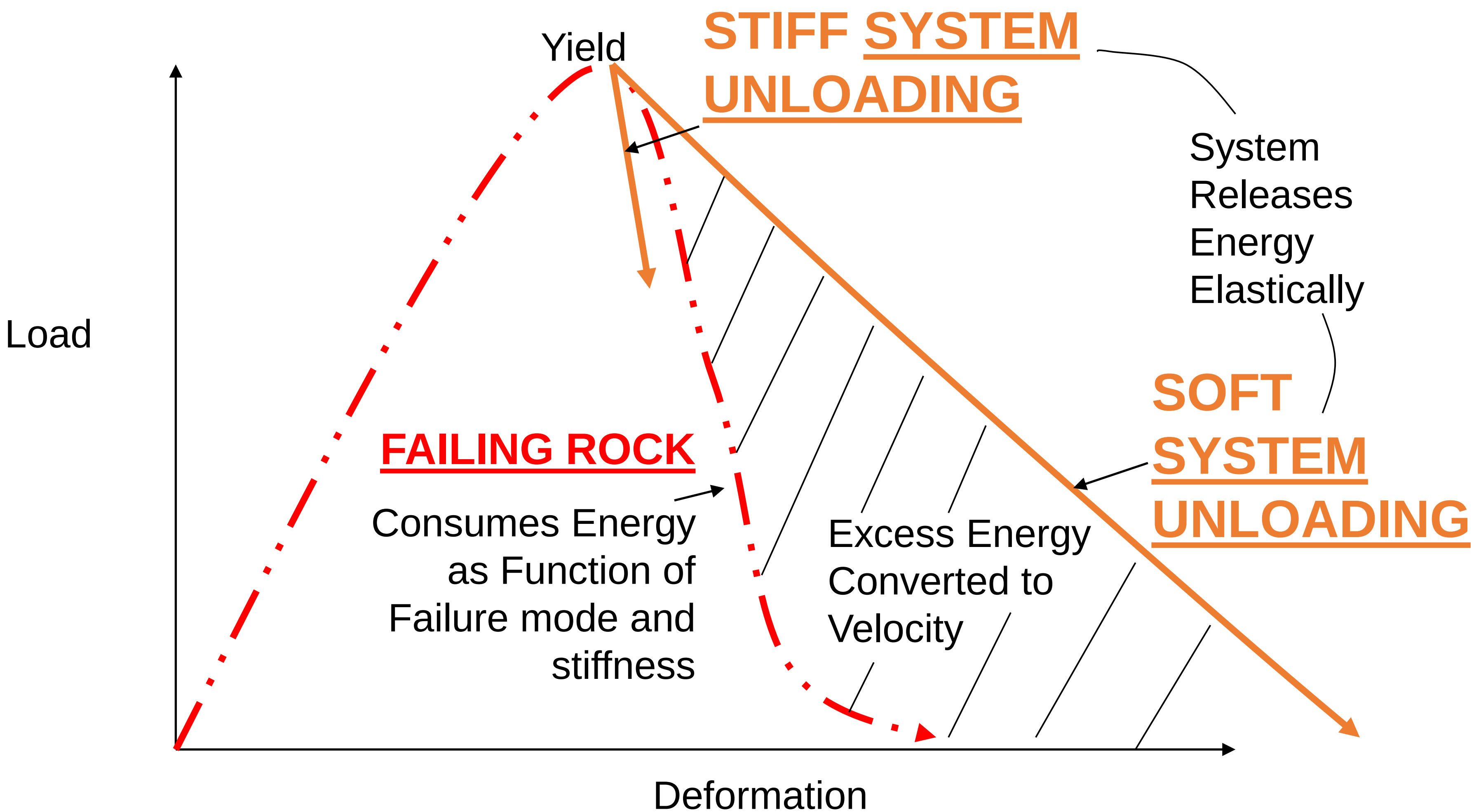
Think Geology
Energy Storage and Release

Think Geology: Moderately Jointed Rockmass

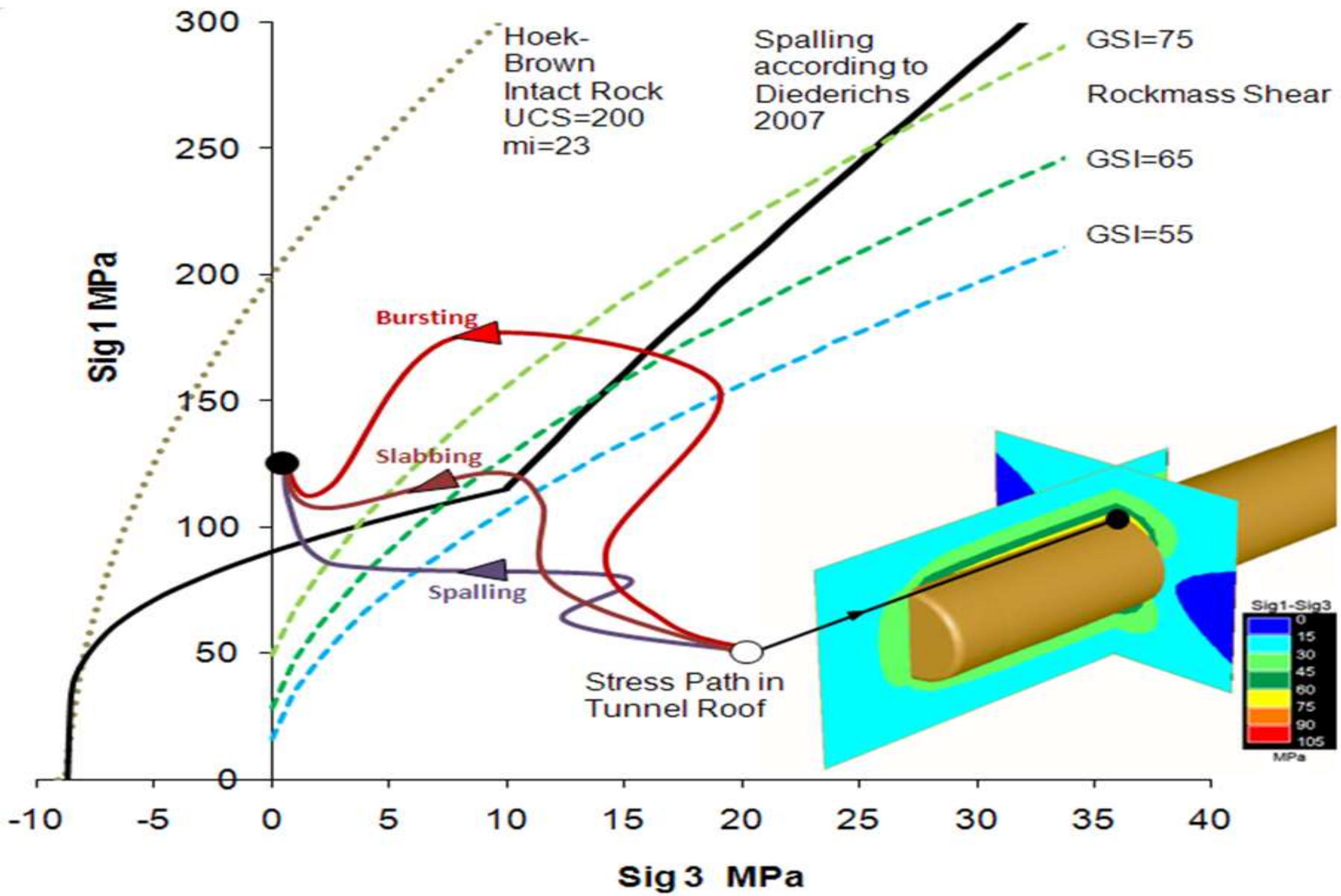


Strength Ratio	GSI < 55	GSI = 55 to 65	GSI = 65 to 80	GSI >80
UCS/T < 8	shear	shear	shear	shear
UCS/T =9 to 15	shear	shear	shear/spall	spall/shear
UCS/T=15 to 20	shear	shear/spall	spall/shear	spall
UCS/T > 20	shear	shear/spall	spall	spall

Energy Storage and Release
High Storage + “Soft System” = Burst Hazard

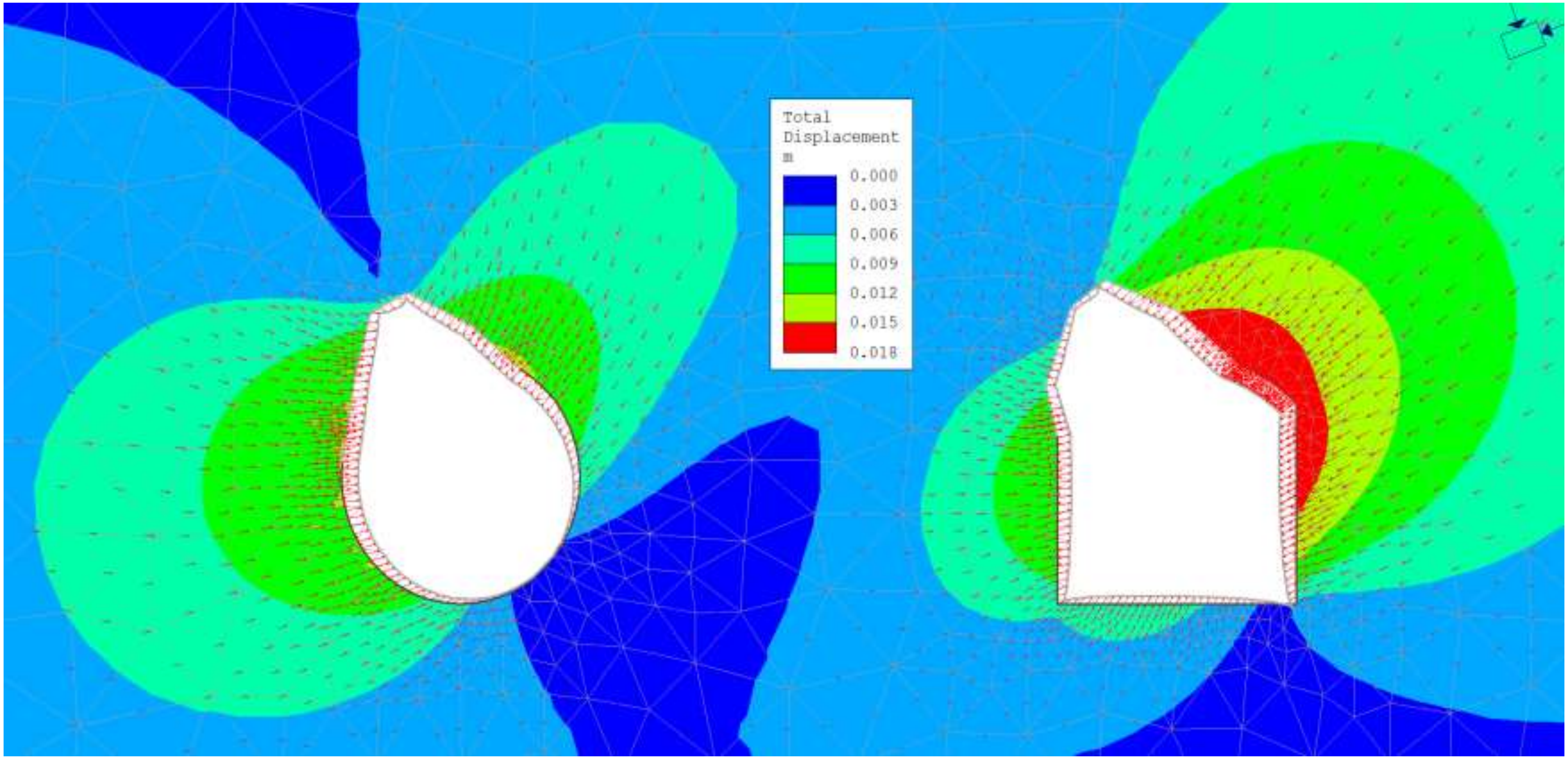


Energy Storage – Face Bursting



Energy storage and Release

- Energy release is controlled by geometry
- Simple modelling can be used to compare profiles

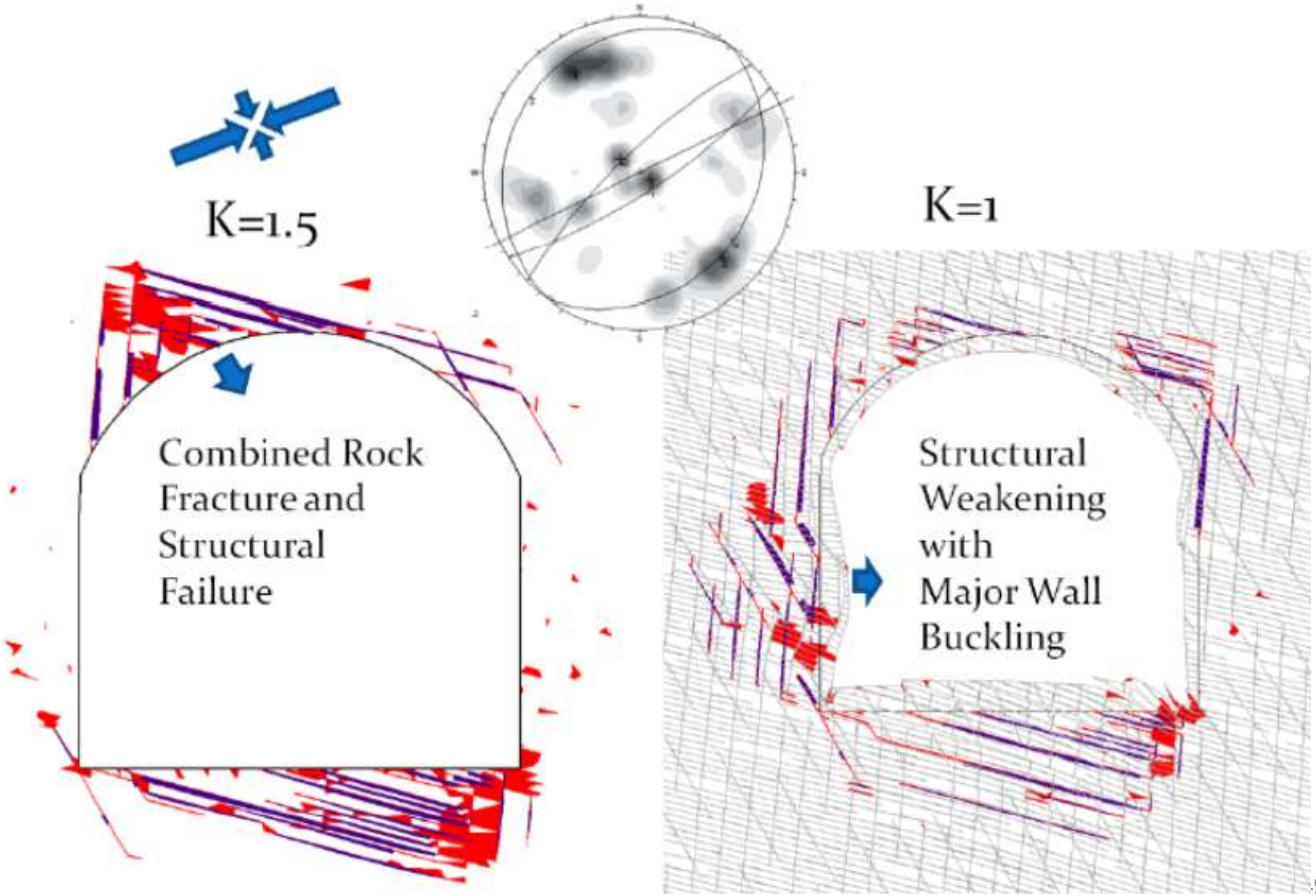


Simpler Geometries are Stiffer – Less Post Failure Closure = Less Energy

Strain Burst

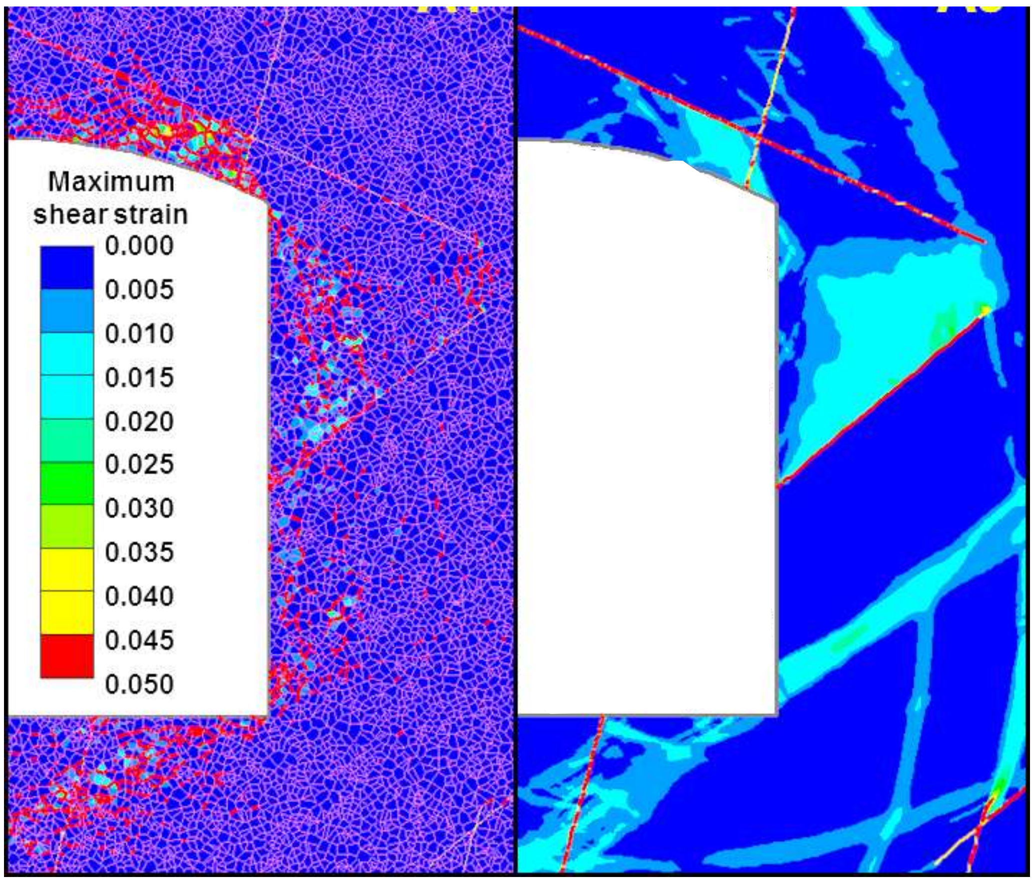
Stress-Structure Interaction

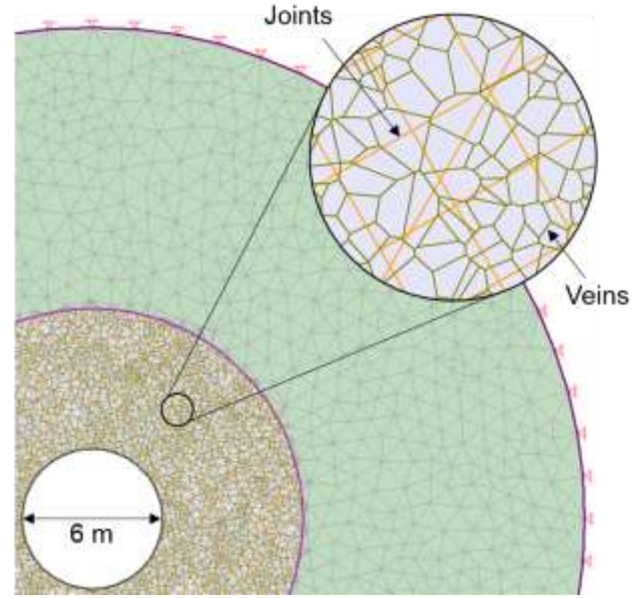
Modern discontinuum models are useful for exploring influence of structure at high stress



Complexities of Joints combined with filled veins = Burst hazard

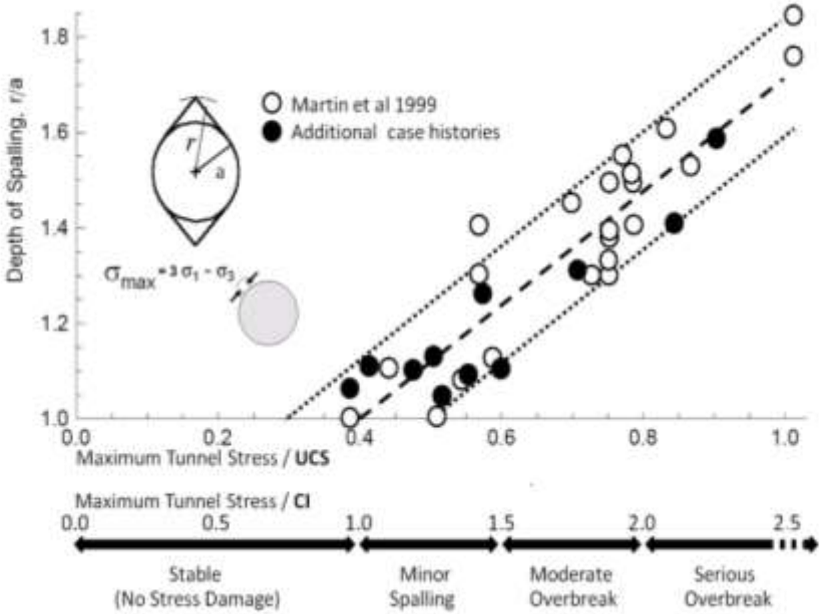
Modern desktop tools can simulate this



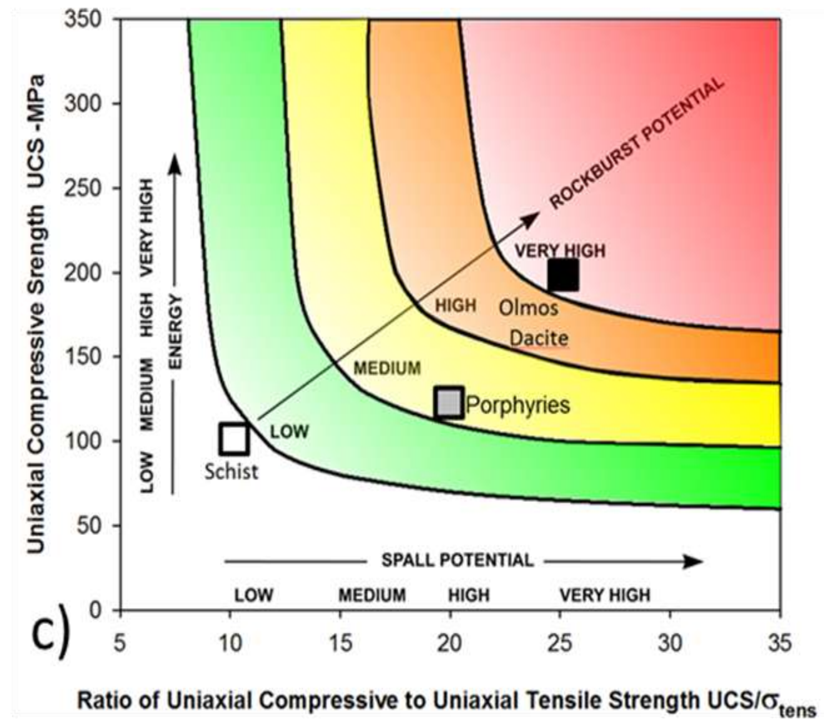


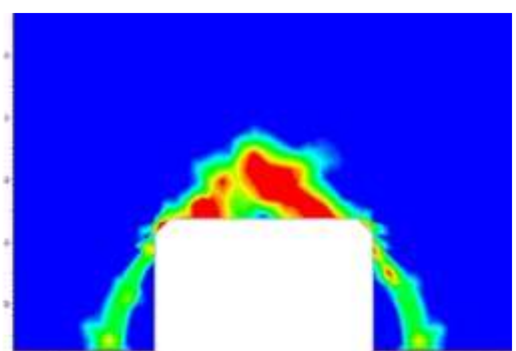
J Day Current Queen's PhD

Combining Empirical and Numerical Tools to Predict Damage and Energy Release



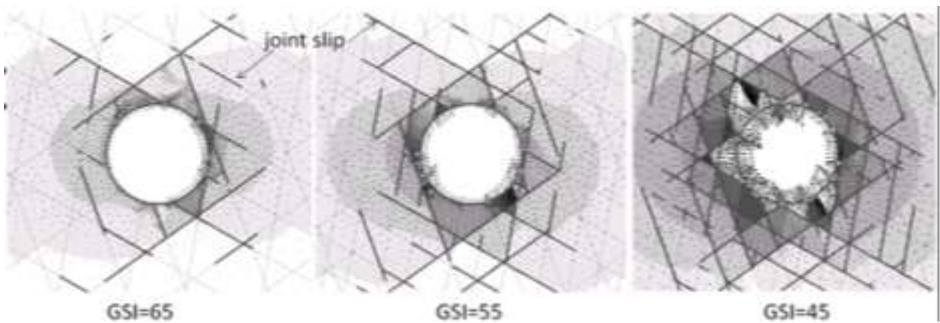
+

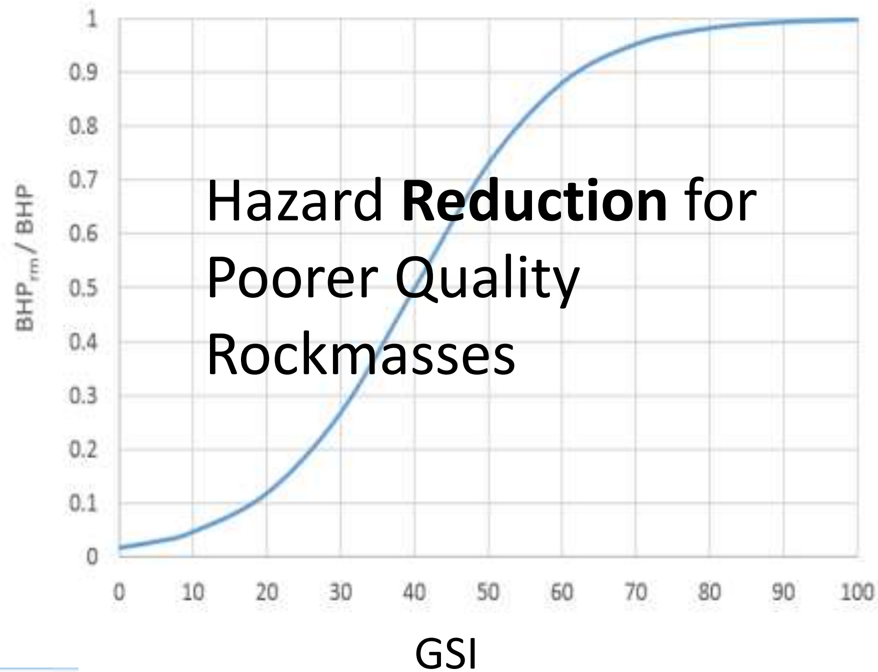




= Baseline Rockburst Hazard

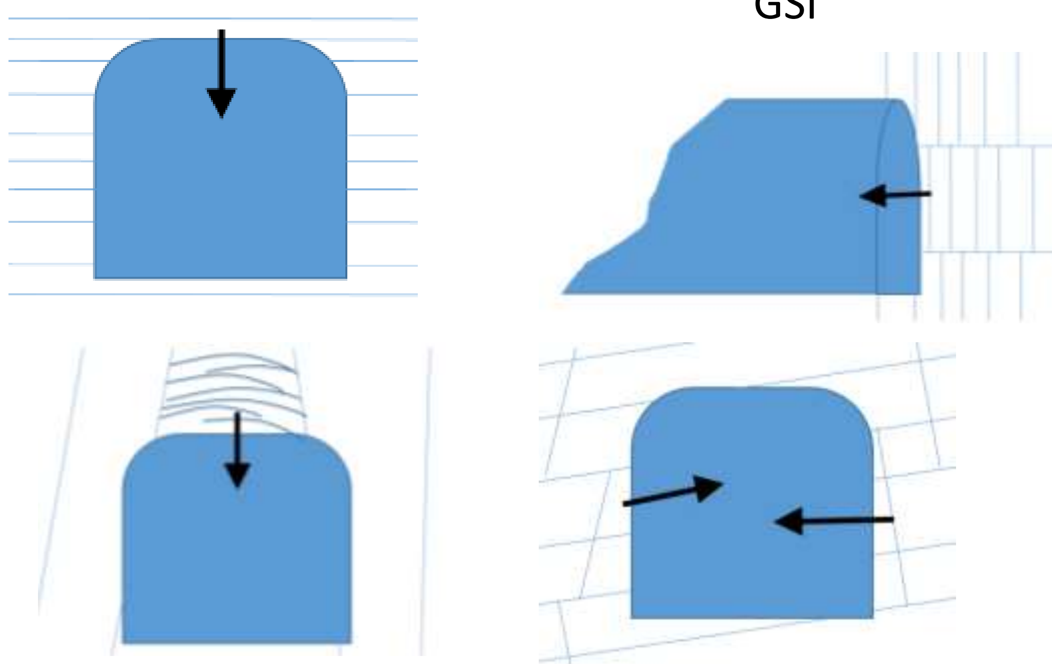
Impact of Structure

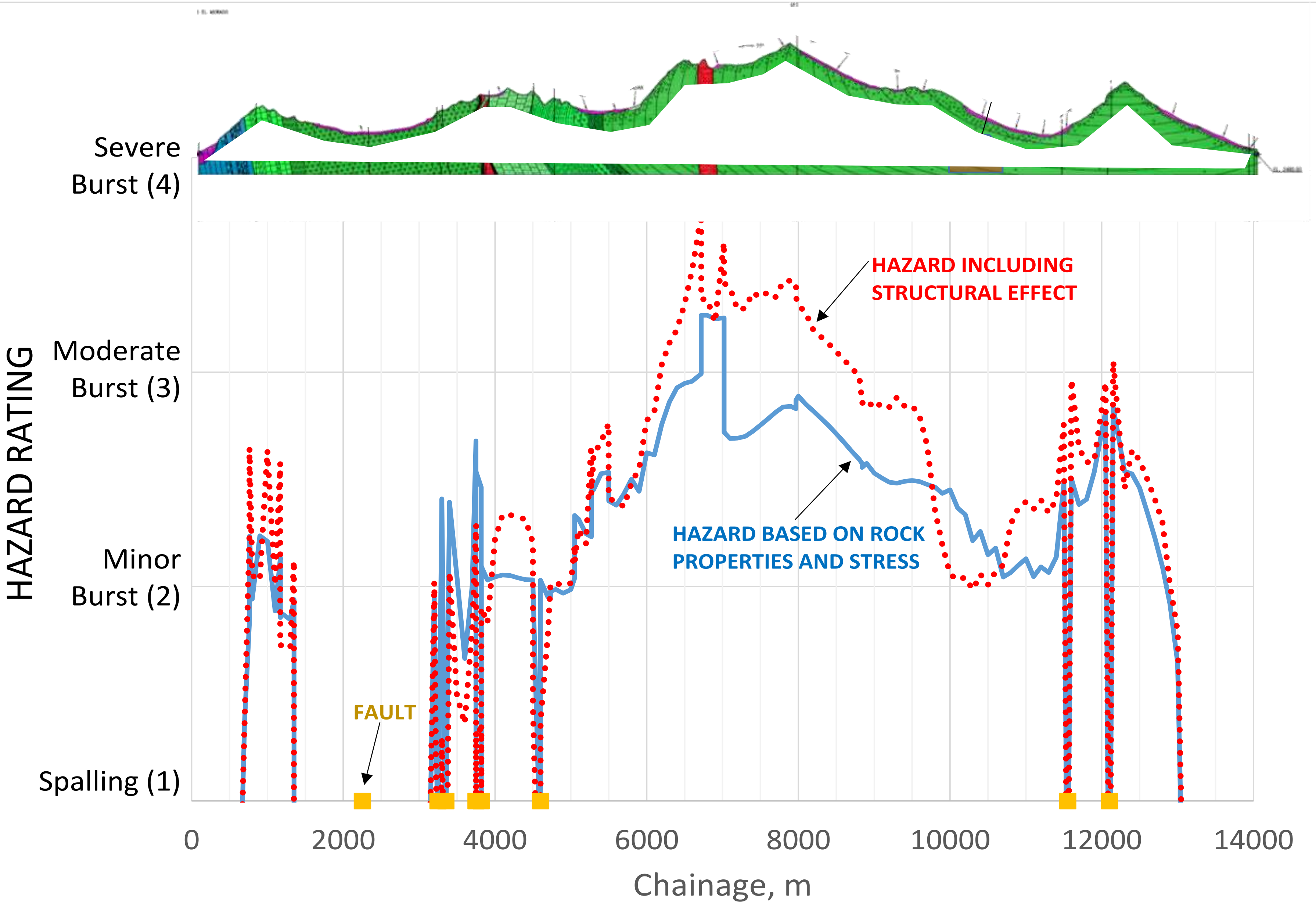




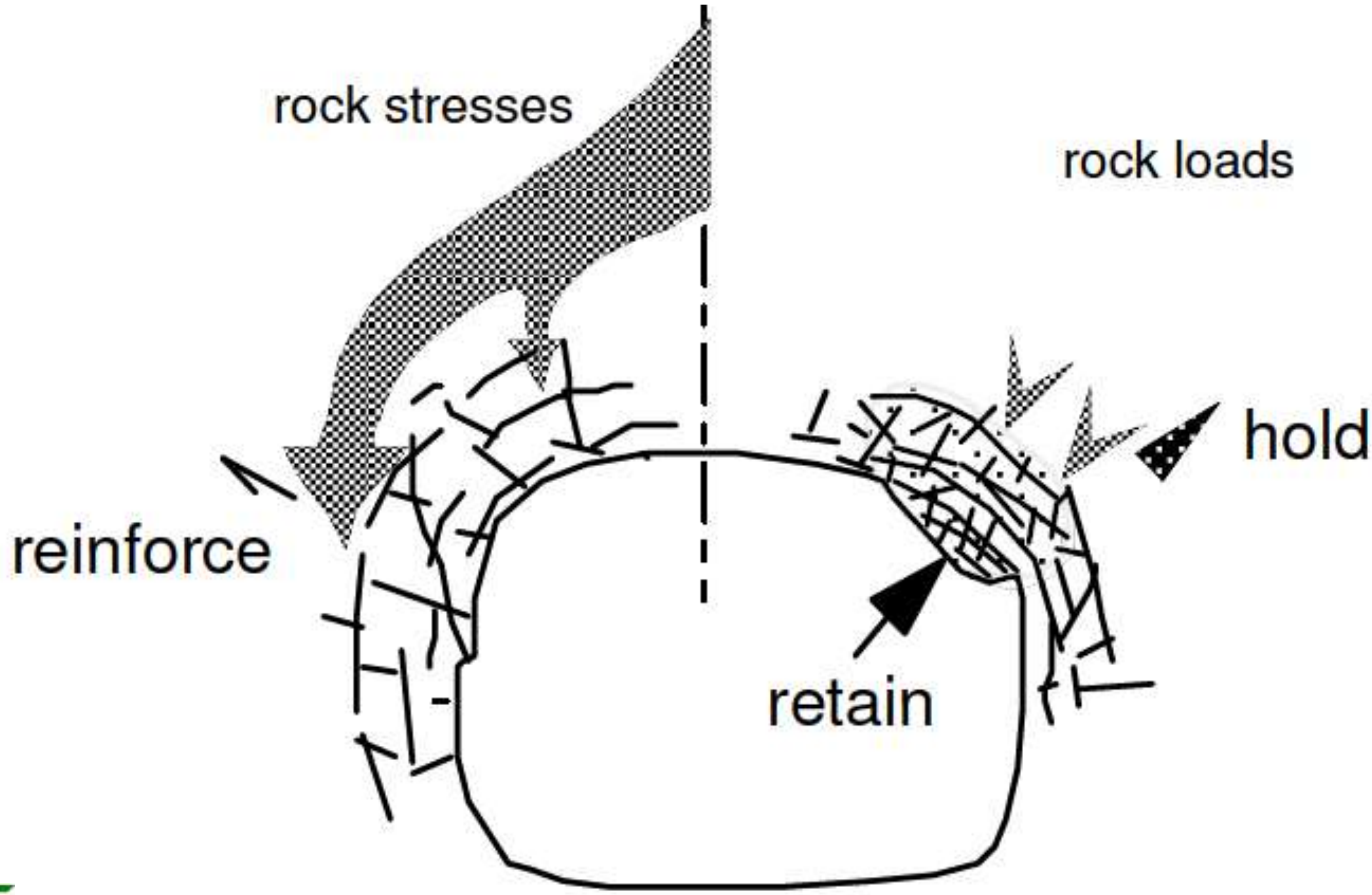
Hazard **Reduction** for Poorer Quality Rockmasses

Hazard **Increase** for Critical Combinations of Structure




Severe
Burst (4)
Moderate
Burst (3)
Minor
Burst (2)
Spalling (1)
HAZARD RATING
HAZARD INCLUDING
STRUCTURAL EFFECT
HAZARD BASED ON ROCK
PROPERTIES AND STRESS
FAULT
0
2000
4000
6000
8000
10000
12000
14000
Chainage, m

Rockburst Support



Rockburst Support System - TBM

Shield – Pressure Control

(Maintain to reduce heave – Release if clamped)

Steel Rings, Channels, Lattice – Load Capacity

Mesh – Retain and Integrate

(Above rings and held by rebar)

Rebar or Super Swellex– Reinforce

Yielding or Deformable Support

(Many products now available)

Shotcrete – System Integration

(Also emergency profile control)

Rockburst Support System - Drill and Blast

Shotcrete - Maintain Profile and Integrity

Rapid Remote Support – Swellex or Resin Bolts

Mesh– Retain and Reinforce Shotcrete

Rebar – Reinforce

must be accompanied by…

Yielding or Deformable Support

(Many products now available)

Surface Mesh - Protection

Combination Bolt (D-Bolt)
Reinforcement and Displacement Capacity

What is Rockburst Risk?

ROCKBURST (Hazard)

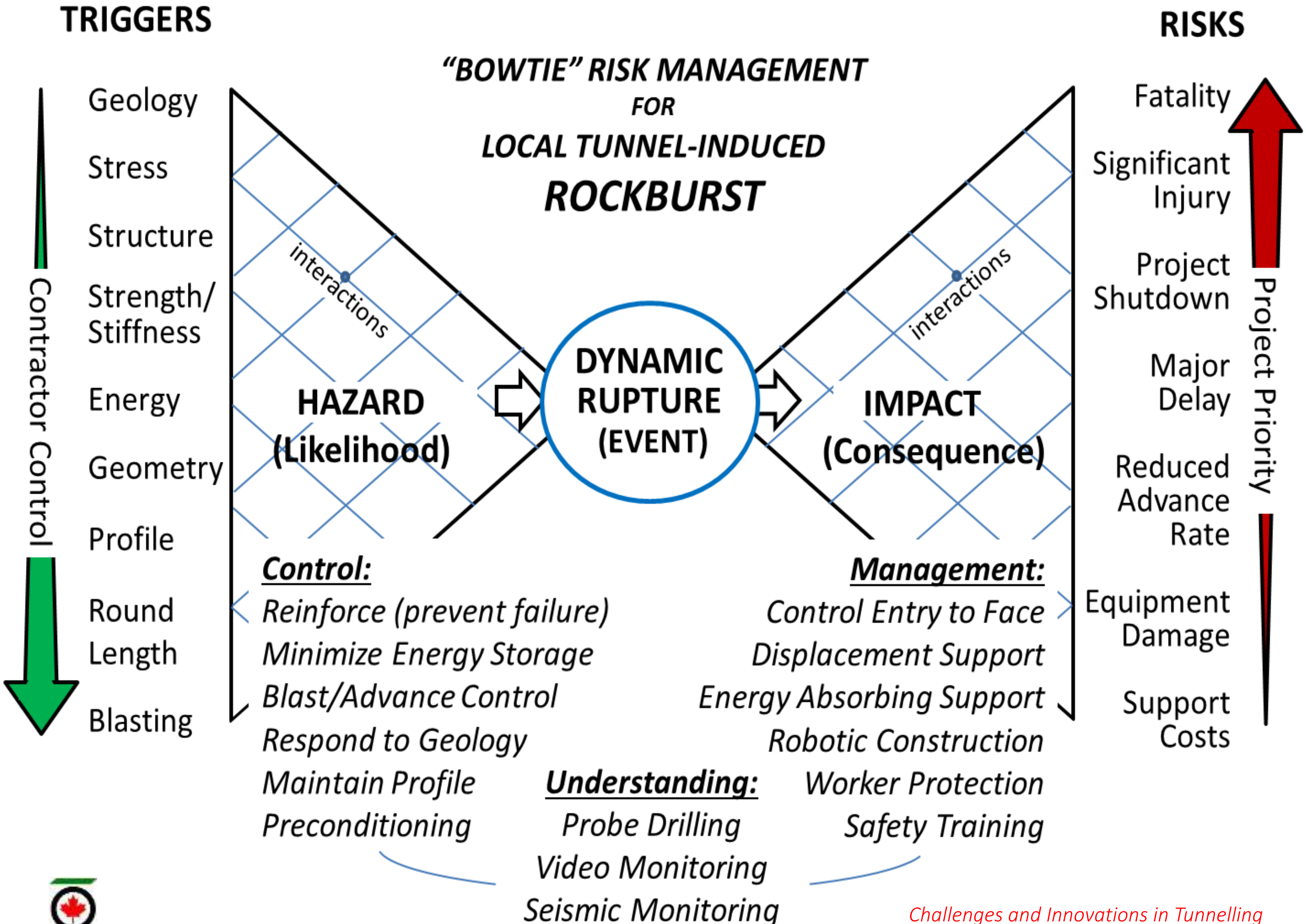
(Likelihood of) Damage to an excavation that occurs in a sudden or violent manner, associated with a seismic event

ROCKBURST RISK

A measure of the potential for impact,
due to damage associated with a rockburst, to:

1) safety of personnel,
2) continuity of construction/operational objectives or
3) equipment and infrastructure

Auto-Seismic HAZARD may be unavoidable
Rockburst RISK is a management issue


TRIGGERS
RISKS
"BOWTIE" RISK MANAGEMENT
FOR
LOCAL TUNNEL-INDUCED
ROCKBURST
Geology
Stress
Structure
Strength/
Stiffness
Energy
Geometry
Profile
Round
Length
Blasting
Contractor Control
interactions
HAZARD
(Likelihood)
DYNAMIC
RUPTURE
(EVENT)
interactions
IMPACT
(Consequence)
Fatality
Significant
Injury
Project
Shutdown
Major
Delay
Reduced
Advance
Rate
Equipment
Damage
Support
Costs
Project Priority
Control:
Reinforce (prevent failure)
Minimize Energy Storage
Blast/Advance Control
Respond to Geology
Maintain Profile
Preconditioning
Management:
Control Entry to Face
Displacement Support
Energy Absorbing Support
Robotic Construction
Worker Protection
Safety Training
Understanding:
Probe Drilling
Video Monitoring
Seismic Monitoring

Rockburst Hazard Assessement

Anticipate geological change:

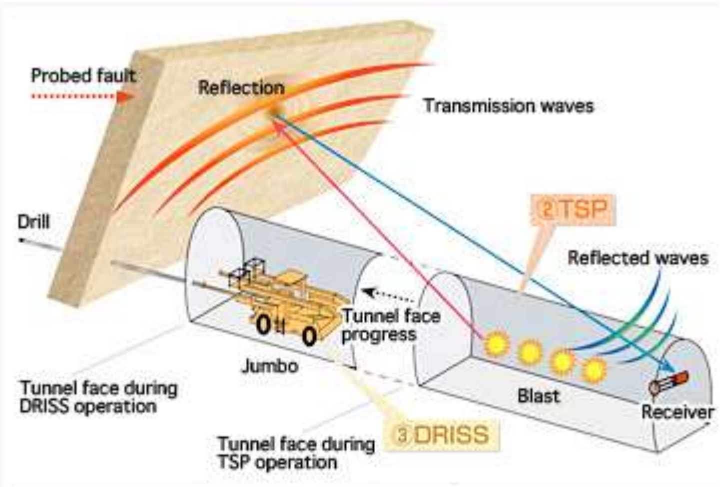
Warnings for Moderately Stress/Strength

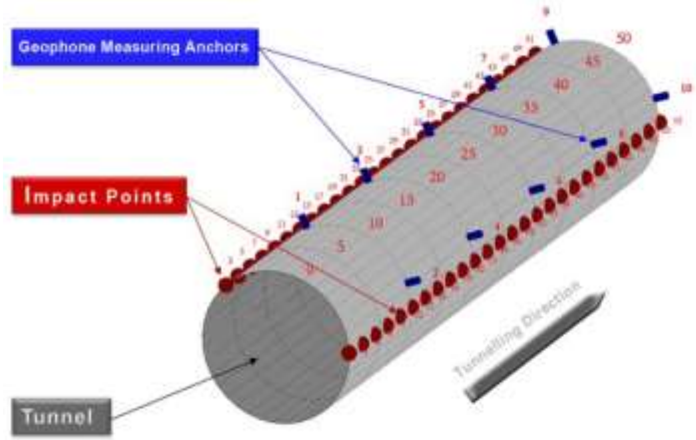
- Moving from soft to stiff or vice versa
- Surface parallel structure
- Heterogeneous rockmass (stiff and soft elements)

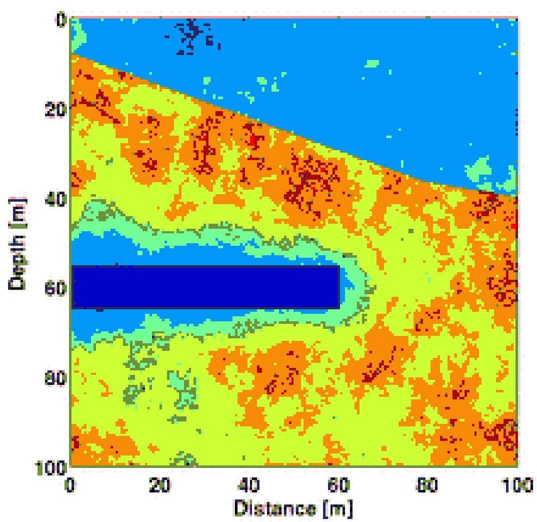
Warnings for High Stress/Strength

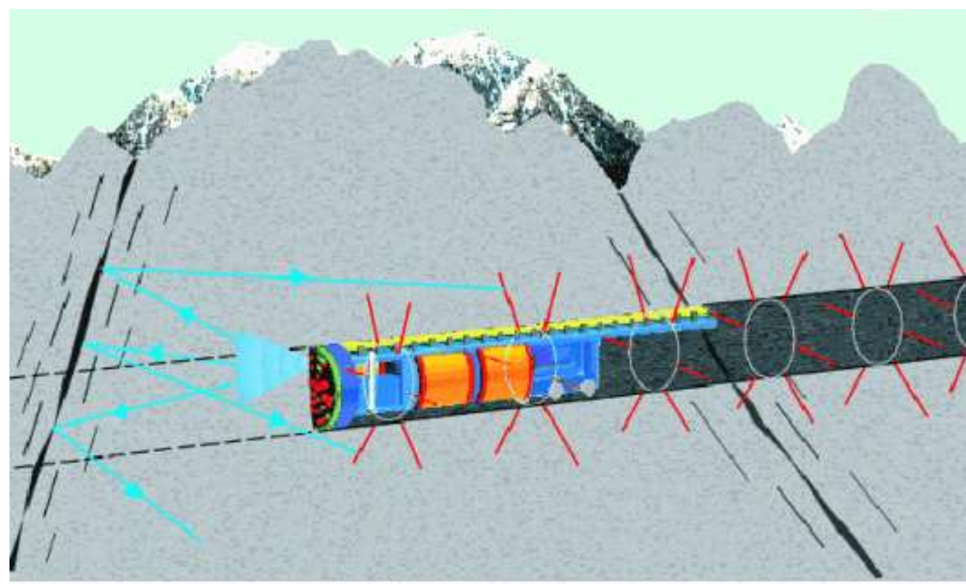
- Any of the above conditions
- Fracture with persistent steep structure
- Massive face in brittle rock

Look ahead Seismic Monitoring





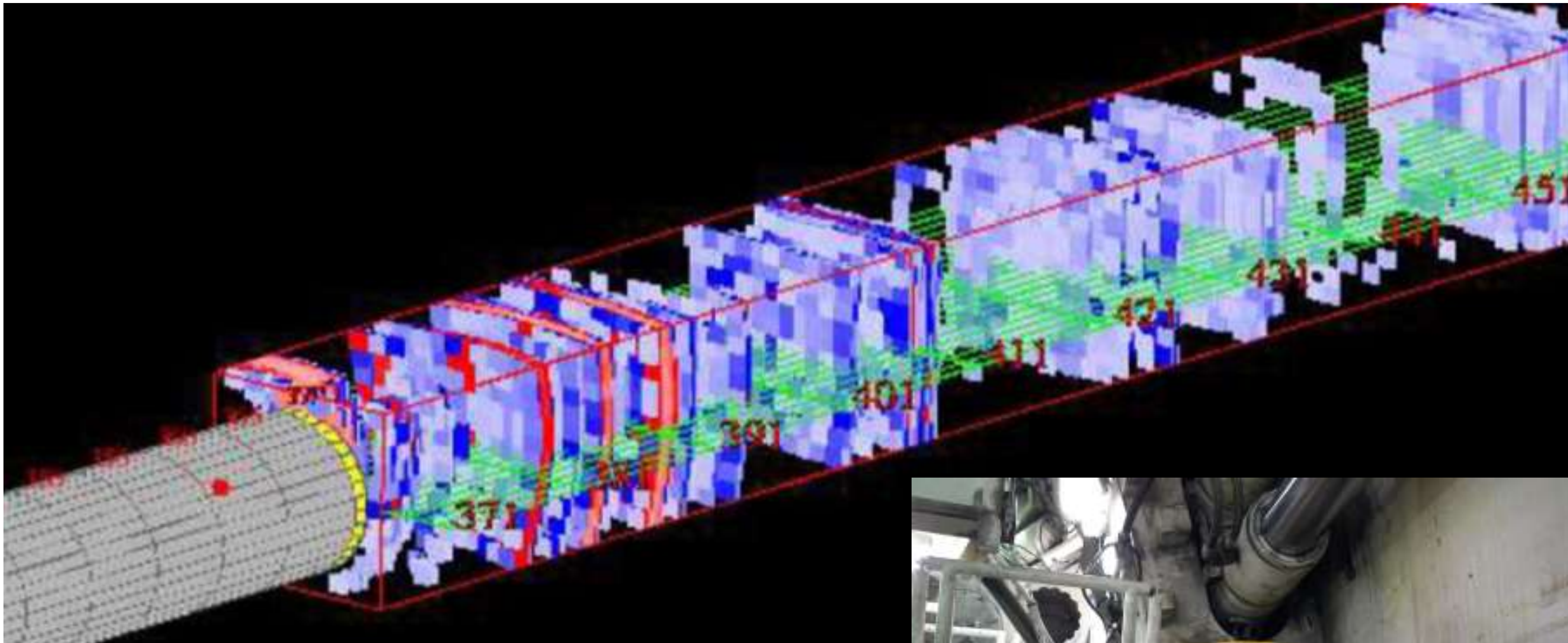




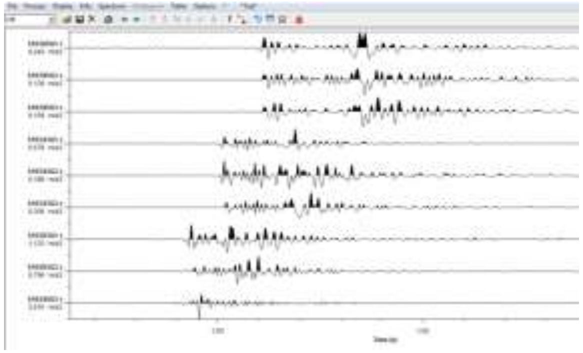
GFZ Potsdam

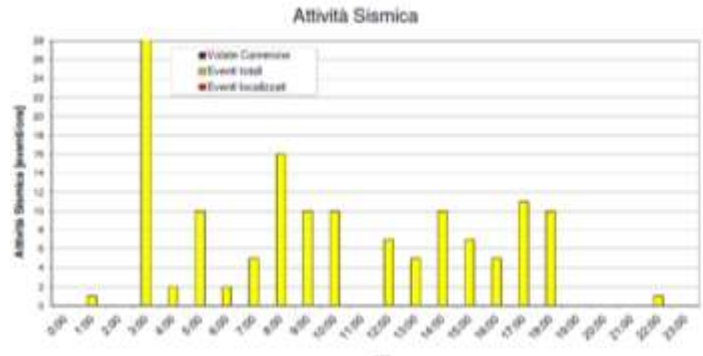
Look Ahead Seismic Monitoring

GFZ and Herrenknecht



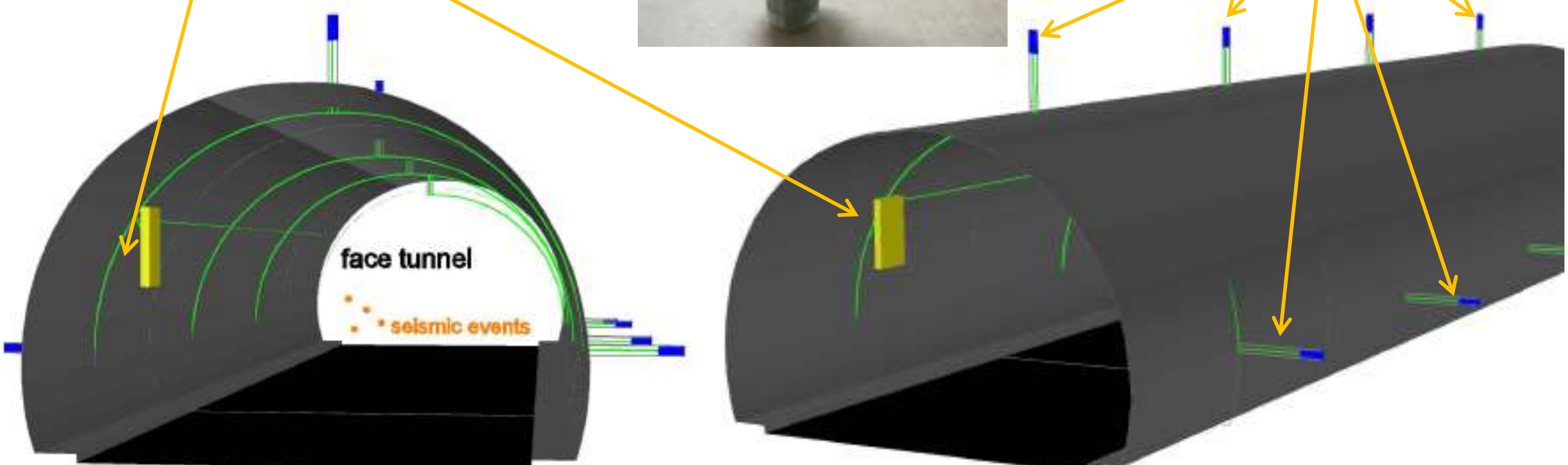
ROCKBURST MONITORING





Acquisition unit

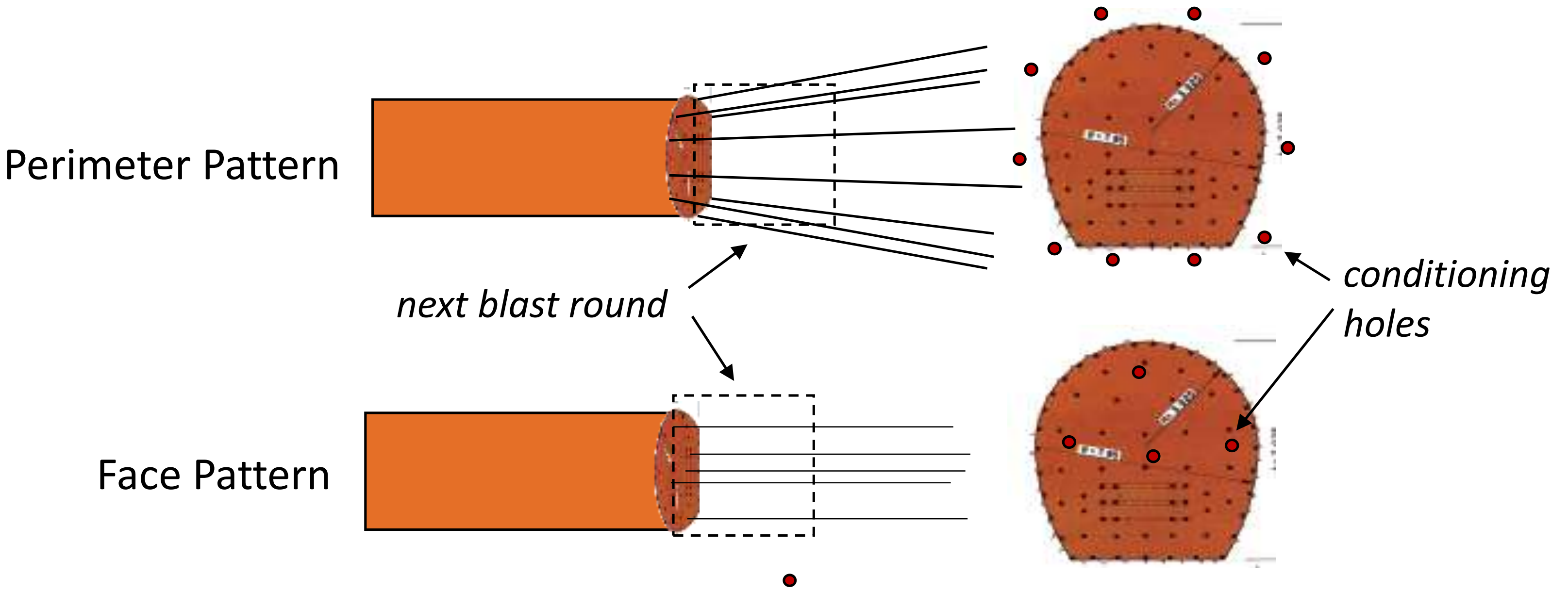
Accelerometers installed in small borehole in a geometric note disposition

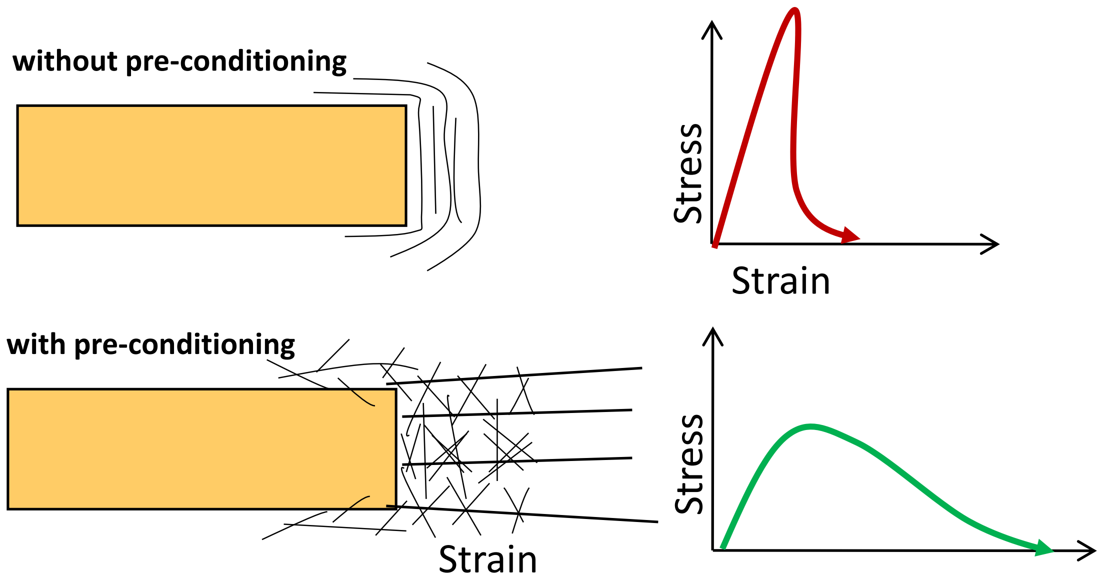


Rockburst Risk Management

- Managing worker exposure during construction
  - Robotic installation, protective cages, re-entry protocols
- Minimizing failure depth (lower available energy)
  - Proper static support with excess capacity, stiff elements
- Maximizing support and energy absorption
  - Deformable Support
- Minimize energy storage and release
  - Preconditioning, sequencing, round and profile control
- Monitoring
  - Seismic System, event records, observations

Mitigation – Preconditioning/Destress Blasting (?)





Scaling vs Excavating

Challenge in Tunnelling

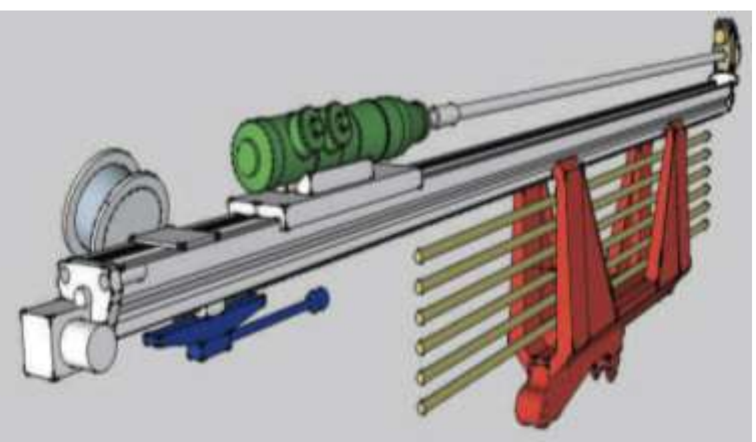
Safely installing rockburst support at face

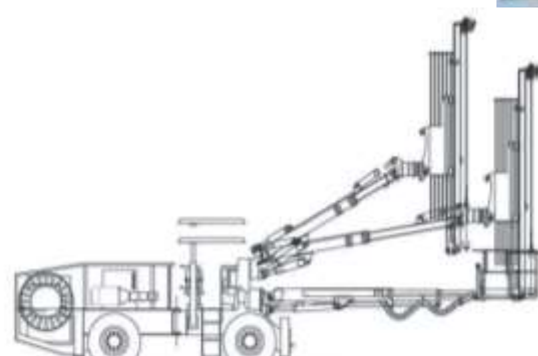
Exposure Control (Drill and Blast)

<u>Risk Balance</u>

Support Increases Safety After Installation

Support Installation Increases Exposure





Mesh Installation Arm

TBM INNOVATIONS

- Expanding Hybrid Shield (Fingers or McNally System)
  - Wide angle bolt support

- Hybrid “McNally System” allows for stiffer finger response when installed


• Hybrid “McNally System” allows for switching to strap mode

CRITICAL ELEMENT:

Rear loading cutters are a must for deep tunnelling

Queen's Geomechanics Group

Thank you

Queen's University, Kingston, Ontario