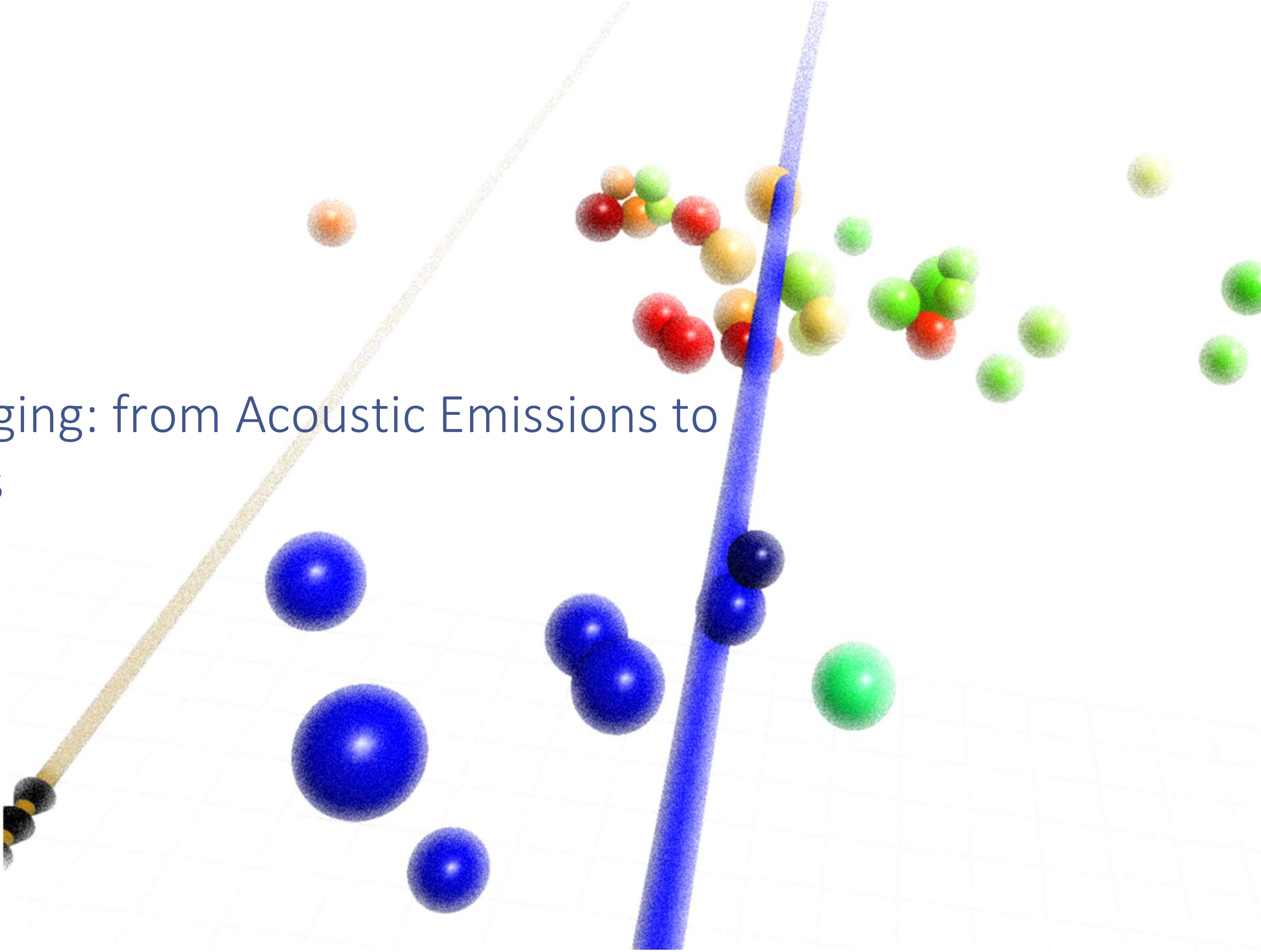
Seismic Imaging: from Acoustic Emissions to Earthquakes



applied seismology.co.uk

Speaker

Juan Reyes-Montes, Senior Consultant, ASC

B.Sc. in Physics and B.Sc. in Geology from the University of Granada and a Ph.D. in Seismology from the University of Liverpool.

Specializes in the design, processing and analysis of acoustic, microseismic and ultrasonic monitoring projects, applied at scales ranging from laboratory tests on rock samples to local and regional induced seismicity.

Worked in several international collaborative projects in mining, radioactive-waste isolation, petroleum and geothermal sectors.

Developed algorithms for the statistical analysis of microseismic catalogues and their correlation with numerical models for the interpretation of rock fracture processes.

j.reyesmontes@appliedseismology.co.uk

- ASC has over 20 years of experience in applying the methods and analyses of seismology to a wide range of engineering applications at all scales from regional earthquake site characterisation to microseismic and acoustic emission studies. Services are targeted at supplying an integrated work package along the full data path through sensor array design, data acquisition, processing and interpretation. These services include reviewing natural and induced seismicity, ground motion prediction and monitoring, working within regulatory systems and designing, operating and reporting on microseismic monitoring. Our main areas of application include:
  - Geothermal,
  - Radwaste storage,
  - Underground storage: Carbon, Hydrogen, Natural Gas
  - Reservoir engineering
  - Civil Engineering/Geotechnical
  - Laboratory-testing applications (Acoustic Emission and ultrasonic monitoring) in association with LEA

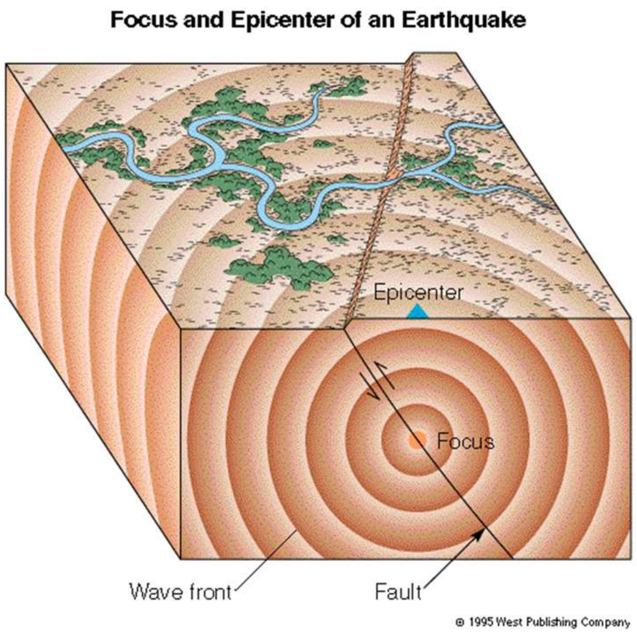
What is a seismic event ?

- Vibration caused by the rapid strain/stress release due to brittle failure
- Failure could result in the opening and shear of fractures and pre-existing structures
- Results in the change in stress distribution, pore fluid pressure, mechanical deformation, and change in material properties

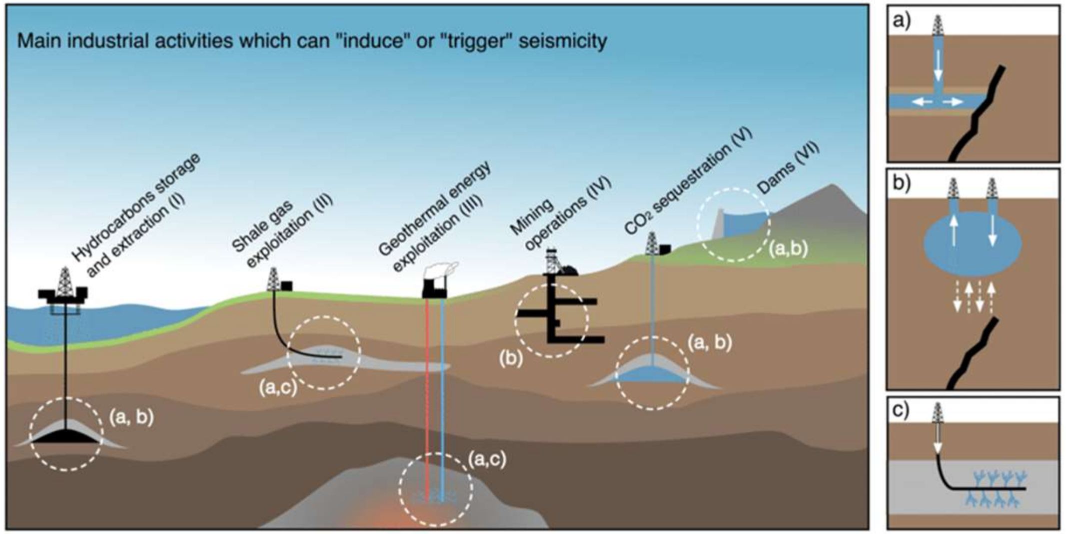
Earthquake Research Centre, University of Tokyo

Seismic Sources

Natural sources



- Induced sources



http://www.destress-h2020.eu/en/home/

Triggered or Induced ?

Induced

Where the causative activity can account for most of the stress change or energy required to produce the seismicity

Triggered

Where the causative activity accounts for only a fraction of the stress change or energy associated with the seismicity (i.e. tectonic loading plays a primary role)

(after McGarr & Simpson, 1997)

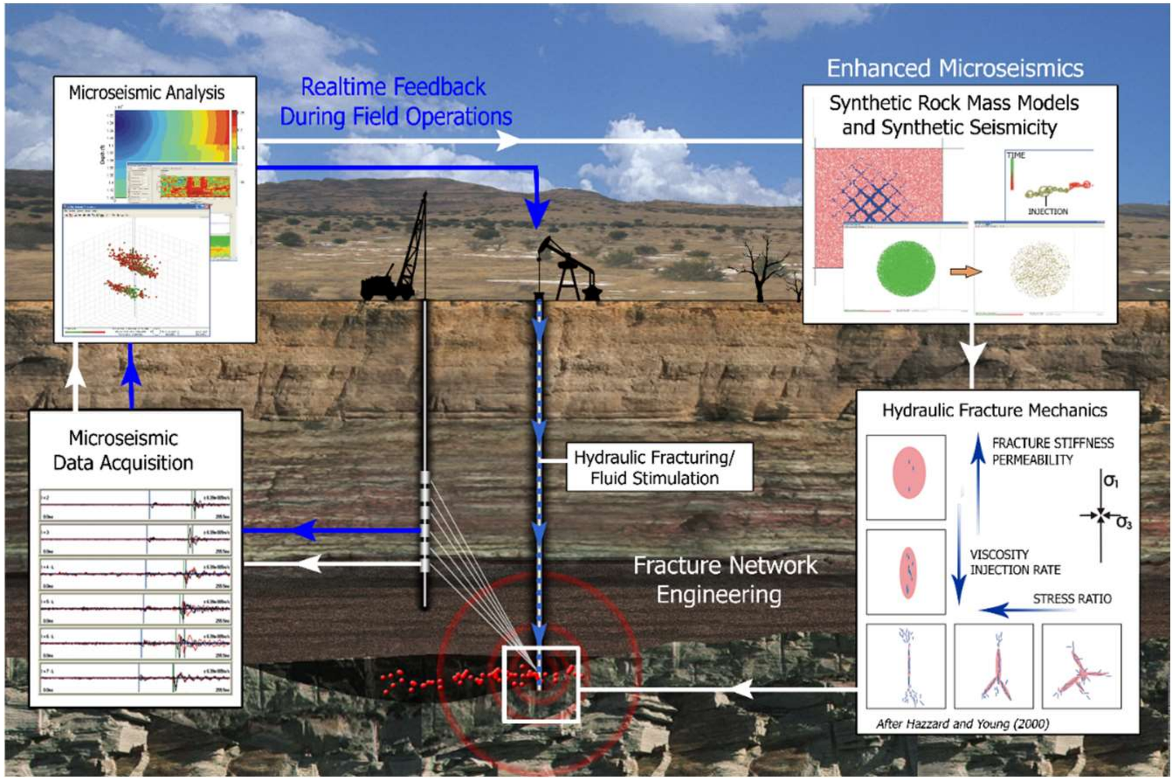
Factors causing stimulated seismicity

- stress changes
- pore pressure changes
- volume changes
- application or removal of a load
- some combination of the above

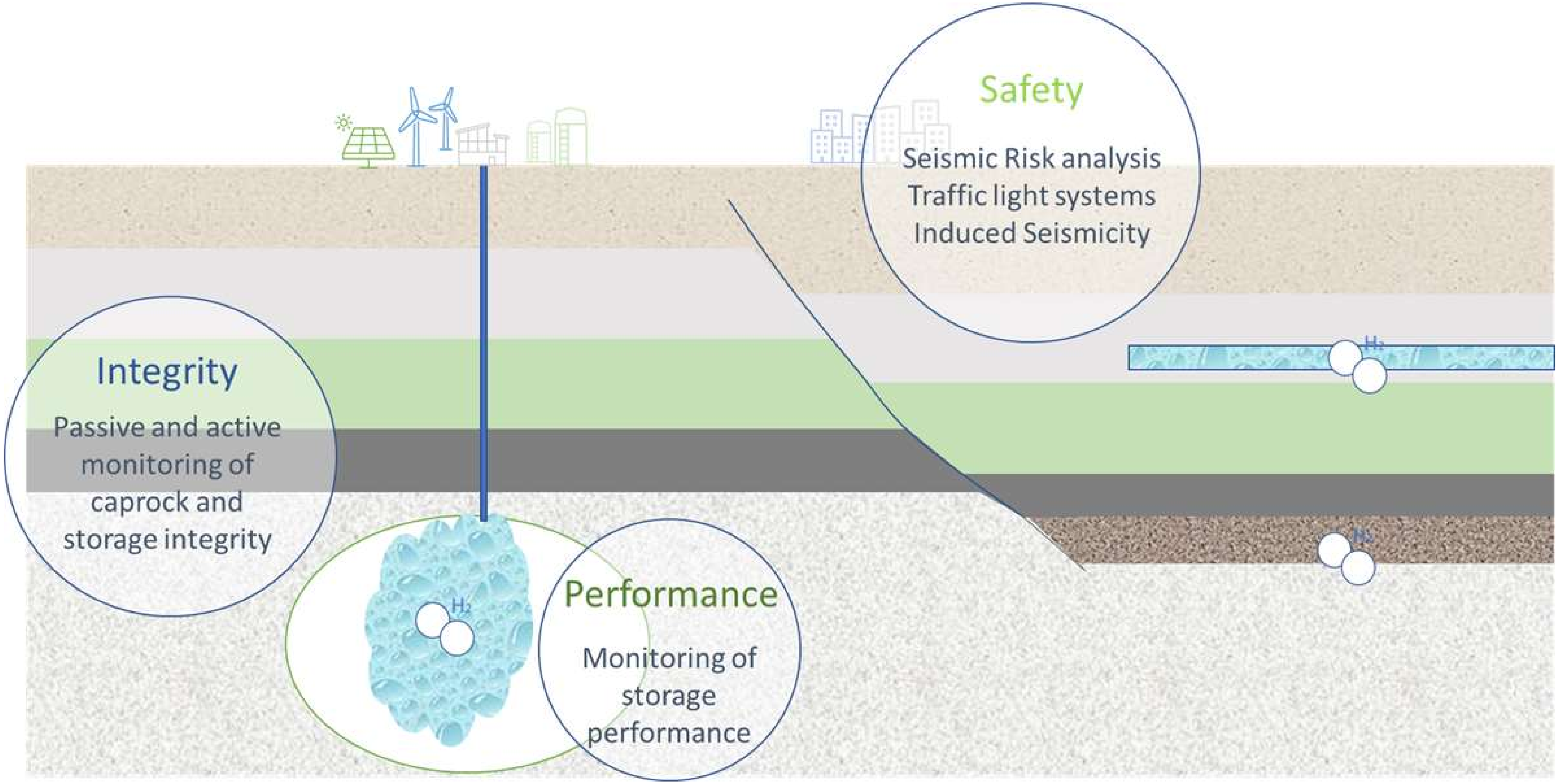
What can Seismic Monitoring do for us?

Reservoir Stimulation

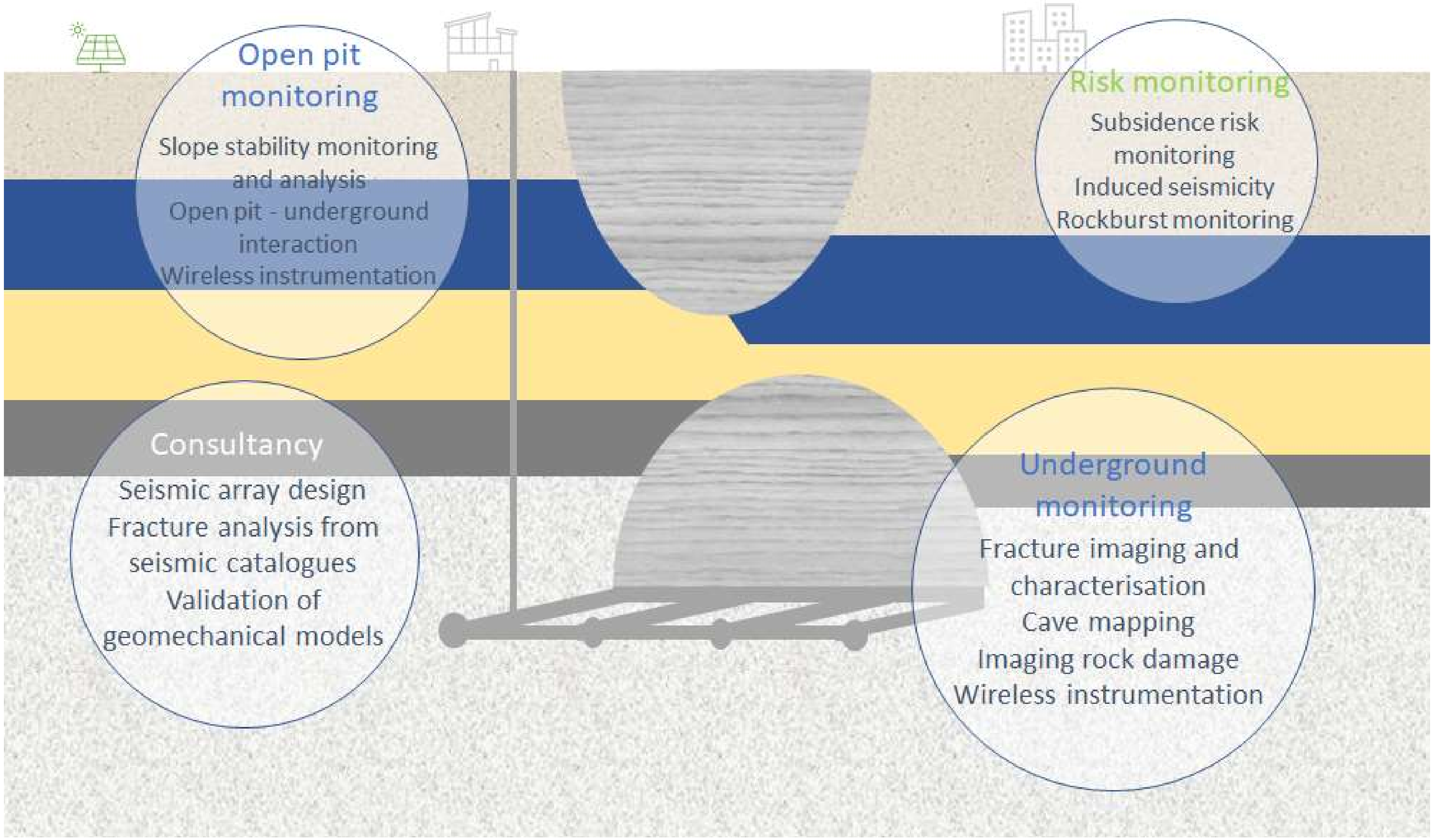
- Real time imaging of stimulated fracture network
  - Real-time feed-back of effectiveness of a hydrofracture stimulation
  - map extraction and injection paths in a producing field.
- assessment of the completion objectives.
- Investigation of active fault zones, compaction and subsidence.
- Traffic light system for induced seismicity



Underground Hydrogen Storage

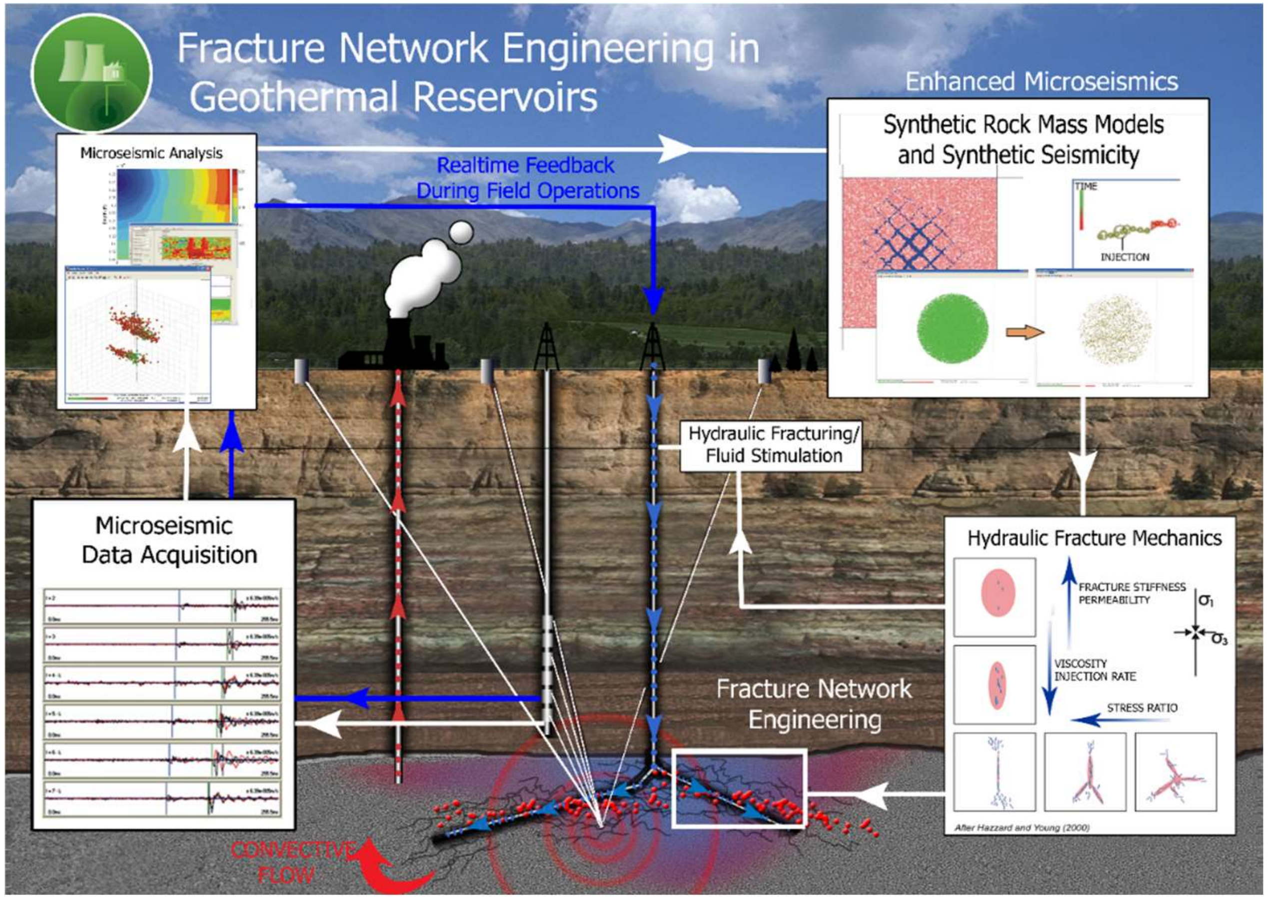


Mining


Open pit monitoring
Slope stability monitoring and analysis
Open pit - underground interaction
Wireless instrumentation
Risk monitoring
Subsidence risk monitoring
Induced seismicity
Rockburst monitoring
Consultancy
Seismic array design
Fracture analysis from seismic catalogues
Validation of geomechanical models
Underground monitoring
Fracture imaging and characterisation
Cave mapping
Imaging rock damage
Wireless instrumentation

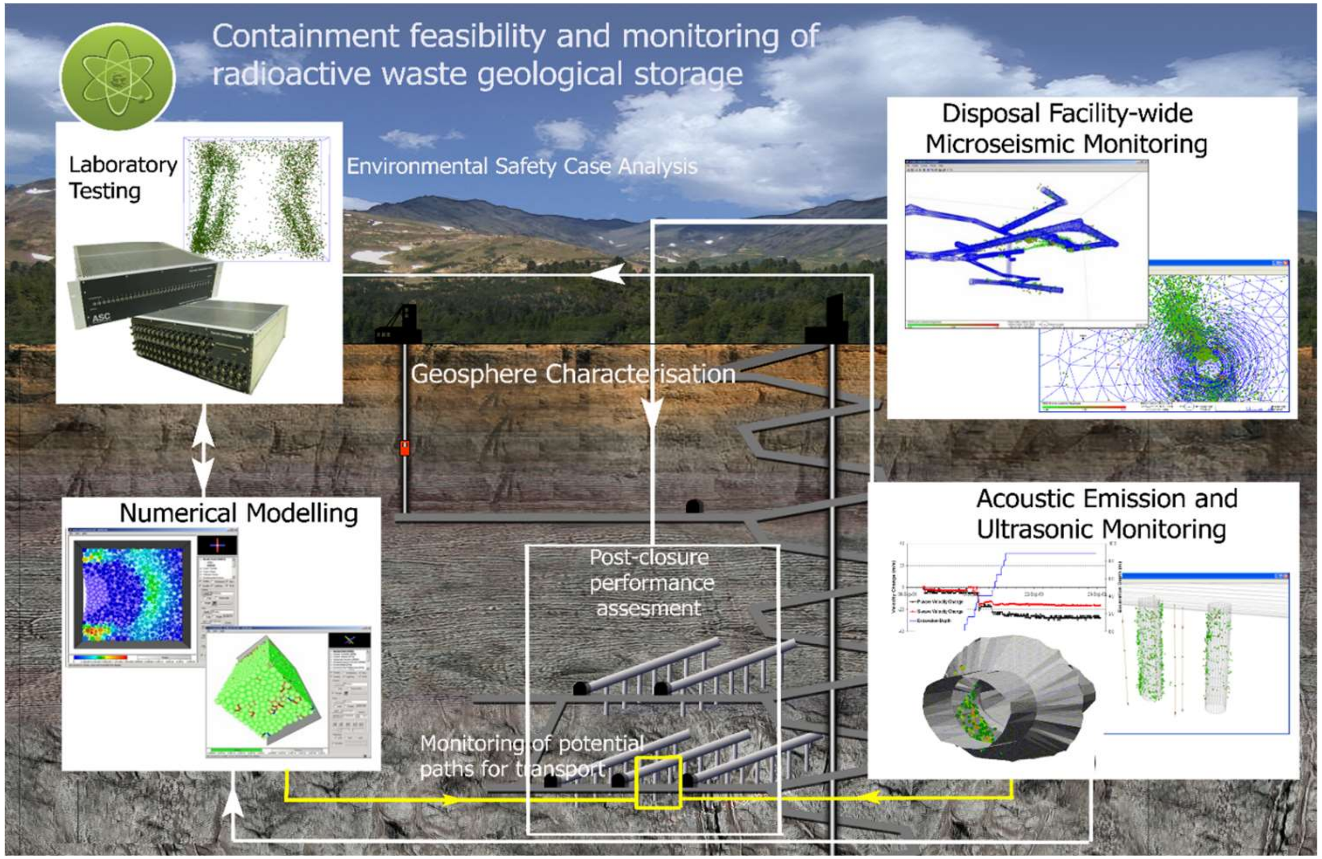
Deep Geothermal Operations

- Gain information on the development of Engineered Geothermal Systems (EGS) and enhance our understanding of long-term reservoir behaviour.
- Increase the productivity and recovery of the reservoir and assist in the design and optimal location of production wells
- Map the position, growth and effectiveness of hydrofracture stimulation to assess completion objectives
- Map extraction and injection paths, treatment history and fluid migration



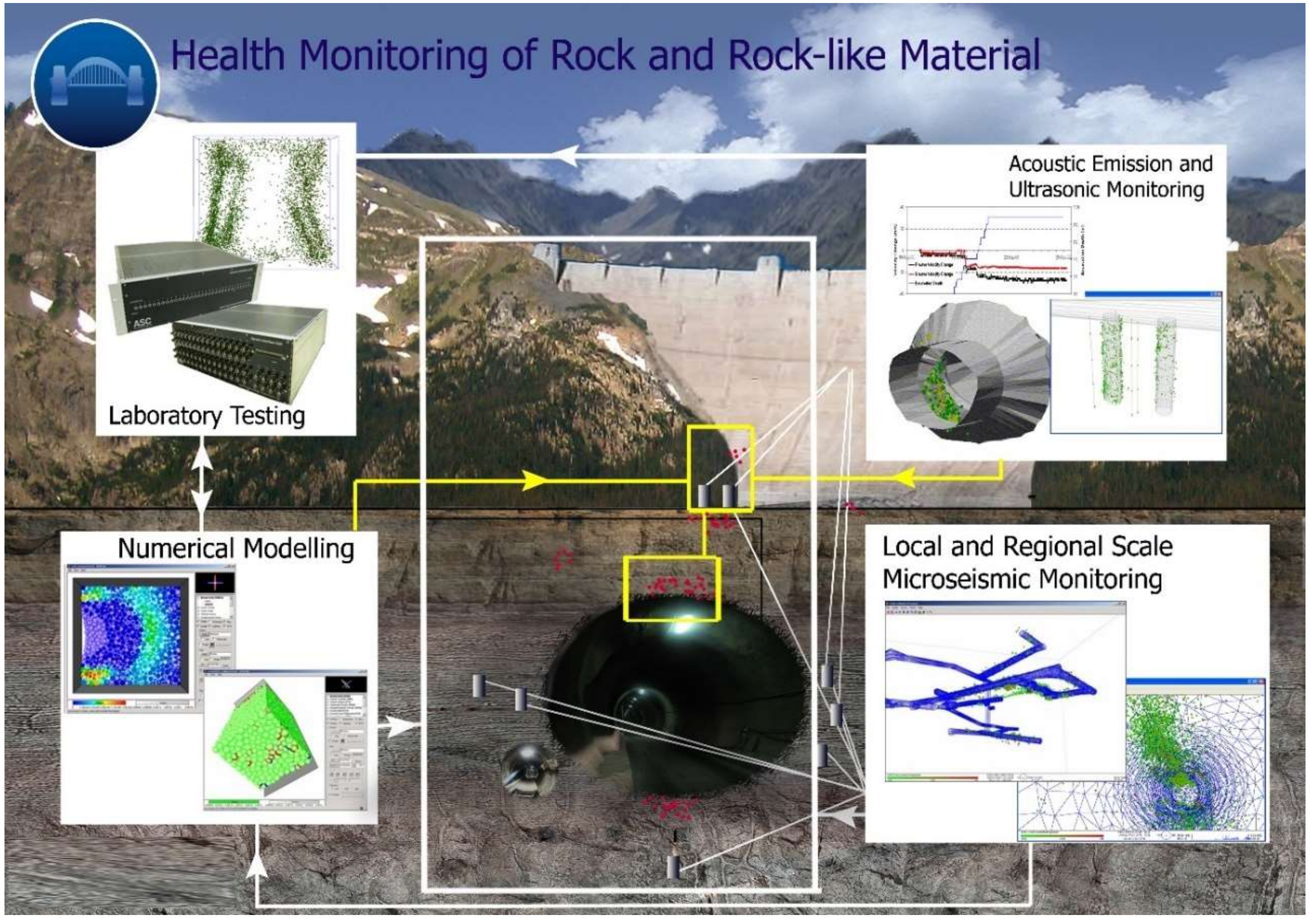
Geological Storage of Radioactive Waste

- Monitoring of site stability and risk against natural earthquakes
- detect fractures around engineered structures and delineate potential fluid pathways
- Quantify damage and disturbance accumulation through excavation and thermal loading
- Assessing the Excavation Damage Zone by spatially and temporally mapping fractures



Civil Engineering

- Monitoring of structural responses during environmental loading and concrete curing.
- Safety monitoring of tunnels and underground infrastructure.
- Site characterisation and suitability assessment
- Slope stability analysis and integrity assurance.
- Early warning of catastrophic failure of rock, concrete and engineered materials.
- Investigation of active fault zones, compaction and subsidence in and around engineered structures.



Rock mechanics in the laboratory

- Full characterisation of rock deformation and fracturing processes under fully controlled conditions
- Understanding Earth processes and geomaterials response to engineering processes
- Material testing and rheological characterisation
- Validation of geomechanical models

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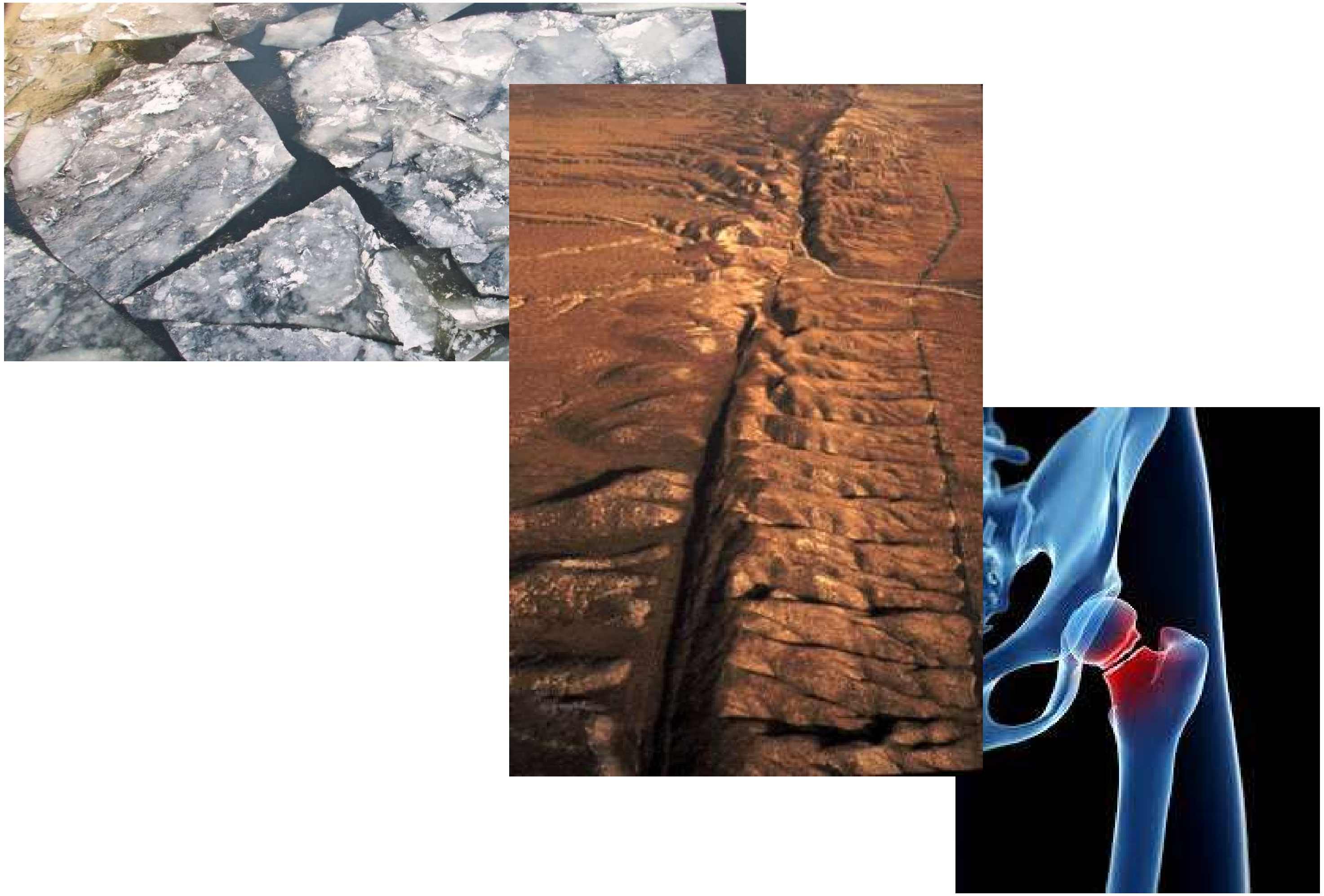
Technology & Innovation

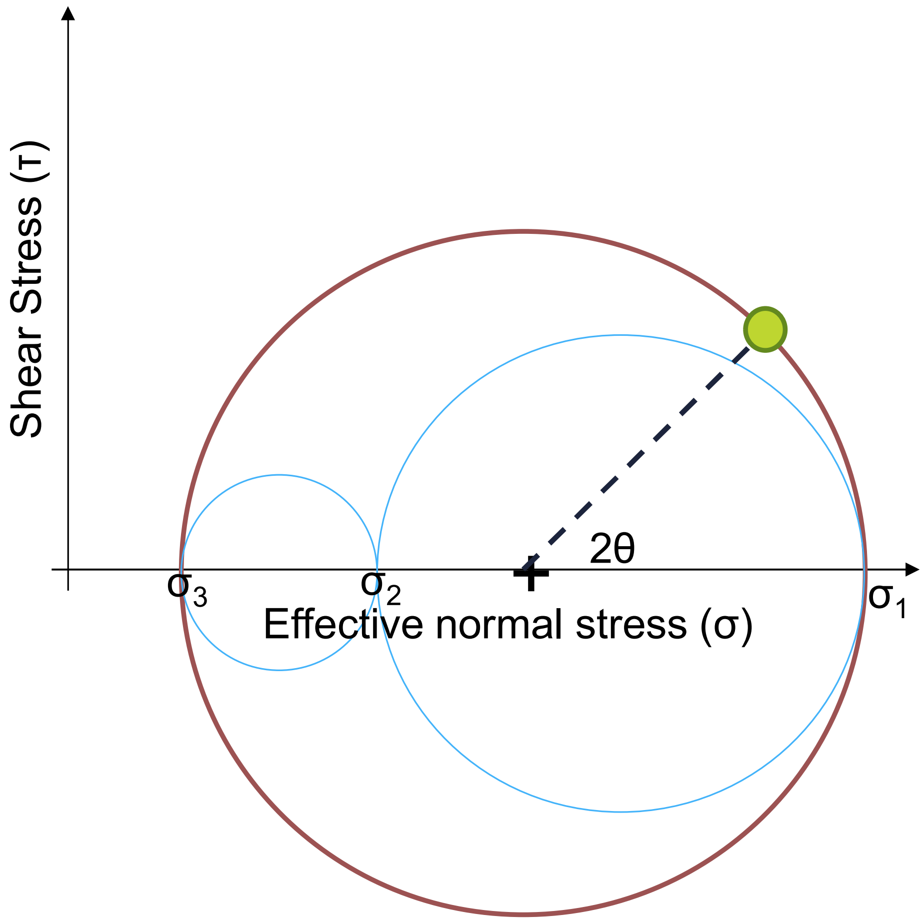
Fractures

- Process in a material as a reaction to stress changes
- Strain beyond the elastic point
- Return to steady state (balance)
- Sudden
- Causes change in material properties



Fracturing and the associated acoustic emission occurs when:

- The magnitude of the stress changes in the material are be large enough to result in failure.
- The nature of the stress change promotes failure.



Stress state for plane with normal in the σ_1 -σ_3 plane at an angle θ to σ_1

The strength of a fault (or shear stress required for failure) is given by

$$\tau = \tau_o + \mu(\sigma_n - P)$$

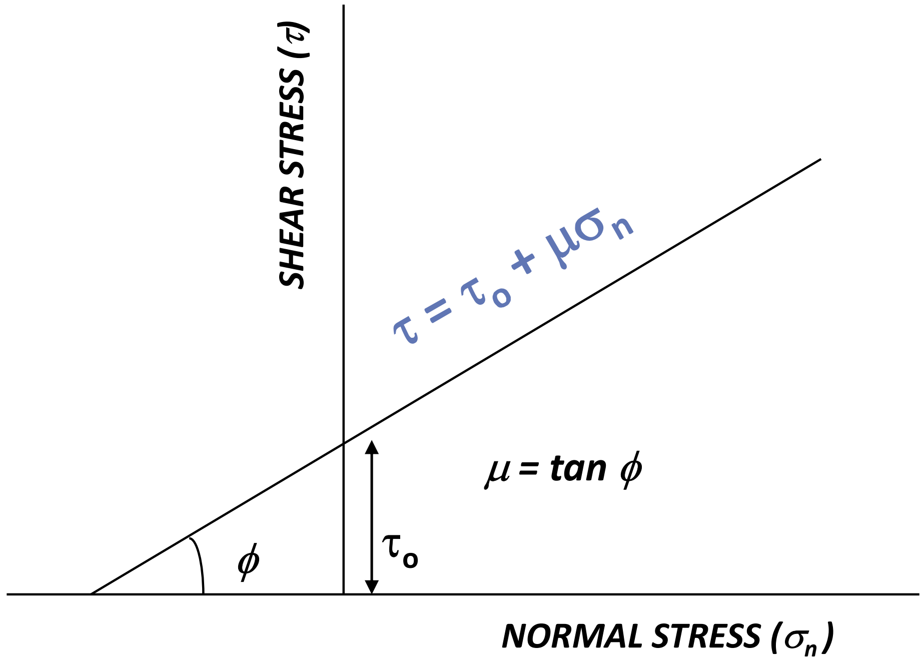
where

τ_o - cohesion

μ - coefficient of friction

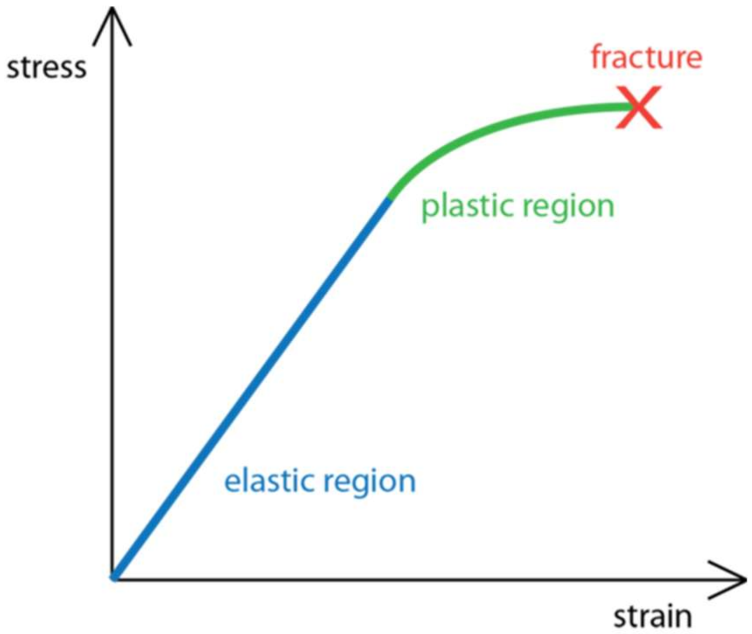
σ_n - normal stress

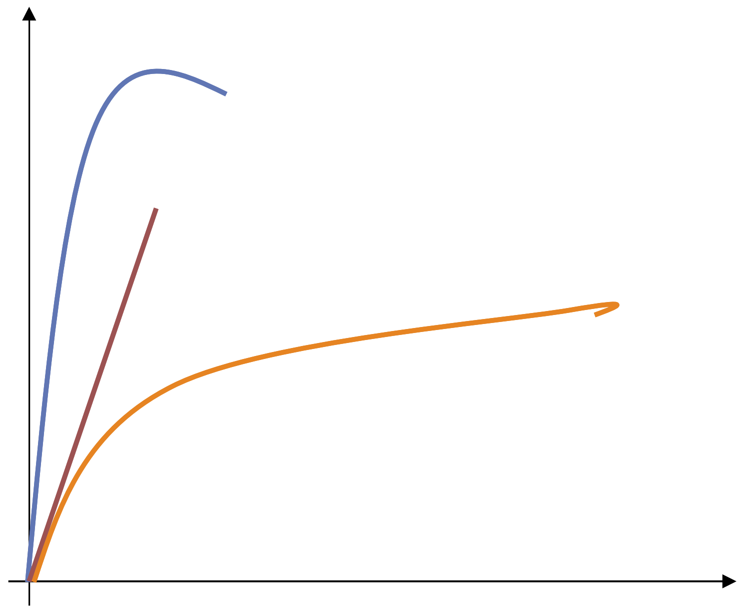
P - pore pressure



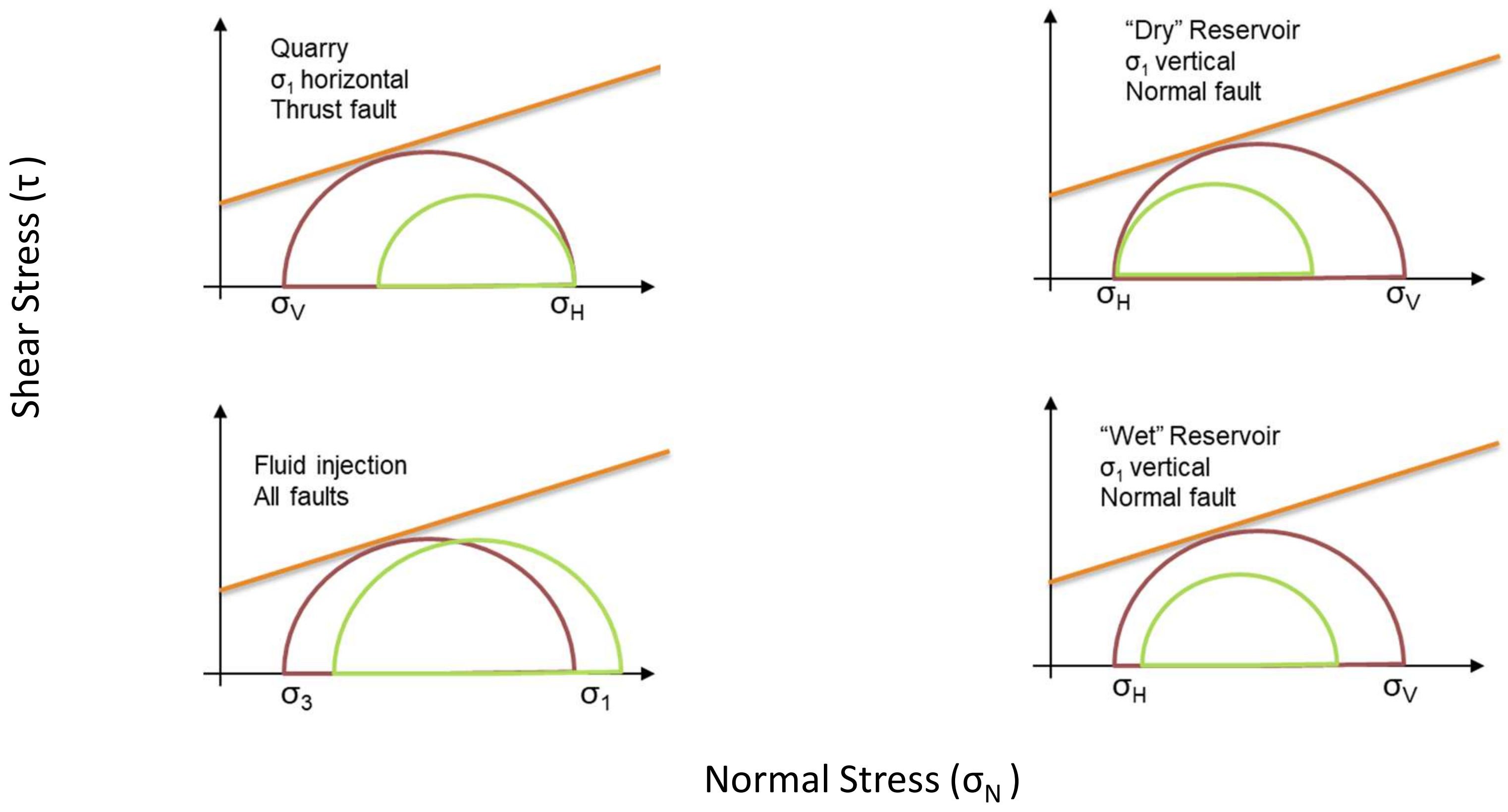
Mohr-Coulomb failure criterion (1776)

Stress-Strain curves



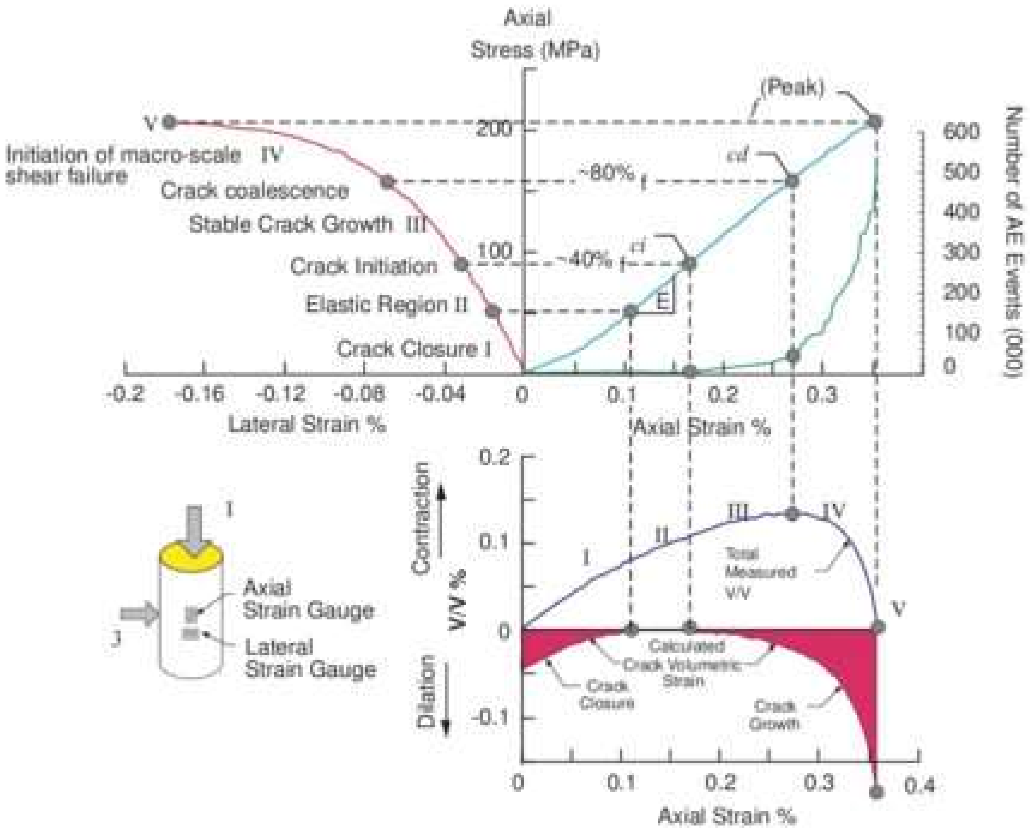


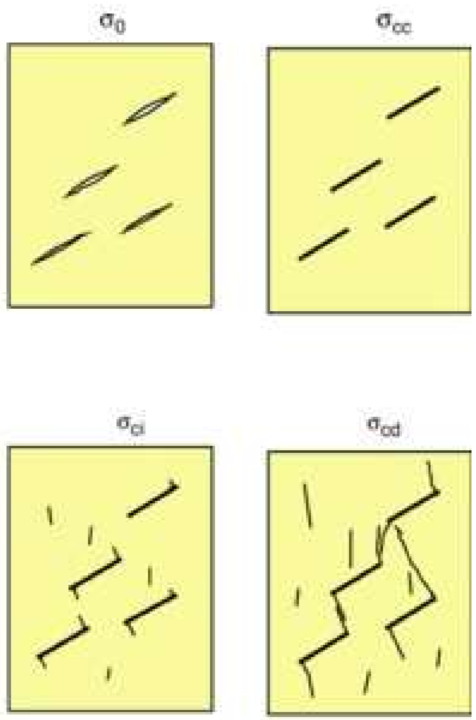
Changing the balance : induced seismicity



After Scholz, 2002

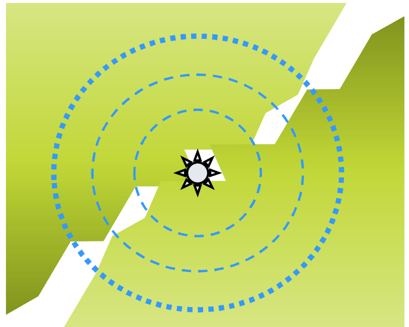
Crack initiation and propagation: Stress-Strain



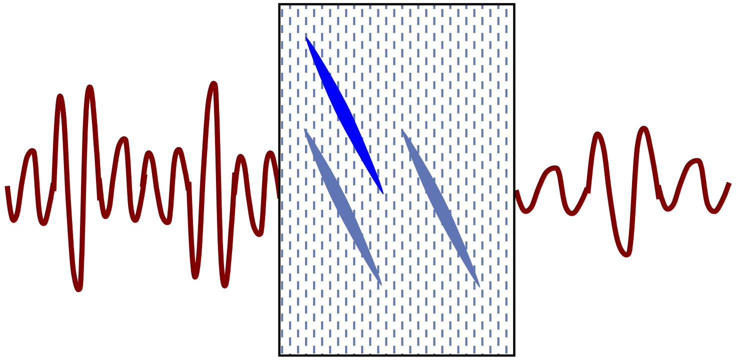


Cai et al., 2004

When a material (e.g. rock) undergoes brittle failure, elastic energy is radiated from the point of failure (or slip) into the surrounding material.



The passage of elastic waves through a material is influenced by the properties (e.g. elastic moduli) of that material.



Active ultrasonic surveys

-Actively examine the rock

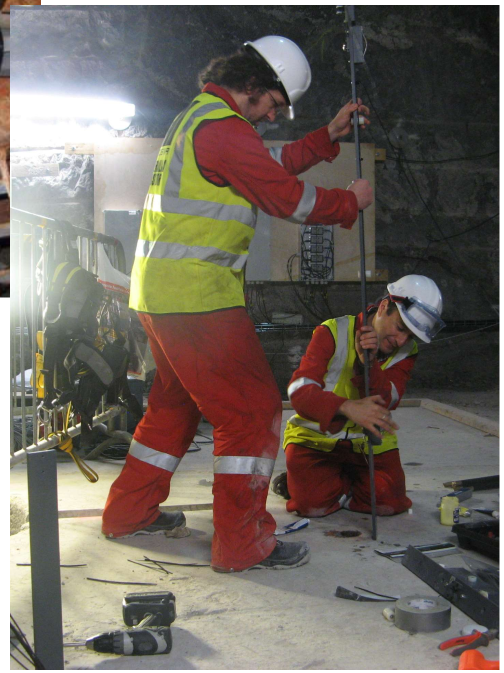
-An array of transmitters sends signals to an array of receivers

-Velocity changes measured between transmitter-receiver pairs using a cross-correlation technique

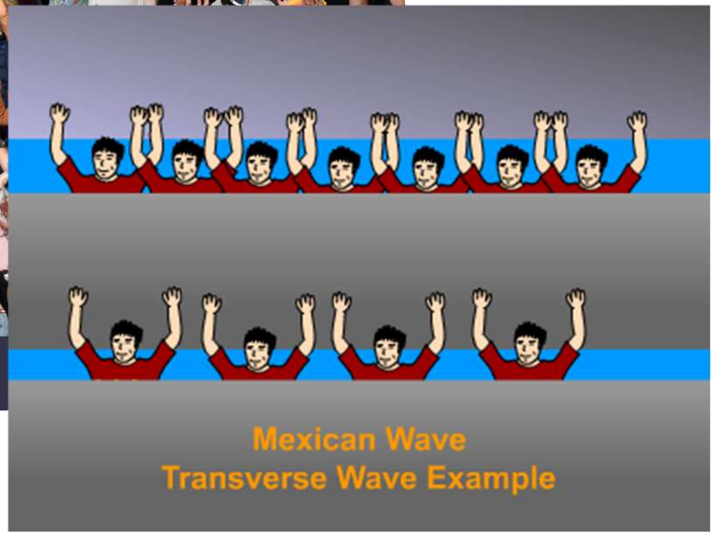
Acoustic Emission/Microseismic monitoring

-Passive technique

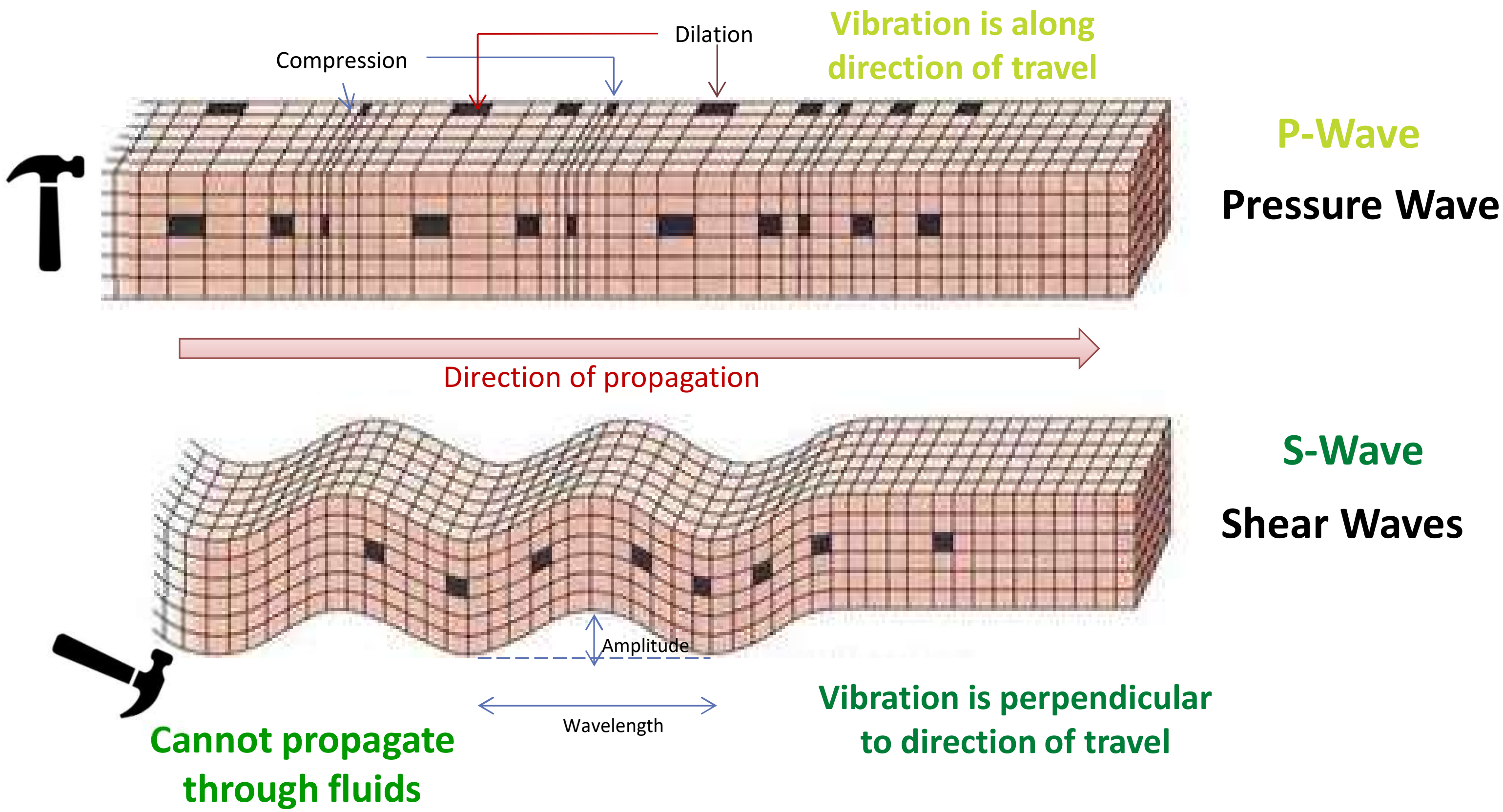
-AE/MS events occur when fractures in the rock are created or when pre-existing fractures propagate.



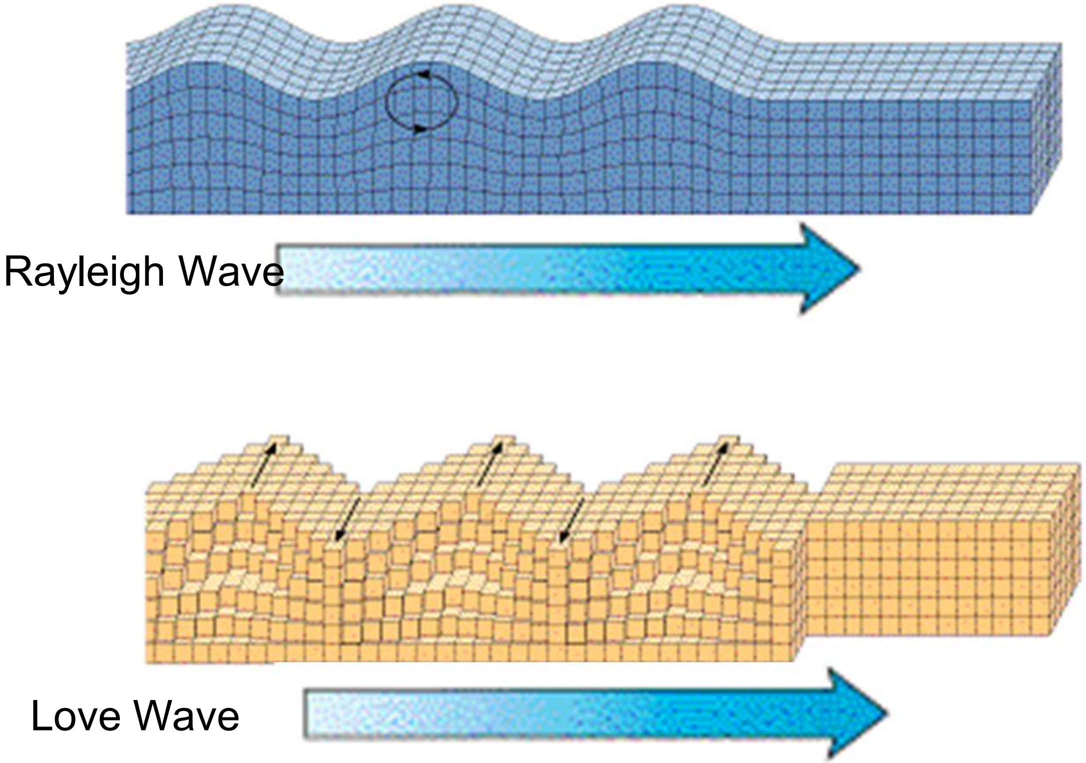
The seismic wave



The Seismic Wave



Surface Waves

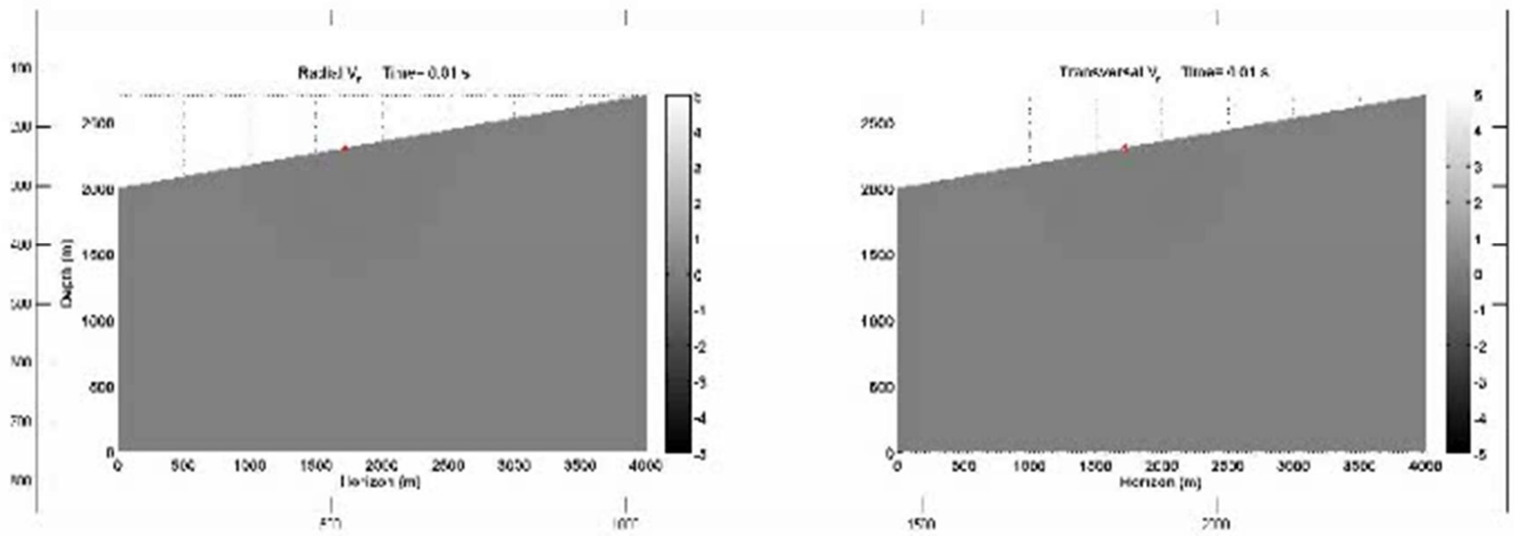


Significant at borehole fluid/solid interface and at free surface of the ground/tunnel wall.

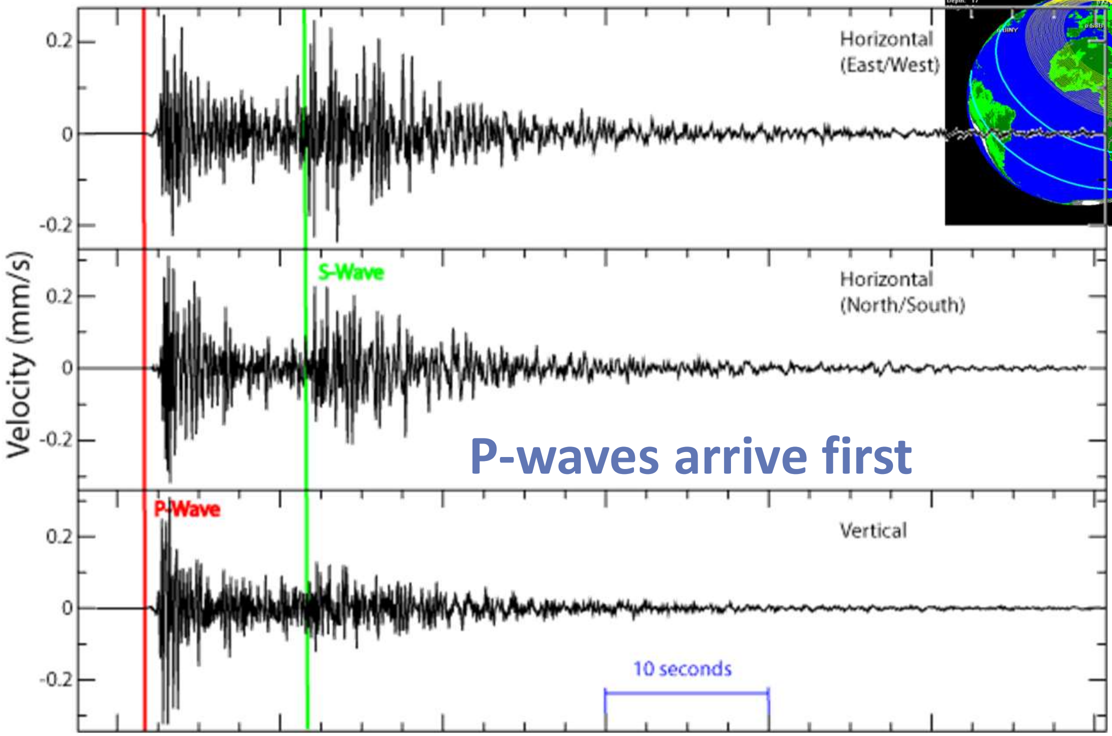
From http://www.geo.utep.edu/kidd/eqwave.html

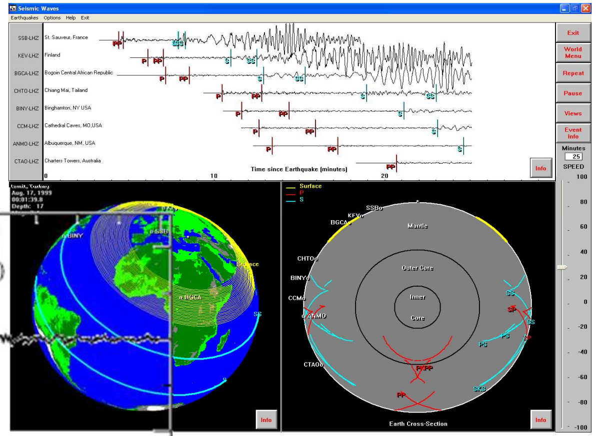
Surface wave at free surface:

1. Ground surface or
2. Tunnel surface



Typical waveform of an earthquake

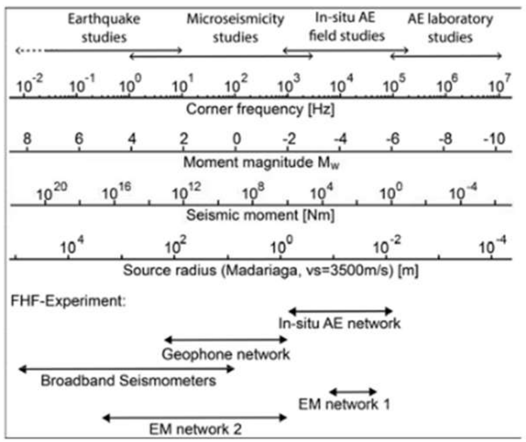


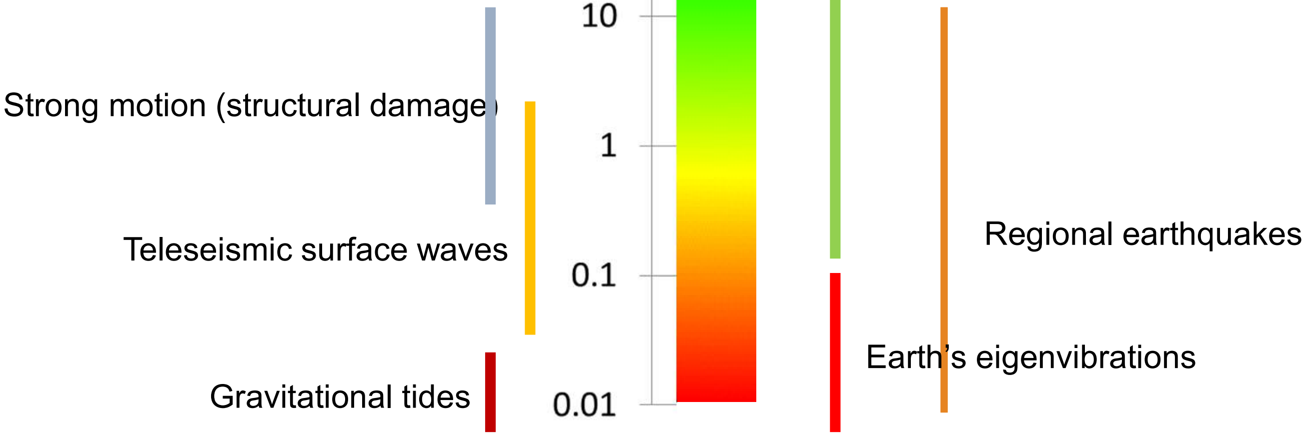


P-waves arrive first

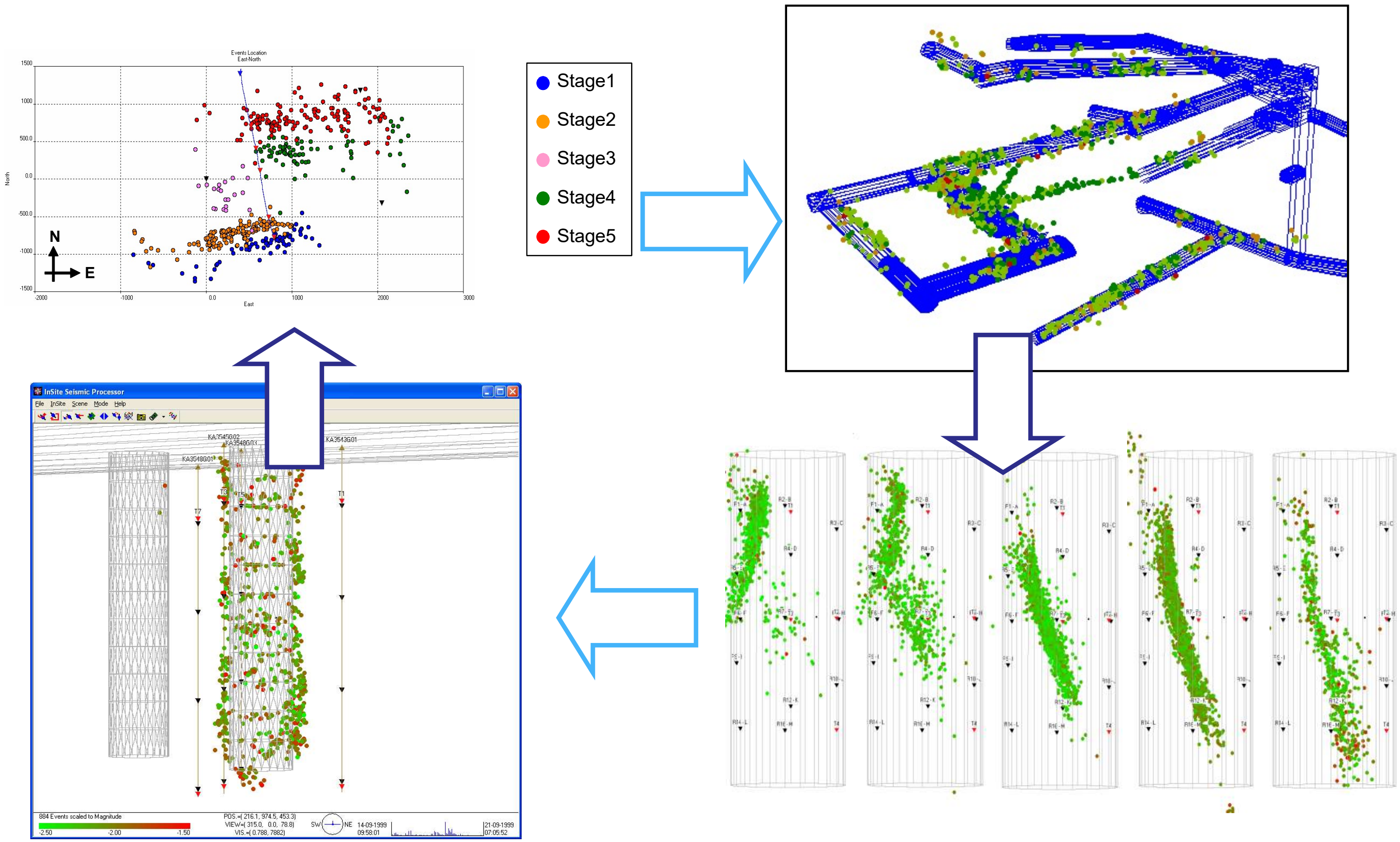
Seismic Frequency Bands of Interest (Hz)

Grzegorz Kwiatek et al. / Procedia Engineering 191 (2017) 618 – 622

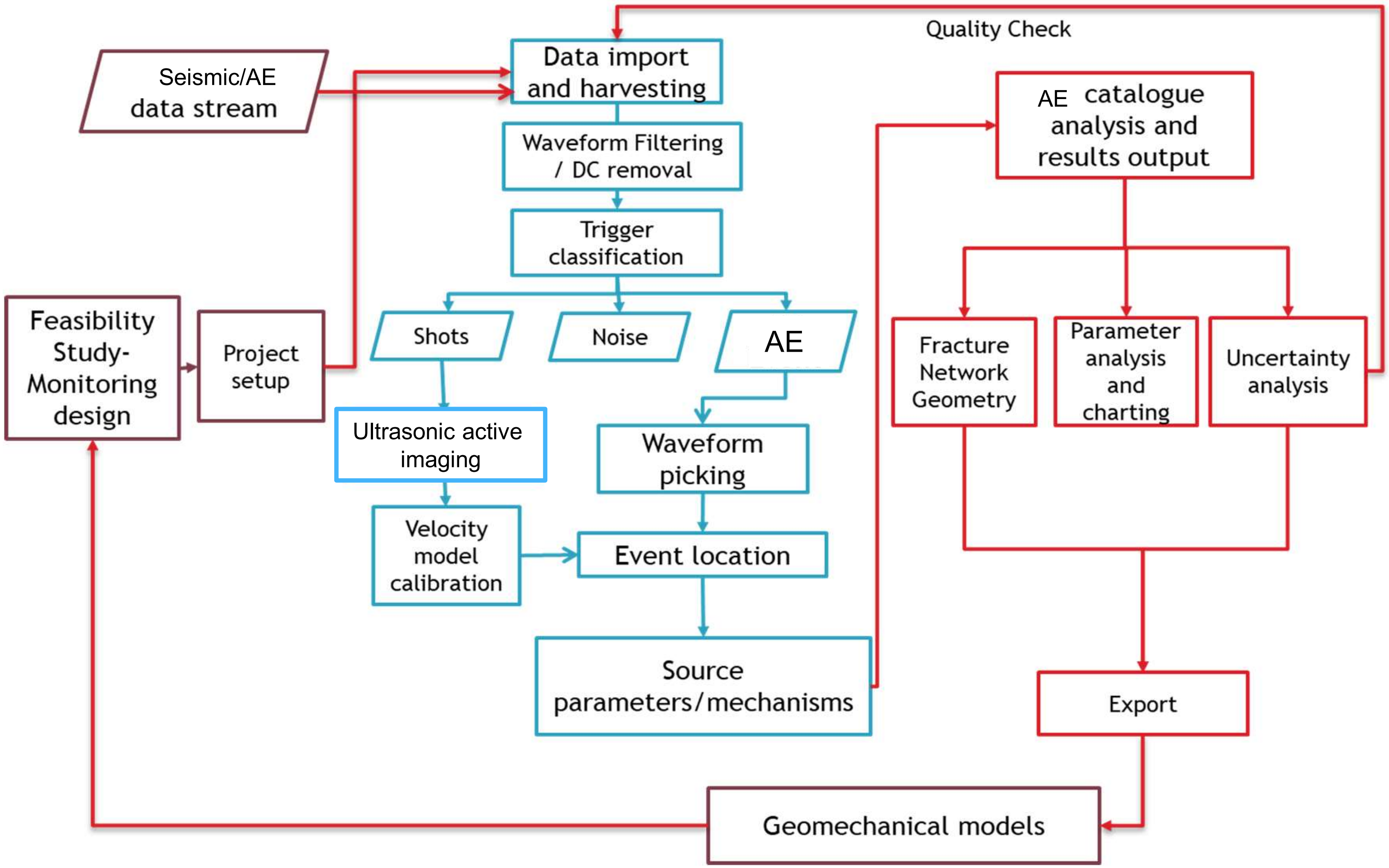




Seismic Scaling



Typical AE/seismic data processing flow



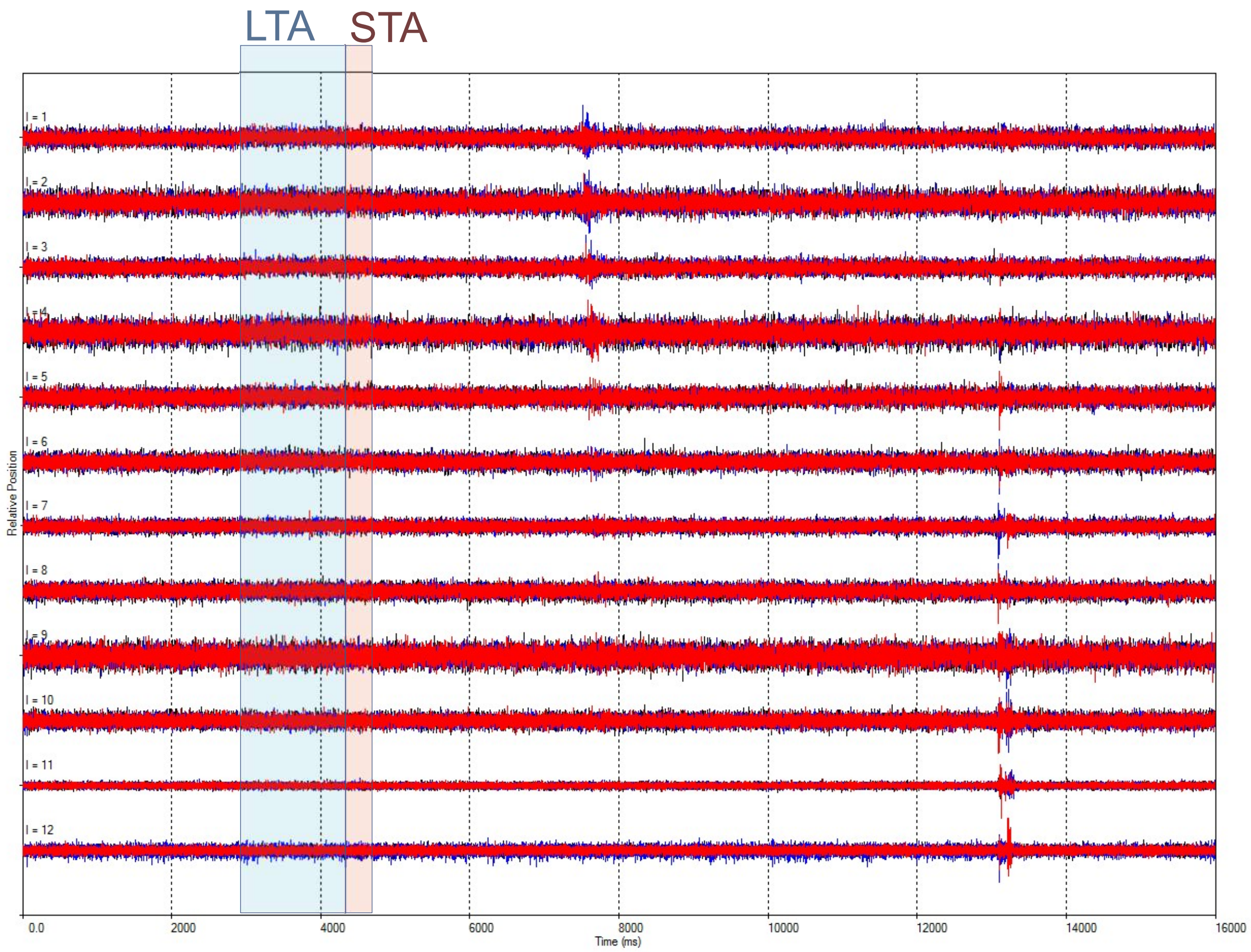
Event Harvesting

First step is the detection of AE arrivals within the recorded data stream

Scan the acoustic stream for triggers (potential events)

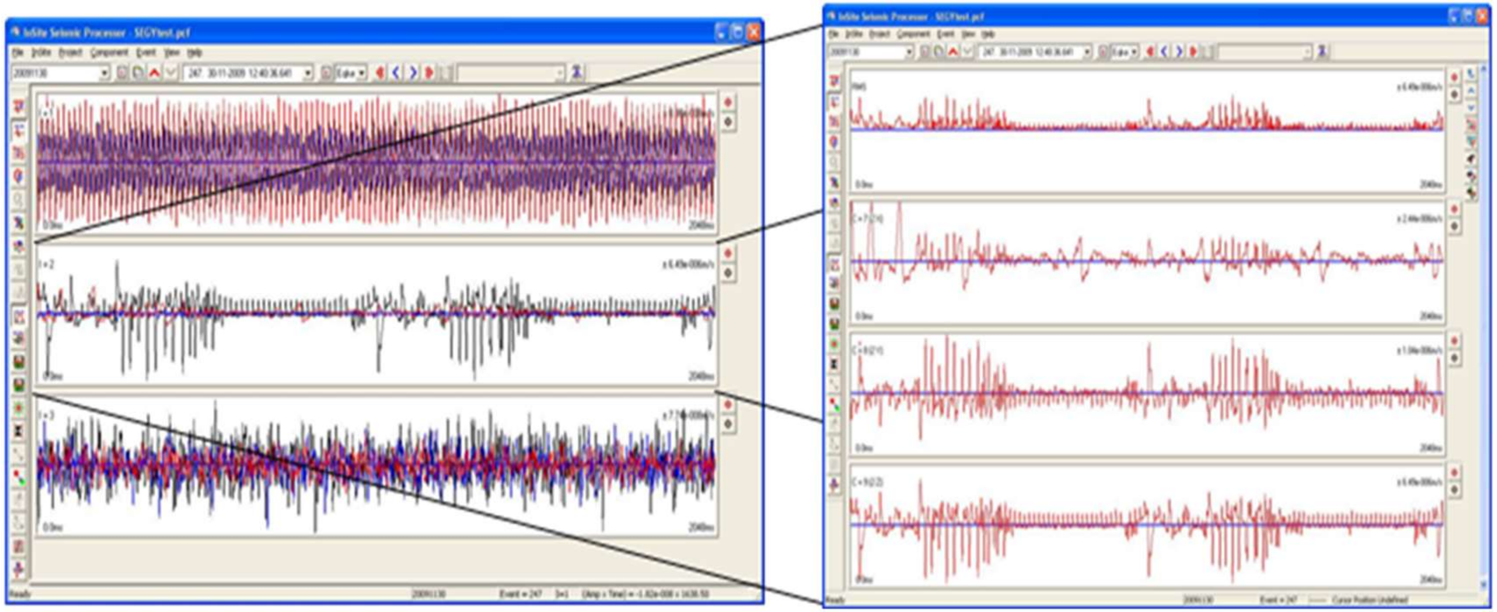
Amplitudes in STA and LTA windows are compared to identify arrivals

Coherence accross the array must also be considered

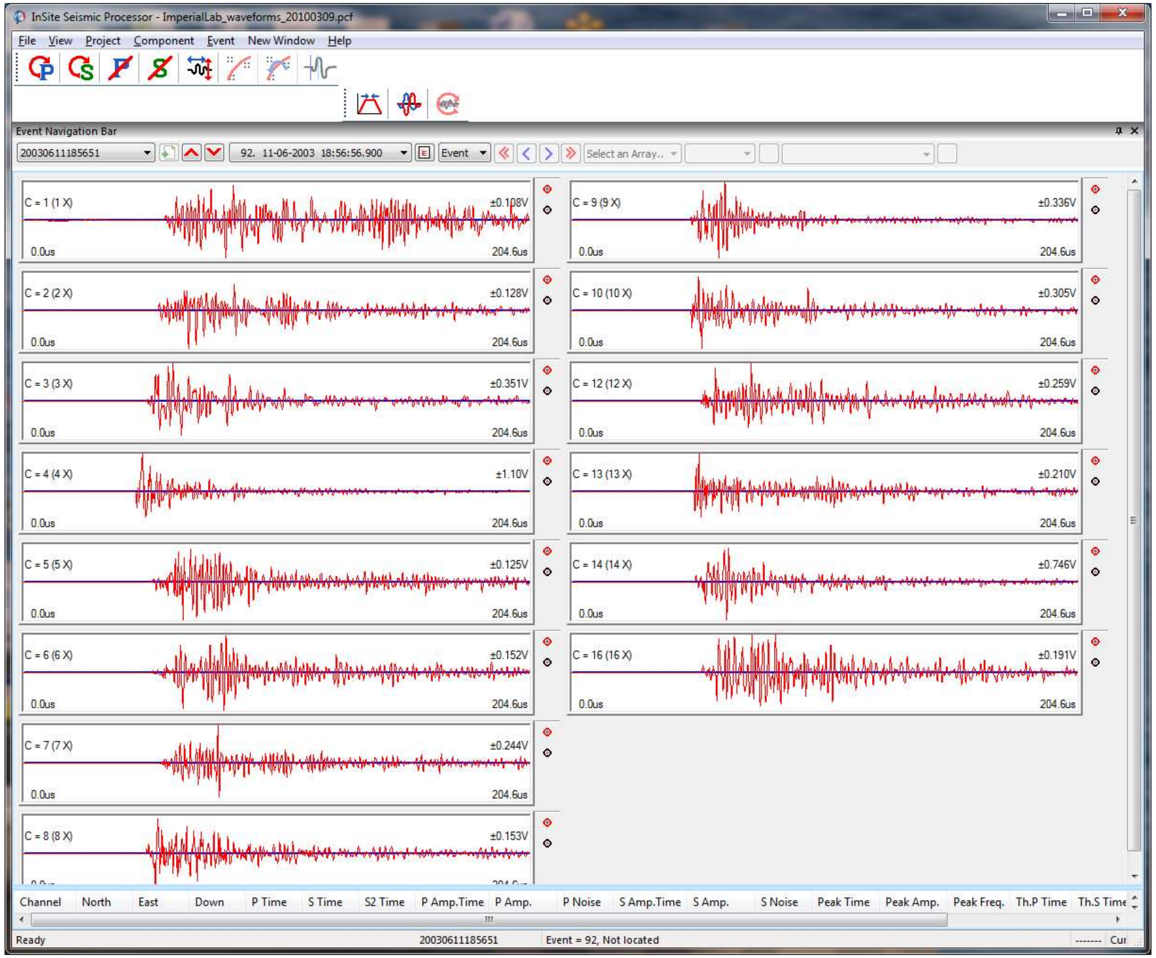


Trigger classification: Noise

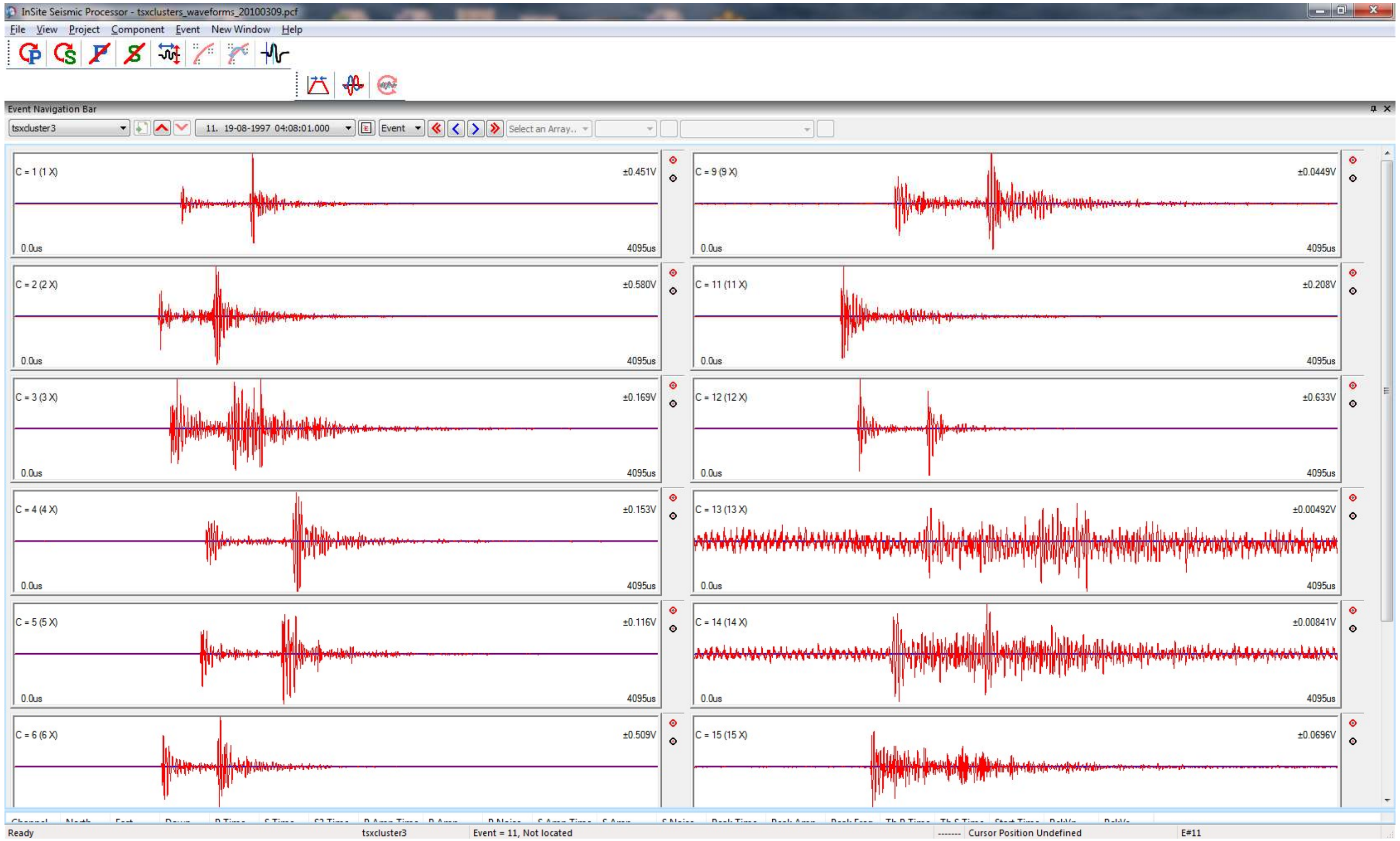
Example electrical noise



Trigger classification: AE event

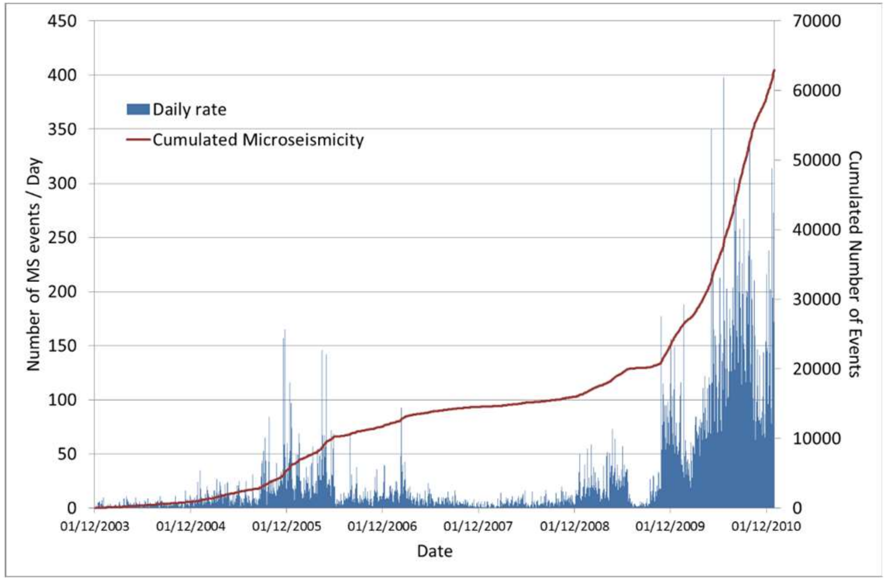


Trigger classification: MS event



Event Rate

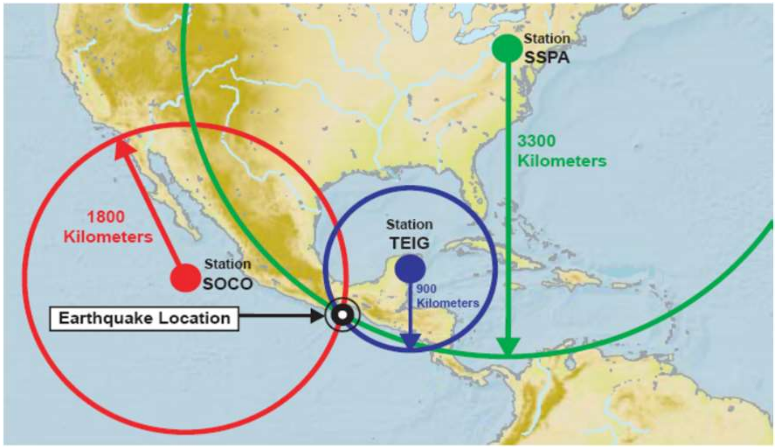
- First order result from seismic monitoring is provided by the MS event rate.
- Activity is closely related to stress changes imposed on the rock.
- Changes in event rate can indicate the development of significant damage or the likelihood of major failure

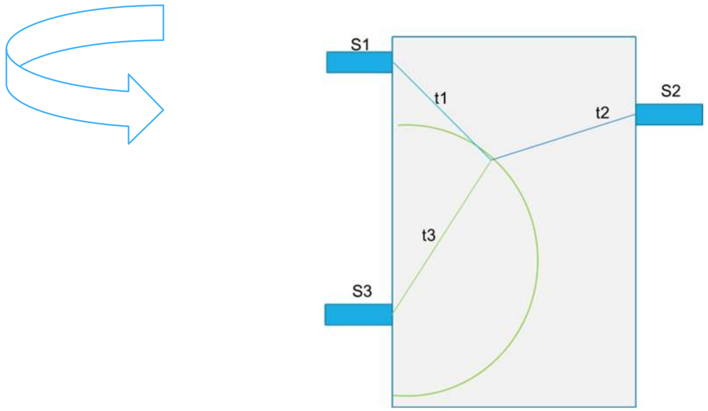


- The interpretation must take into account any external factors affecting the array sensitivity:
  - Changes in monitoring times
  - Array upgrades or loss of instruments.
  - Sources of “noise”

AE event location

- Standard Iterative Methods
  - Simplex
  - Geiger
- Direct Grid Search Methods:
  - Single velocity models
  - Complex velocity models:
    - Raytracing
    - Wavefront construction.
- Other
  - Joint Hypocenter
  - Relative Location
  - Genetic Algorithms, etc



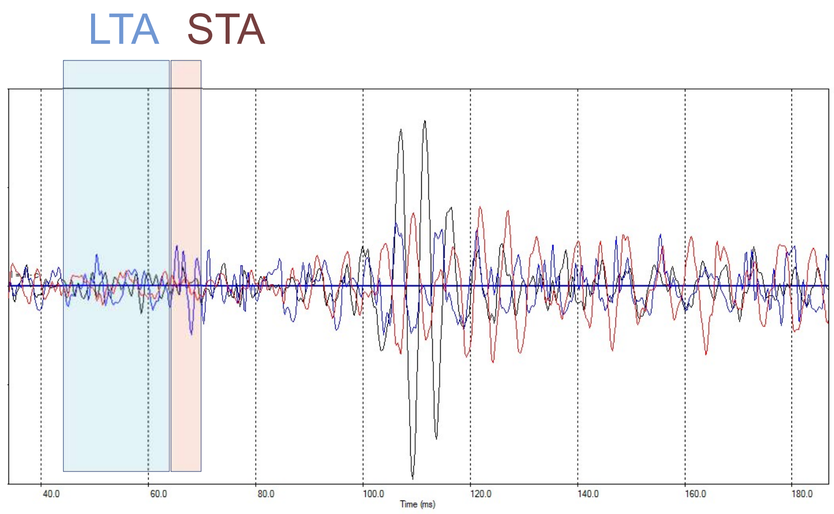


Phase Picking

Similar to Event harvesting, typically double window (STA/LTA) are used to automatically identify phase arrivals.

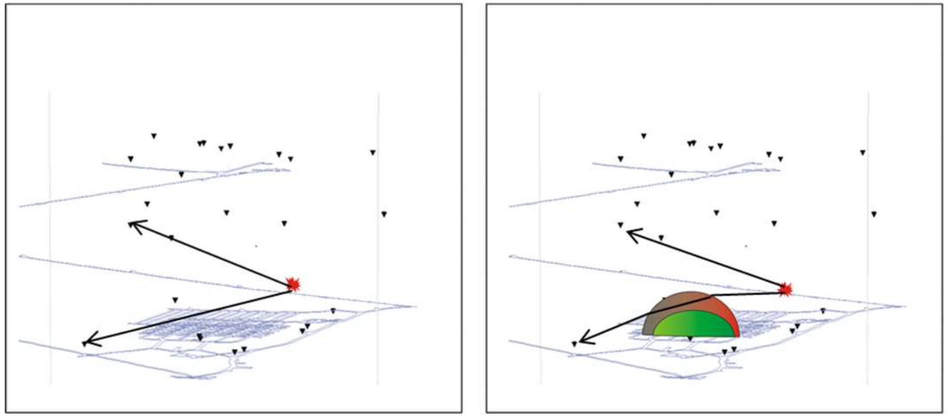
Picking function value and window sizes are determined by the signal-to-noise ratio of the signals.

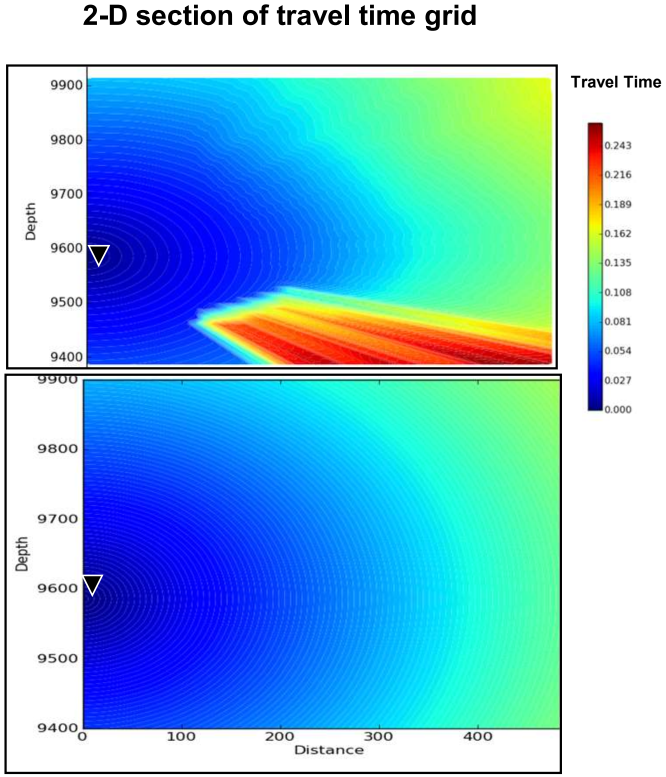
Alternative options include searching for polarisation, or changes in frequency domain.



Picking function = Amp(STA) / Amp(LTA)

Microseismic event location





Event location is based on finding the position in space that minimises the residual

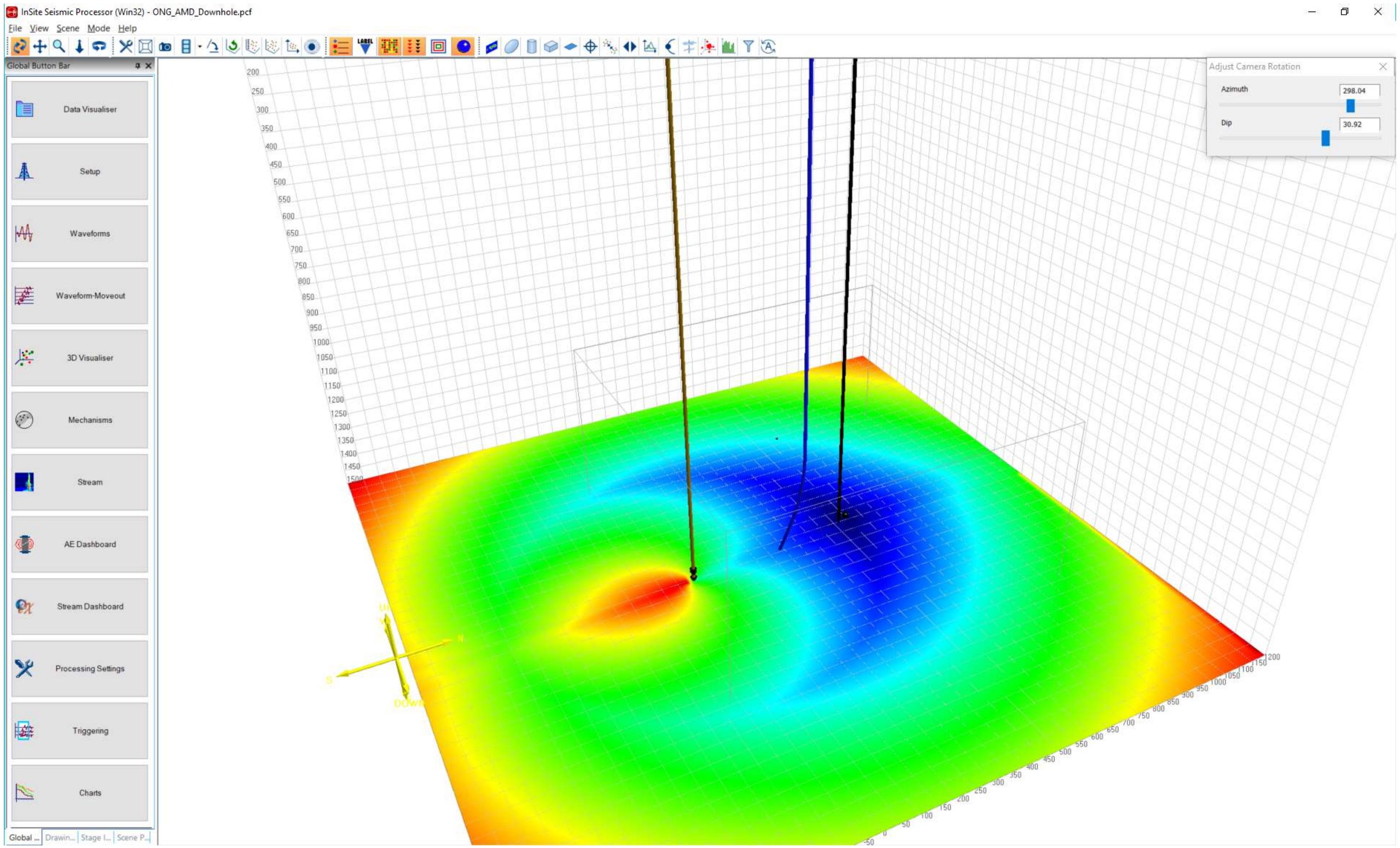
$$r_i = t_i - t_0 - T_i(x_0, y_0, z_0)$$

where t_i=measured arrival time; T_i= theoretical arrival time

Different search algorithms are used in the inversion process, i.e. the finding of the optimal solution for all sensors.

Depending on the complexity of the velocity model and the array geometry, solutions might not be unique. This requires further inputs (e.g. source vector, fracture information..)

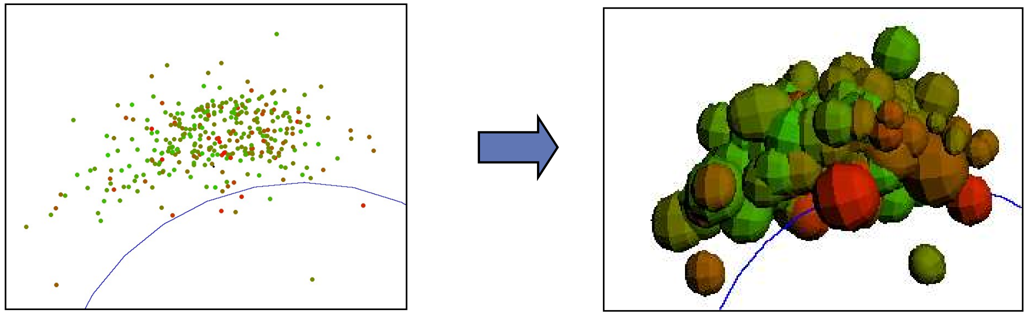
Residual Space



Location Uncertainty

A number of factors affect the quality of the location results:

- Uncertainty in the positions of sensors.
- Knowledge of velocity structure.
- Picking errors on waveforms.
- Method and norm applied for the solution.
- Spatial coverage of sensor array.
- Perturbation to raypaths by voids or damaged material.

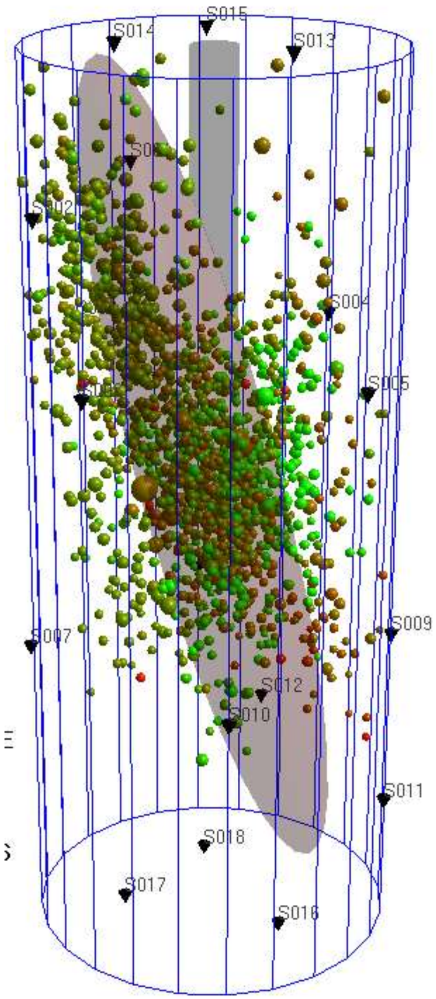


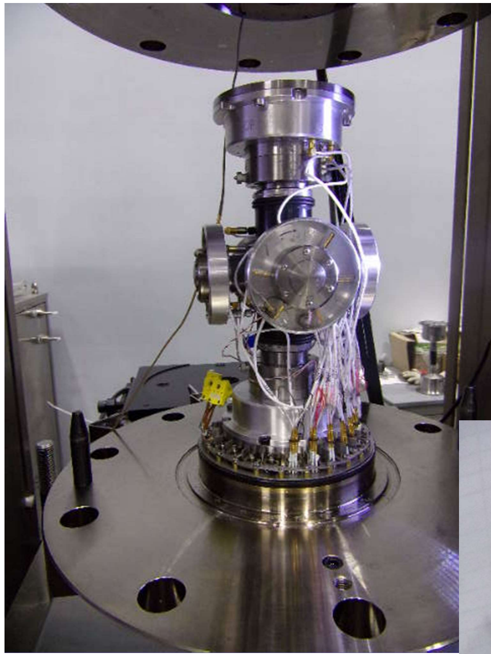
Distribution of Events

ASC

Main source of information of the fracturing process is provided by the number and location of AE events.

Analysis of spatial and temporal distributions of AE activity during different stages allows the detection of different fracturing behaviour and responses to stress changes.





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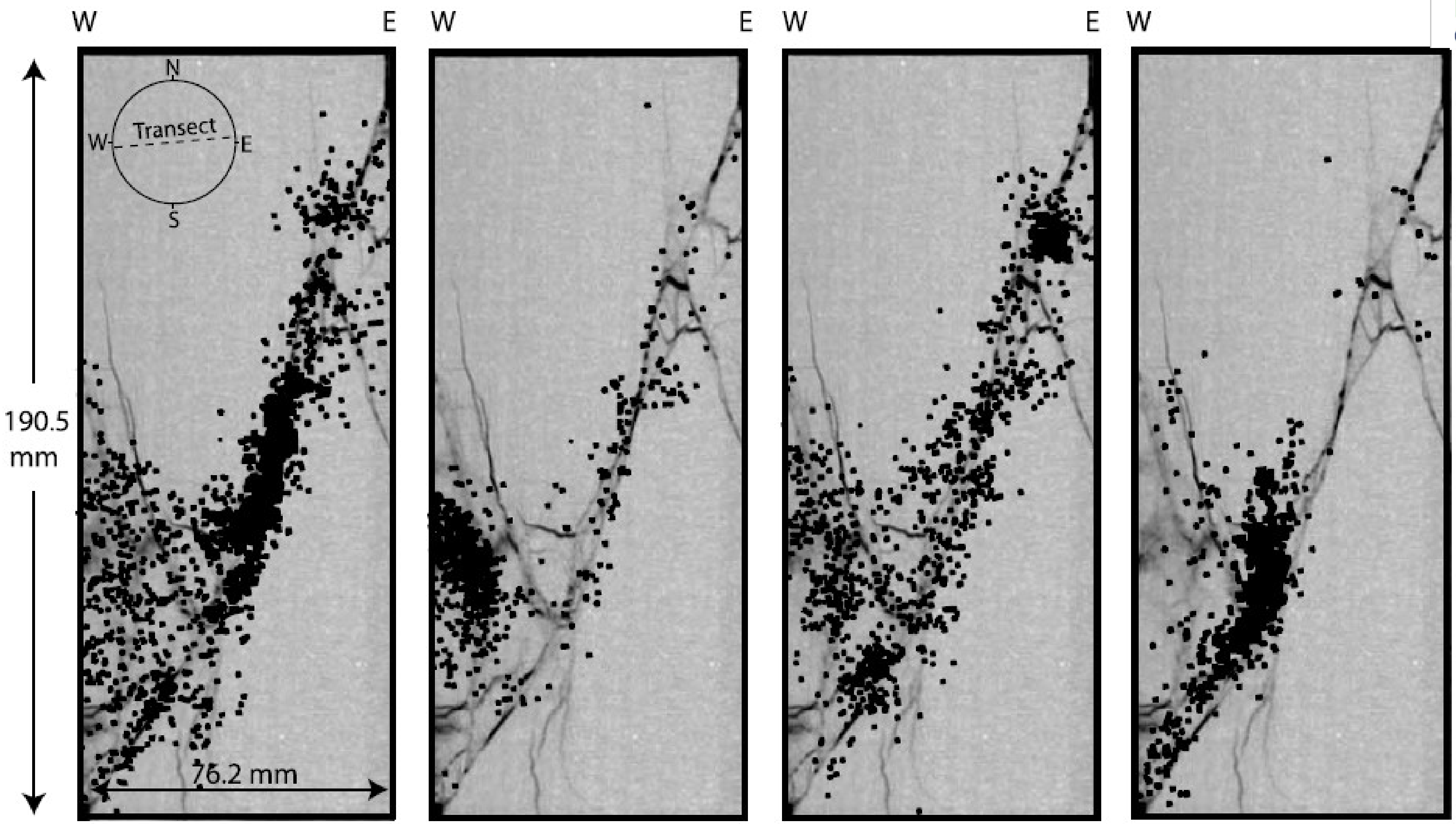
Lab-scale seismicity: Understanding Earthquake Cycles



A: Cycle 1 B: Cycle 2 (0 - 450 MPa) C: Cycle 2 (465-476 MPa) D: Aftershocks

Thompson, BD Young, RP and Locker, DA, (2009). JGR, Vol;.114, B02205.

Lab-scale seismicity: Understanding Volcanic Seismicity

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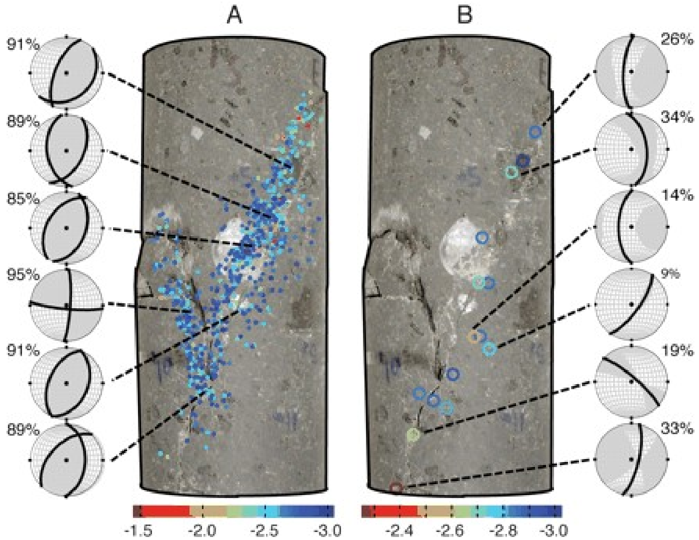
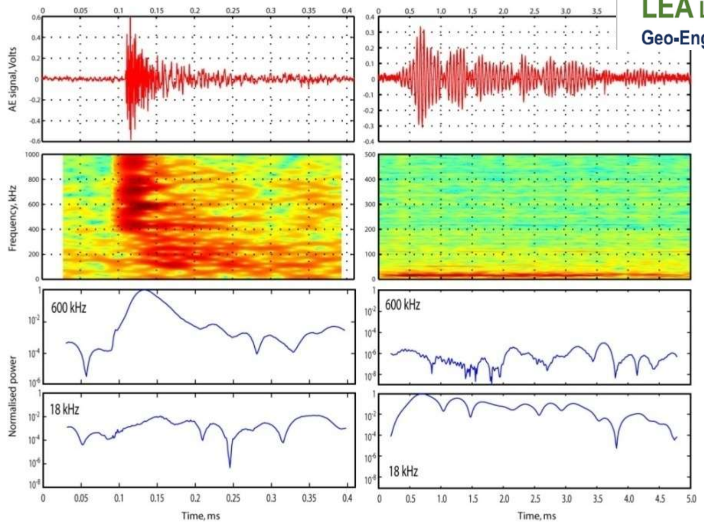
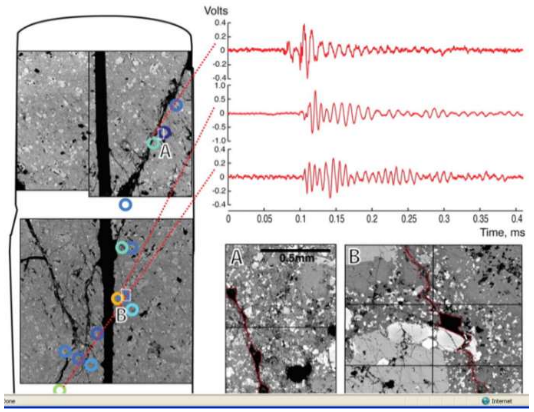
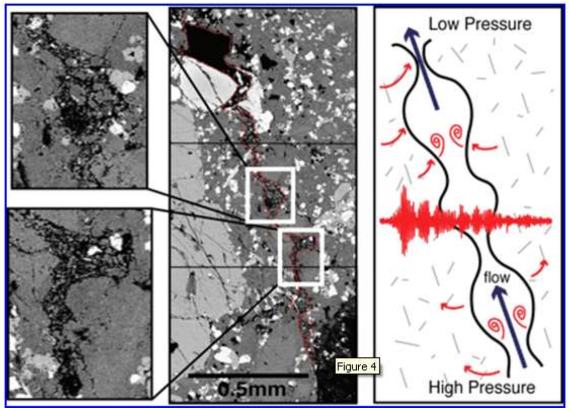
Geo-Engineering Instrumentation Systems



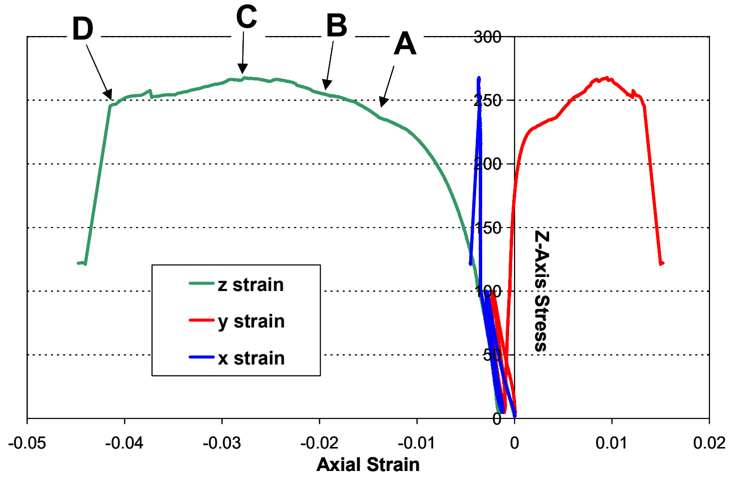


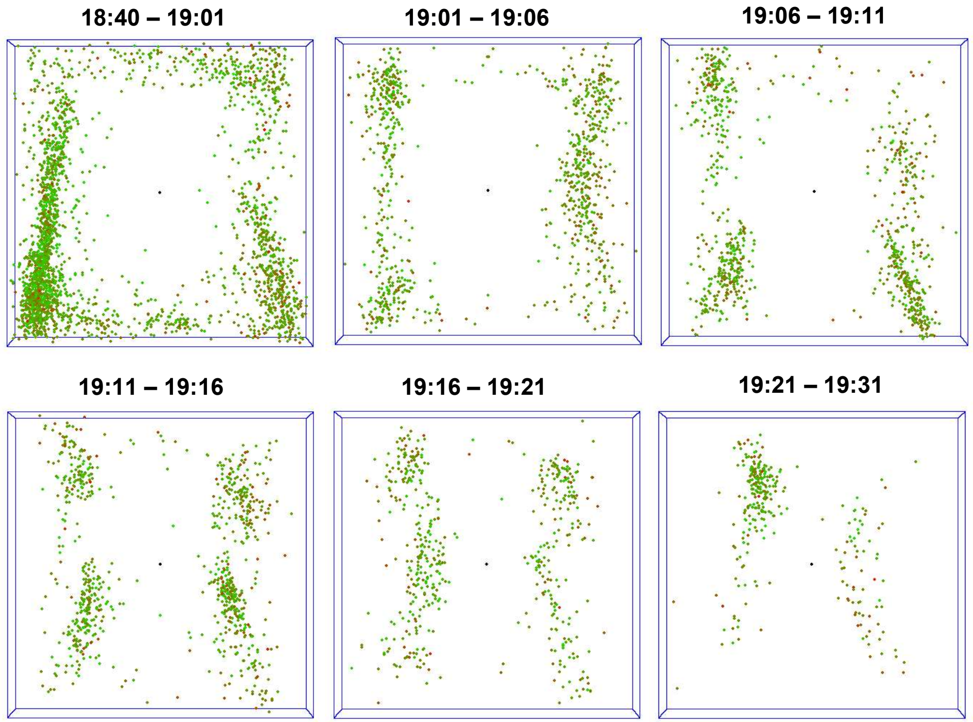




Benson PM, Viciguerra S, Meredith PG and Young RP (2008), Laboratory Simulation of Volcano Seismicity, Science, Vol 322, 249-252.

An brittle failure example





A	19:01
B	19:11
C	19:21
D	19:28

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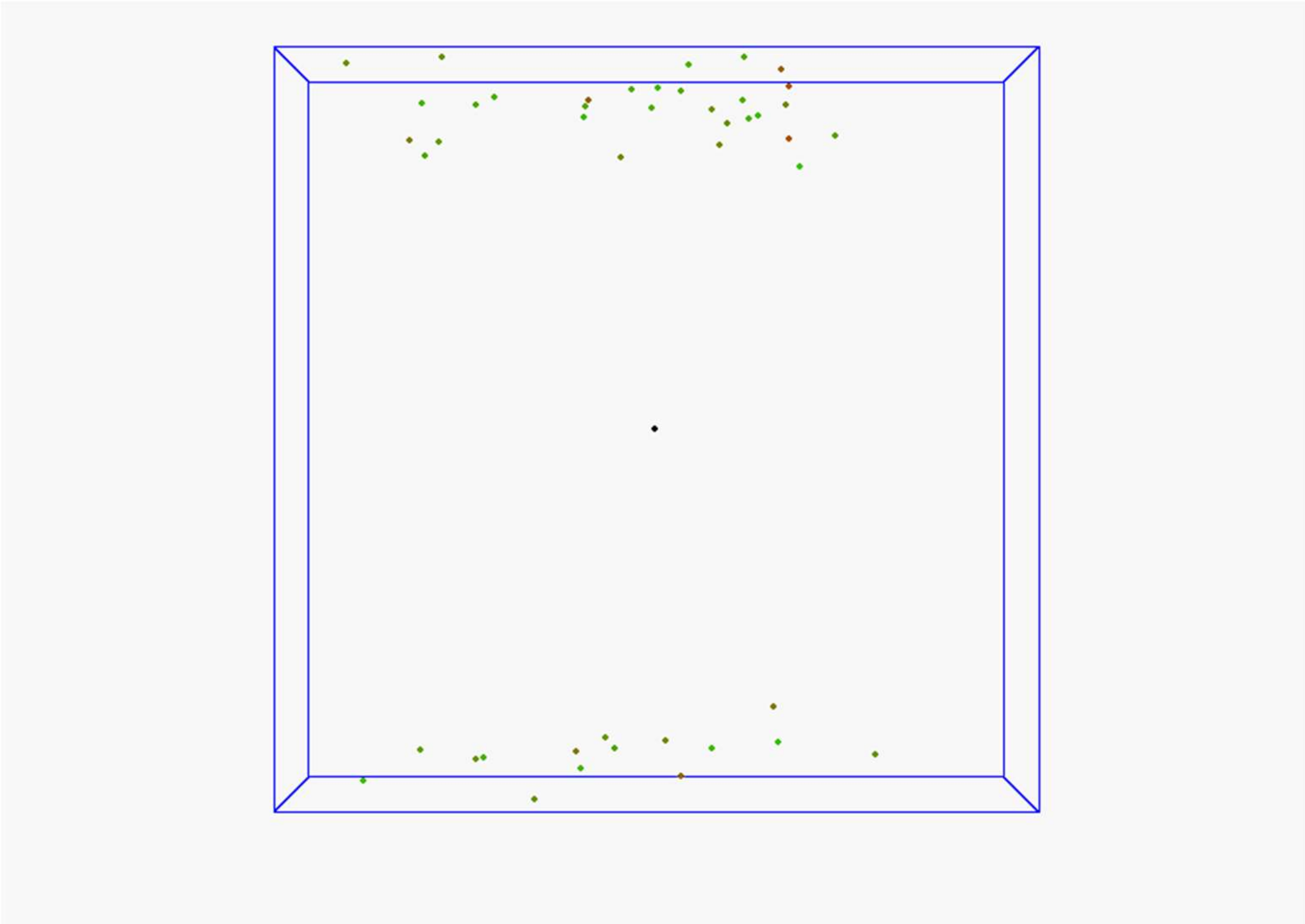
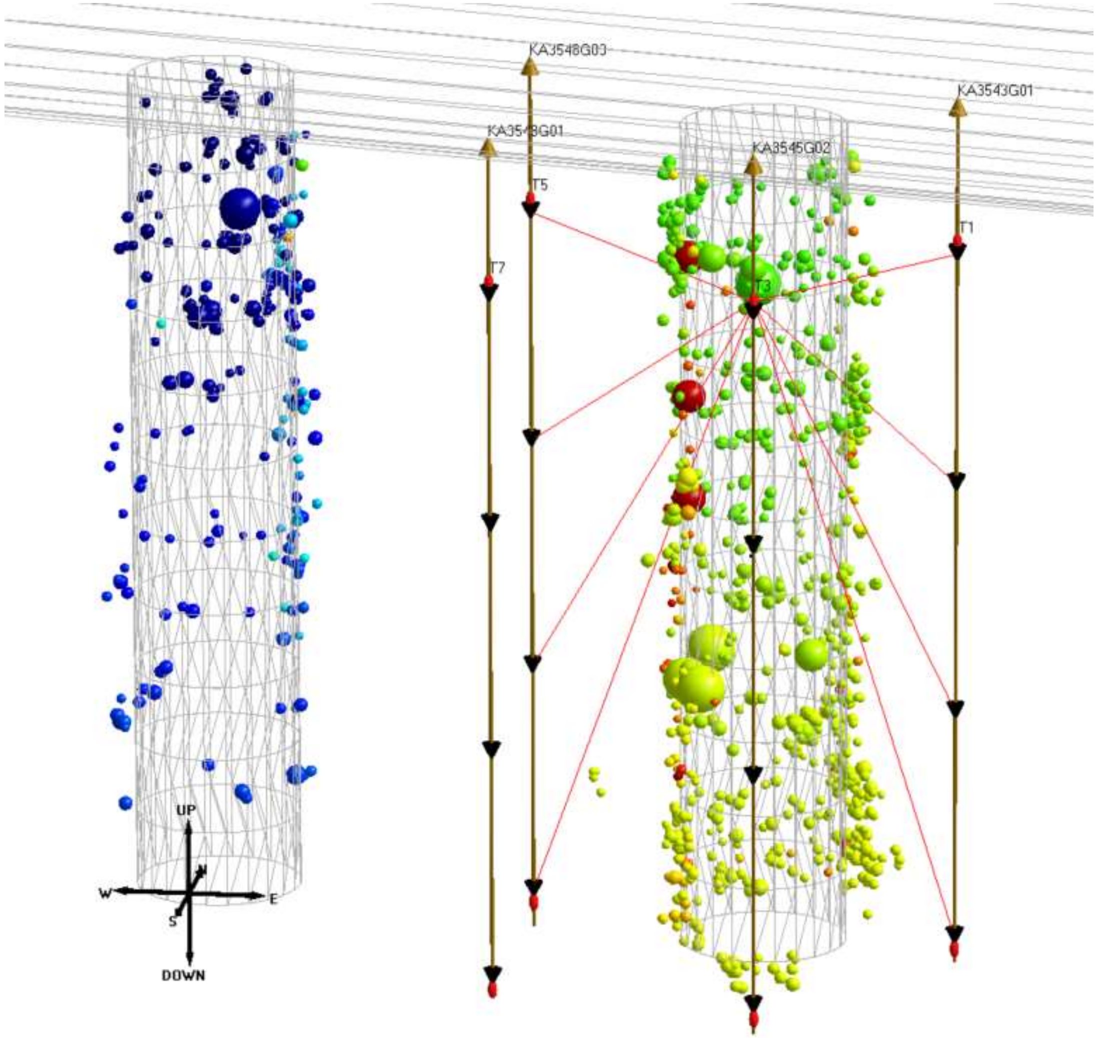
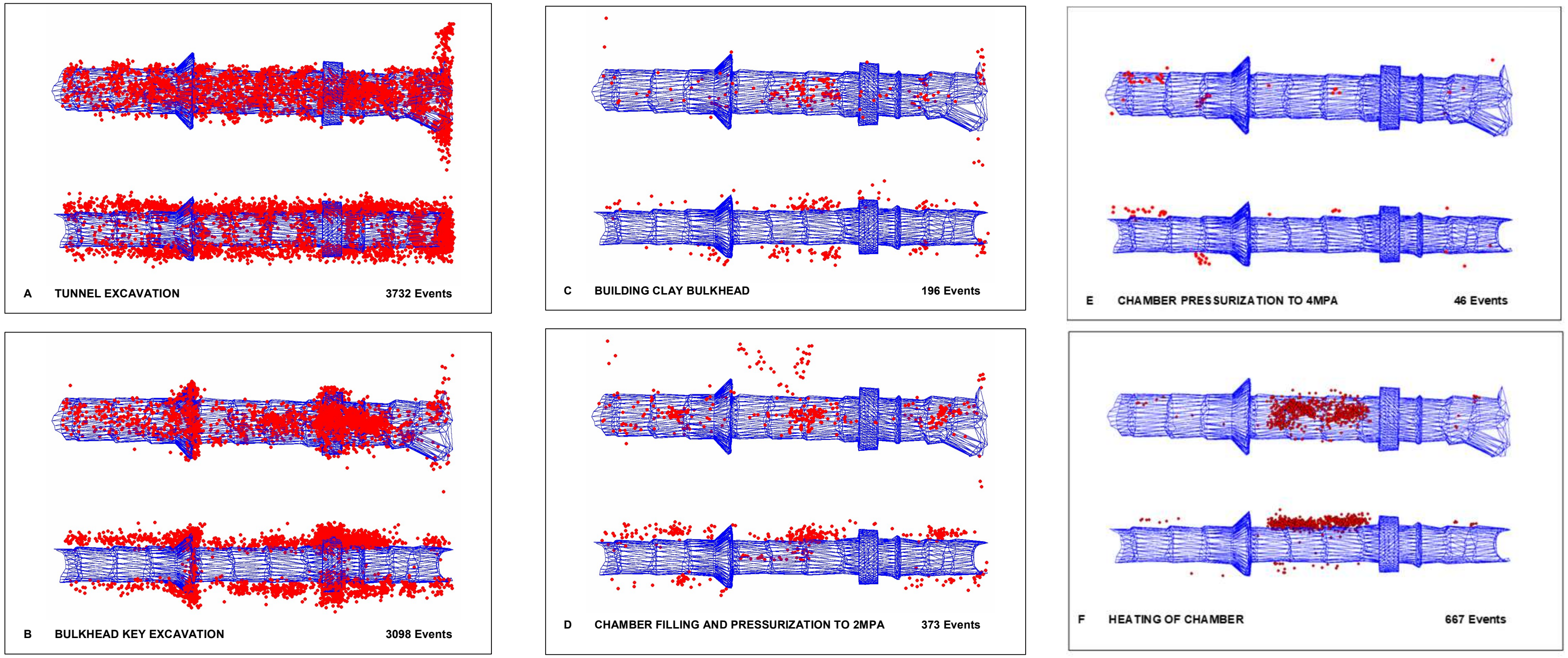
An brittle failure example

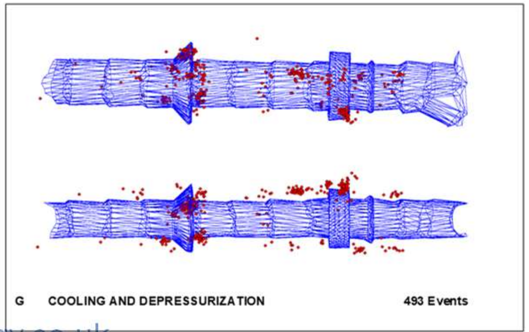


Integrating timing and location: SKB example



MS Monitoring of EDZ Evolution: TSX Case

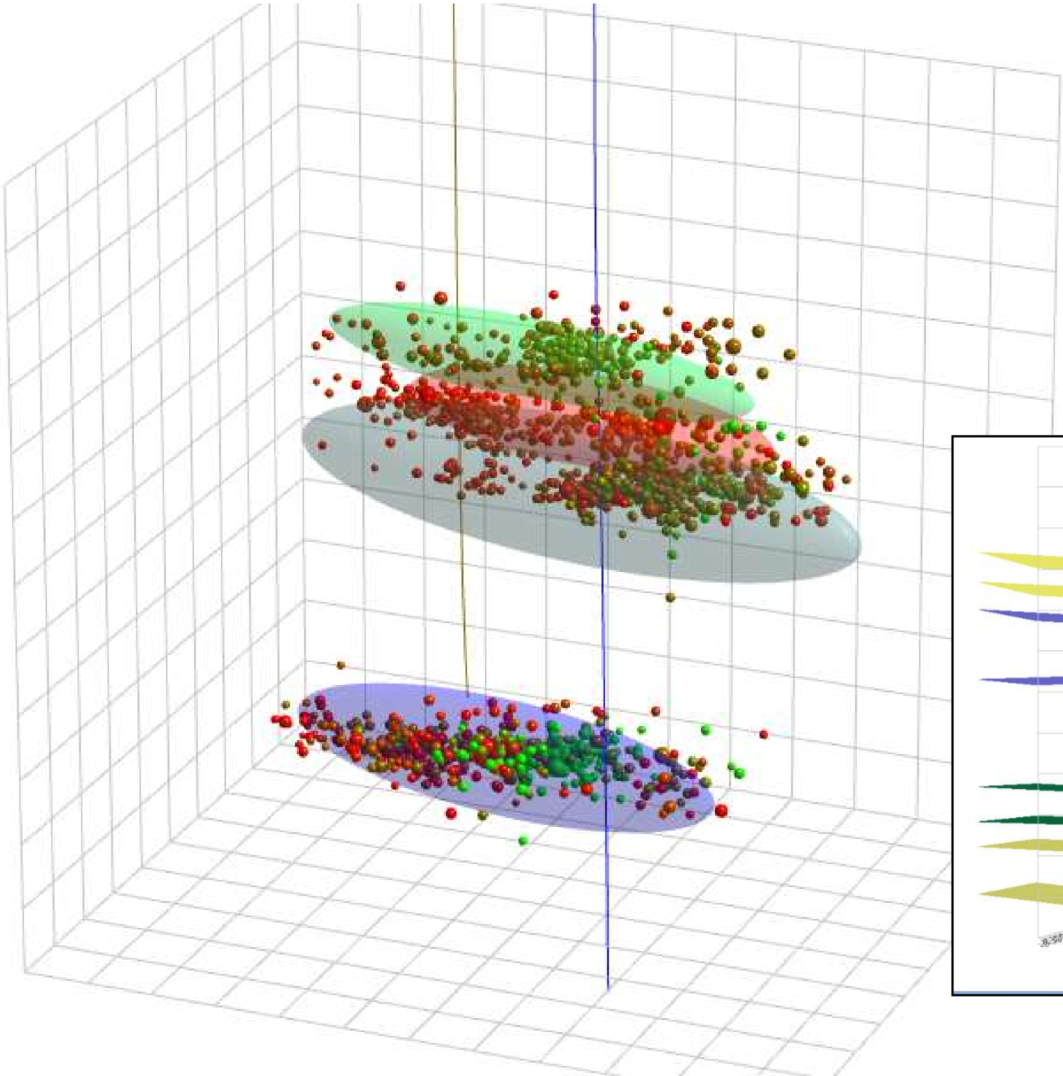


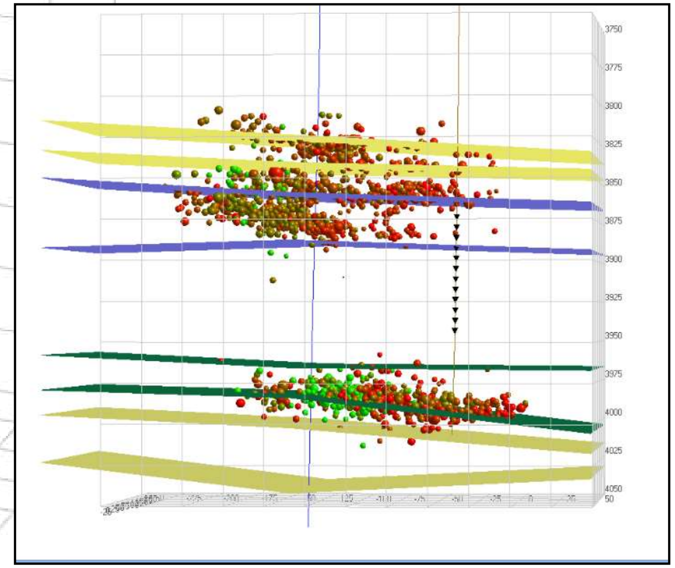


- Repository-wide lower-frequency geophone network can be used to monitor microseismicity during and post-excavation of the facility in order to get a full image of the EDZ and the stability of the facility against stress changes imposed by thermal loads and pressurization

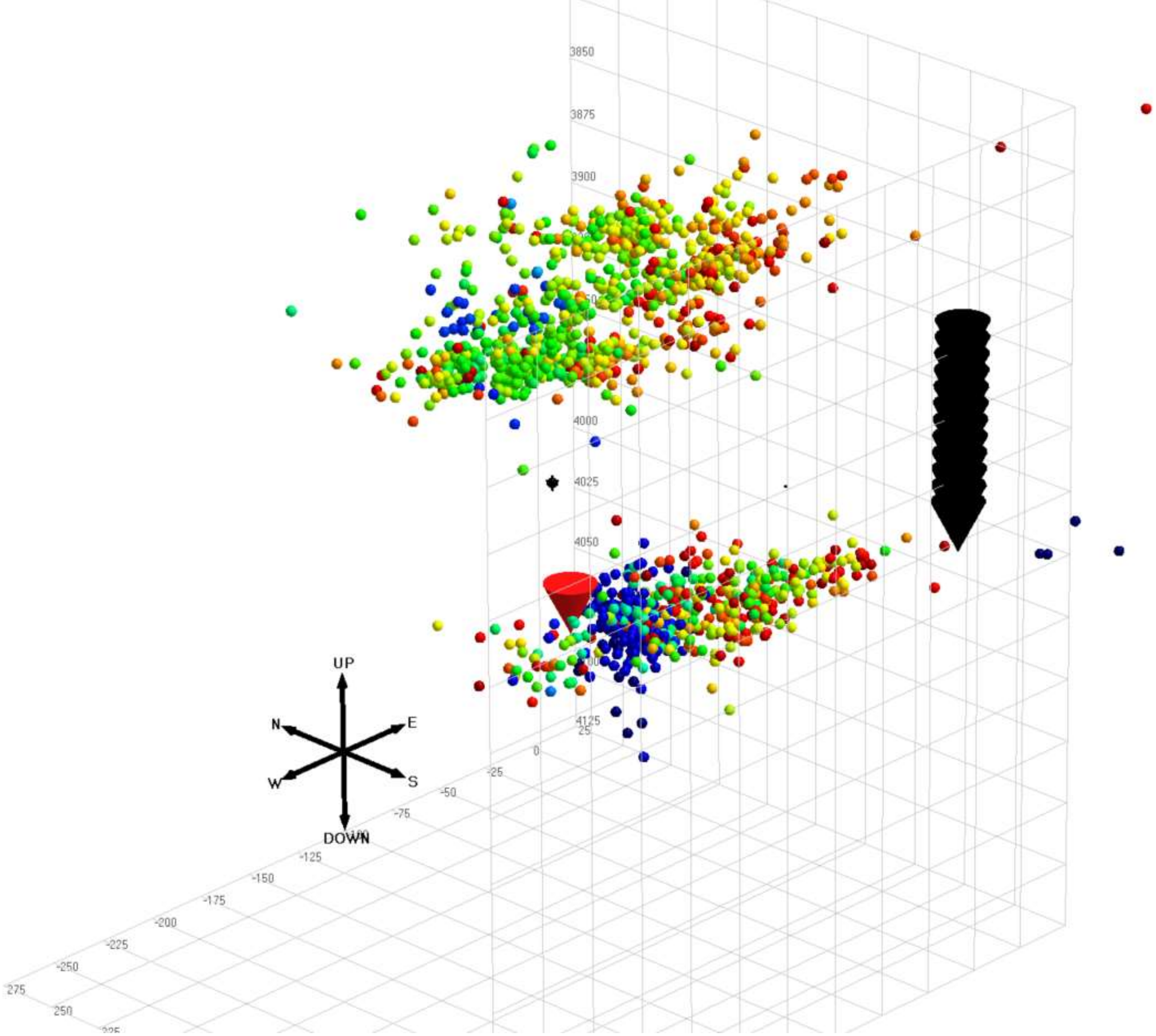
Distribution of Microseismicity

Analysis of spatial and temporal distributions of induced seismic activity during different stages allows the detection of different fracturing behaviour and responses t stress changes.



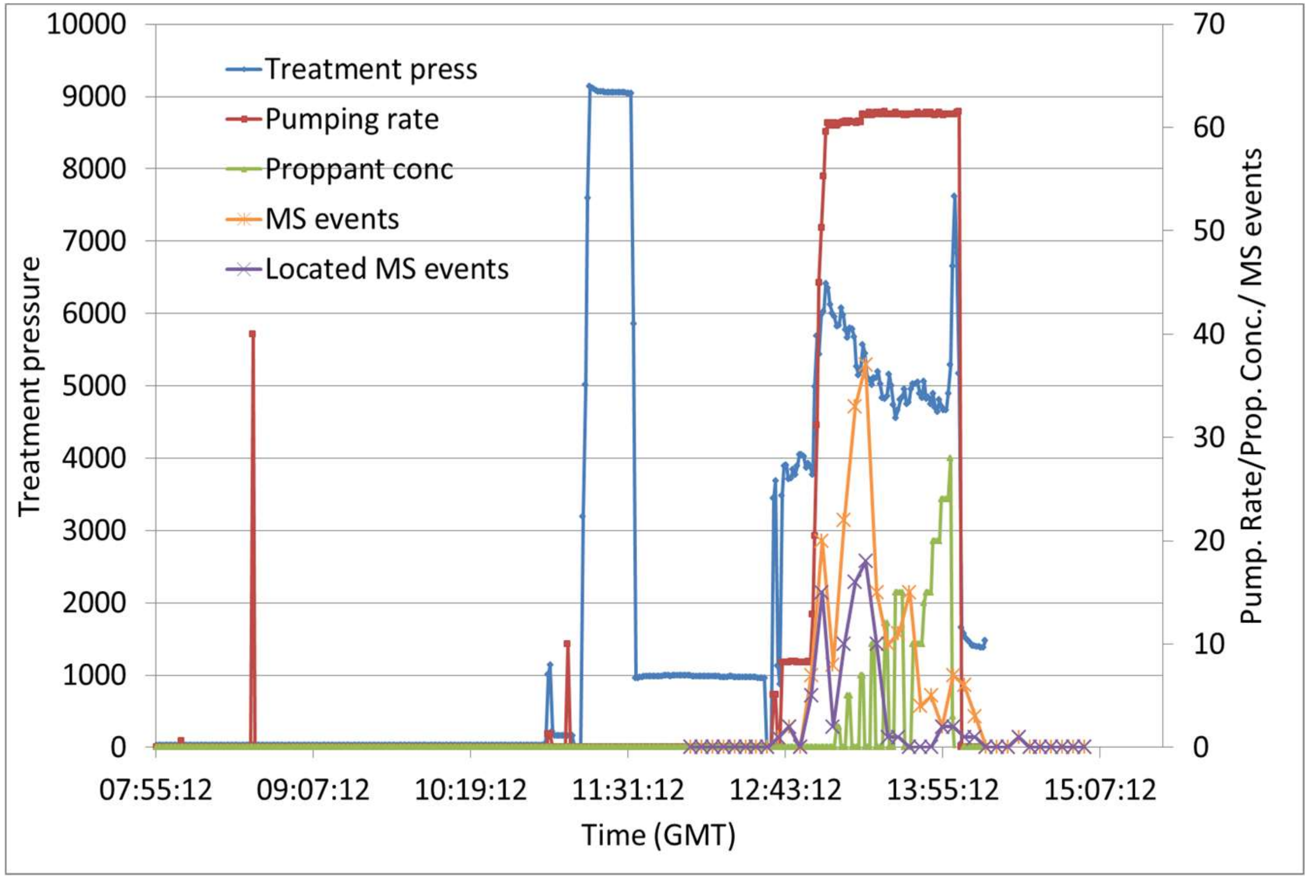


Fractures imaged by gaps in seismicity: Downhole example



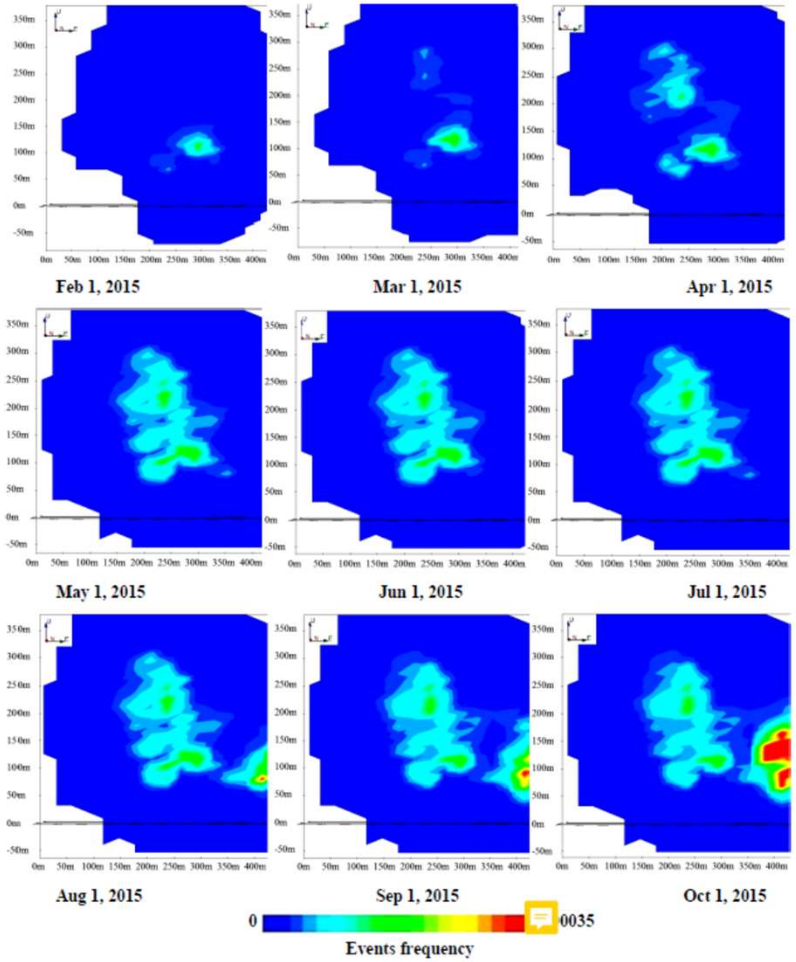
Correlation with engineering data

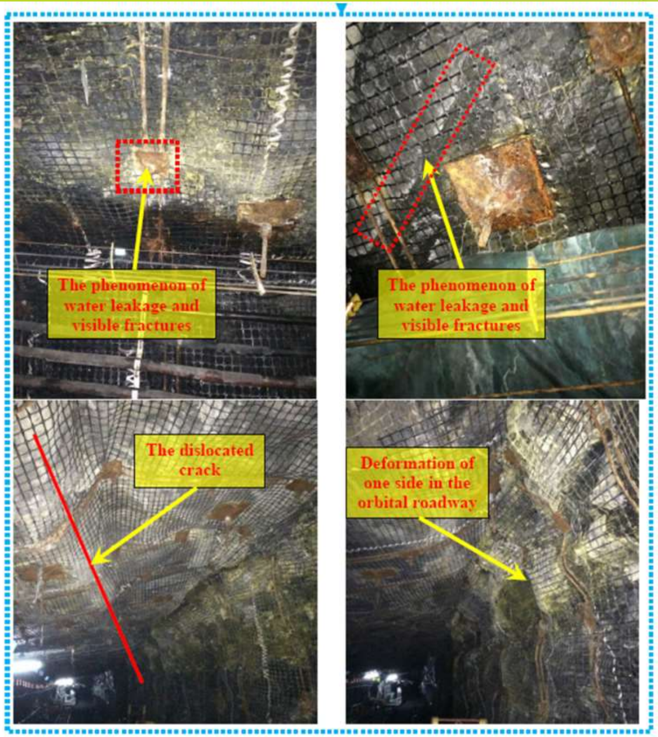
Seismicity compared with Treatment Procedure



MS Monitoring: Identification of Active Faults

Engineering operations trigger seismic activity that can be used to delineate pre-existing faults activated through the stress changes imposed



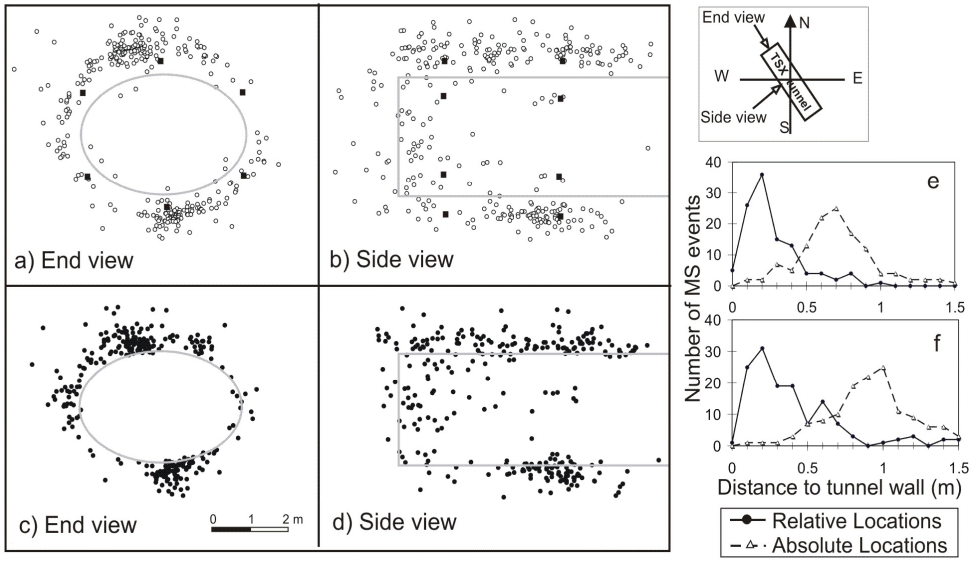


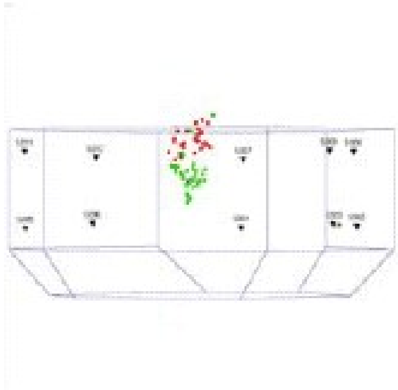
MS activity concentrated around pre-existing fault in Dongjiahe Coal Mine (Cheng et al., 2018)

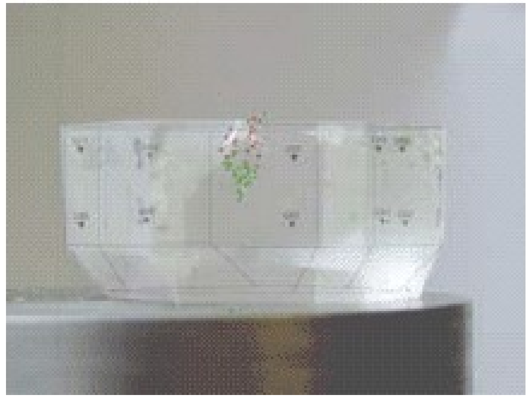
Focusing the image: Relative location of induced events

An alternative method to overcome the uncertainties in velocity model during location inversion is the relative location of events located in close proximity

This provides an accurate image of the internal structure of the seismic cluster.

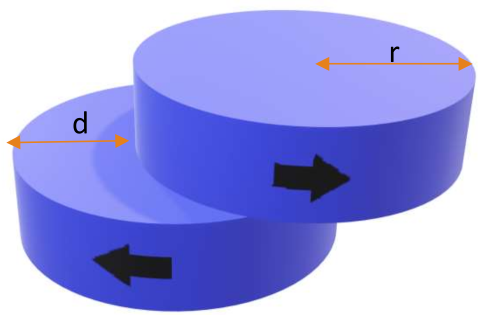






Source parameters: characterising the fractures

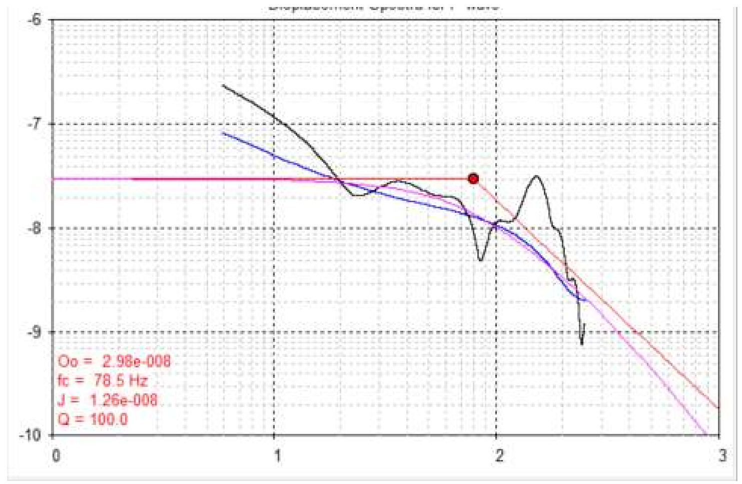
Fitting a source model to the recorded displacement spectra allows computing parameters that describe the source



$$\Omega(f) = \frac{\Omega_0 e^{-\left(\frac{\pi f t}{Q}\right)}}{\left[1 + (f/f_c)^2\right]}$$

$$M_0 = \mu A d \iff M_0 = \frac{4\pi\rho c^3 R \Omega_0}{F_c}$$

$$r_0 = \frac{K_c \beta_0}{2\pi f_c}$$



where:

- μ =shear modulus (units N/m^2)
- d=slip displacement, A=fault area

Event Magnitude

- The traditional measurement of earthquake size/strength is 'magnitude', which is a number based on the measurement of the maximum motion recorded by a seismic instrument, corrected for distance and instrument response.

- Earthquake magnitude (M_L) was first introduced by Charles Richter in 1935. Determined from the log of the peak amplitude of displacement on a Wood-Anderson seismograph.

Most common magnitude calculations:

- M_L=local or Richter magnitude
- M_s=surface wave magnitude
- m_b=body wave magnitude
- m_w=moment magnitude

All magnitude scales should yield approximately the same value for any particular earthquake.

M_w is considered appropriate over the largest range.

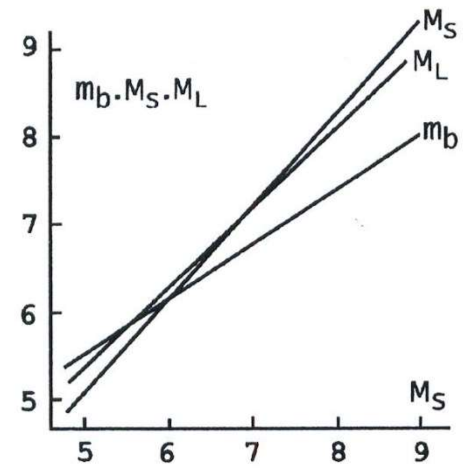


Fig. 15.5. The relation among the magnitudes M_S, m_b, and M_L.

(Udias, 1999)

- Seismic moment has become the most universal measure of the size of a seismic event.

$$M_w = C \cdot \log M_0 + D$$

where:

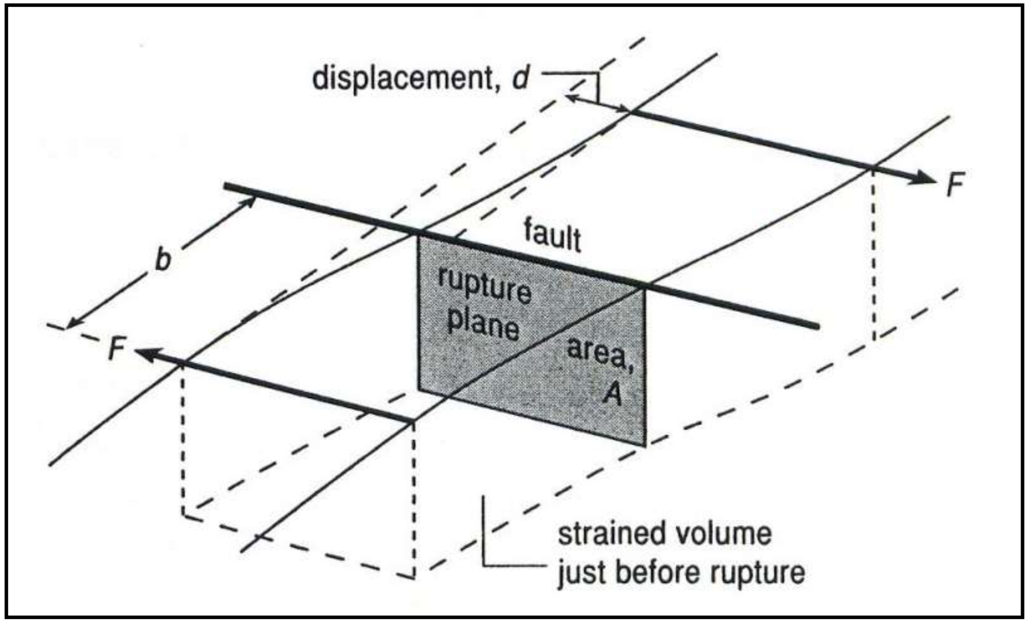
- M_0 = seismic moment (units Nm)
- C,D = variables; (e.g. C=2/3 ,

D= -6 from Hanks and Kanamori (1979))

$$M_0 = \mu \cdot d \cdot A$$

where:

- μ =shear modulus (units N/m^2)
- d=slip displacement, A=fault area



Seismic Magnitude: estimated source strength

Magnitude	Explosive equivalent	Fault radius	Slip
6	1 Megaton	10-40 km	5 cm - 1 m
4	1 kiloton	1-4 km	0.5-10 cm
2	1 ton	100-400 m	0.5 mm – 1 cm
0	1 kg	10-40 m	0.05-1 mm
-2	1 g	1-4 m	5-100 µm
-4	1 mg	0.1-0.4 m	0.5-10 µm

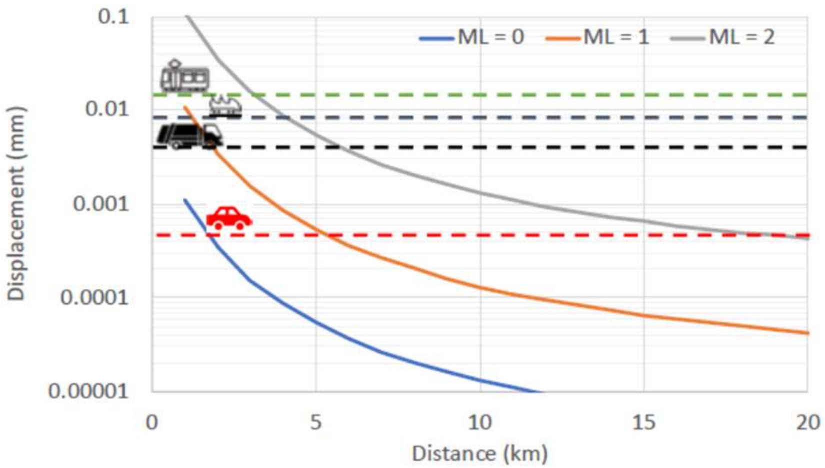
Magnitude	Energy (Joules)	Potential Energy (1 m weight drop)	Kinetic energy (Projectile)
0	63,000	6,300 kg	
			Rifle
-1	2,000	200 kg	
			Pistol
-2	63	6 kg	
			Air rifle
-3	2	200 g	
			Champagne cork
-4	0.06	6 g	

After Maxwell, 2014

Equivalent Magnitude

Vibration Source	M_L @ 2.5 km	M_L @ 5 km	M_L @ 10 km
Car	0.4	1.0	1.8
Bin-Lorry	1.3	1.9	2.7
Bus	1.2	1.8	2.6
The Big One	1.6	2.2	3.0
Tram	1.8	2.4	3.2

Edwards and Reyes-Montes, 2018

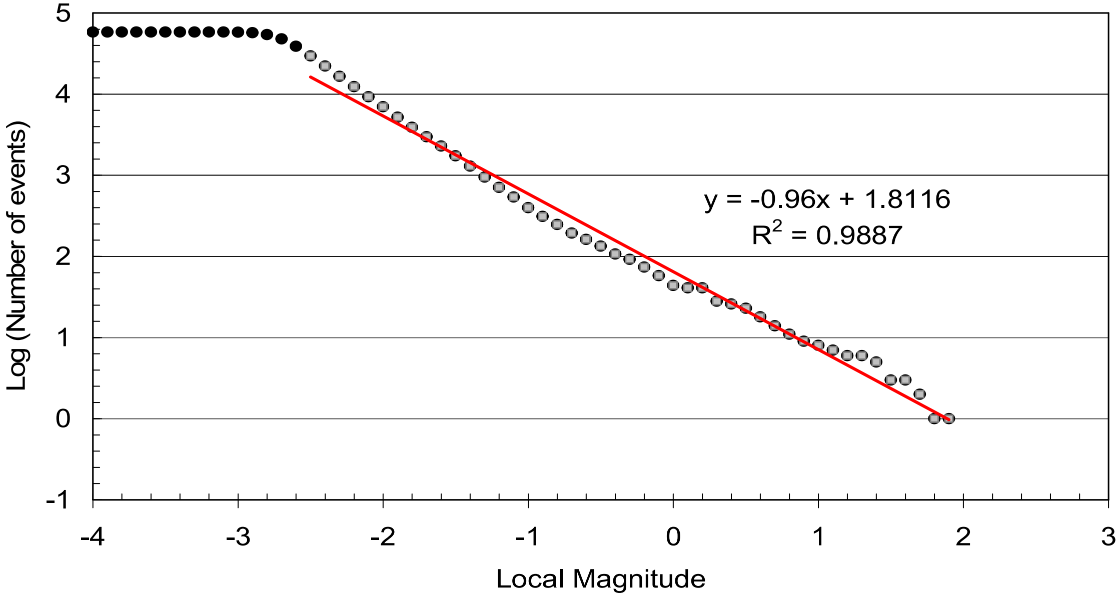


Analysis: b-value

Based on Gutenberg Richter Magnitude-Frequency law (1954):

$$\log_{10} N = a - b\,M ,$$

where **N** is the number of events with magnitude <M.



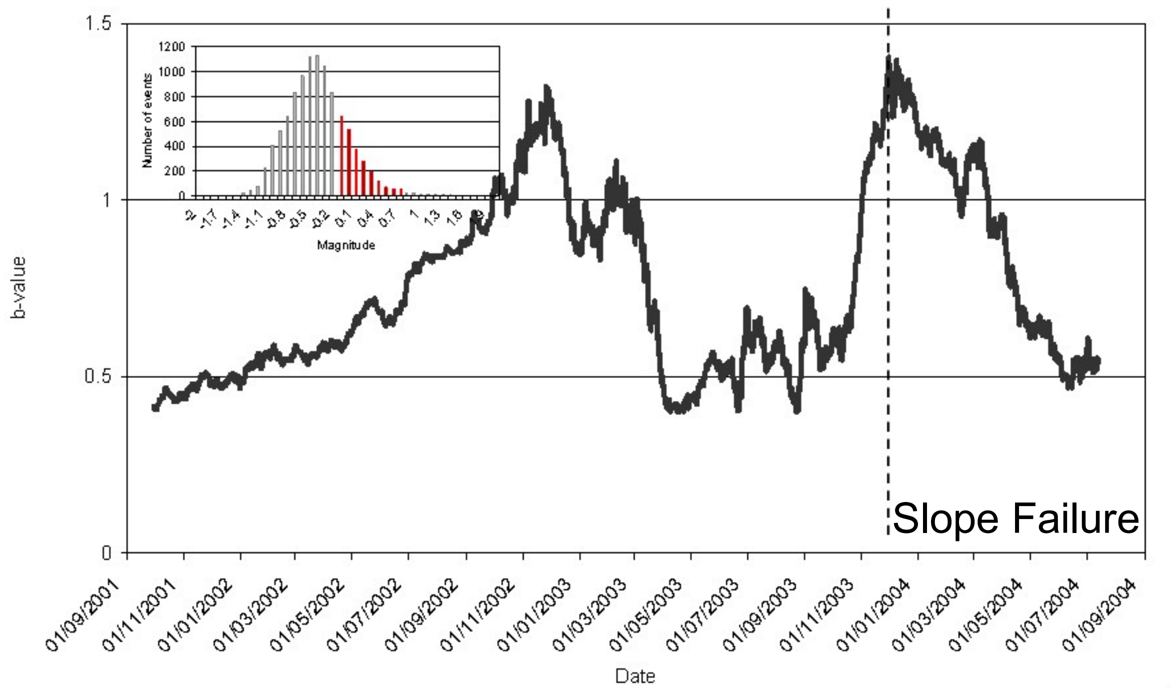
The worldwide tectonic average is b ~ 1

B-value: Failure Precursor

Evolution of the b-value for the events located at the bottom of the open pit of Palabora mine.

Mw = -1.4 ~ 1.3

b-value using Mw > 0.1



Analysis: b-value

High b-values are associated with having a greater proportion of smaller events, i.e.:

- Normal faulting; whilst low values suggest thrust faulting (Schorlemmer et al., 2005).
- High thermal gradients (Warren & Latham, 1970)
- High heterogeneity & fracturing (Mogi, 1962)
- Low applied stress (Wyss, 1973)

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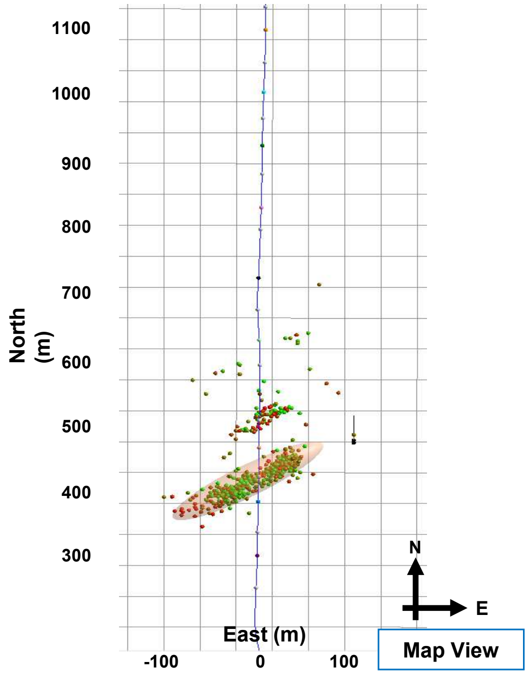
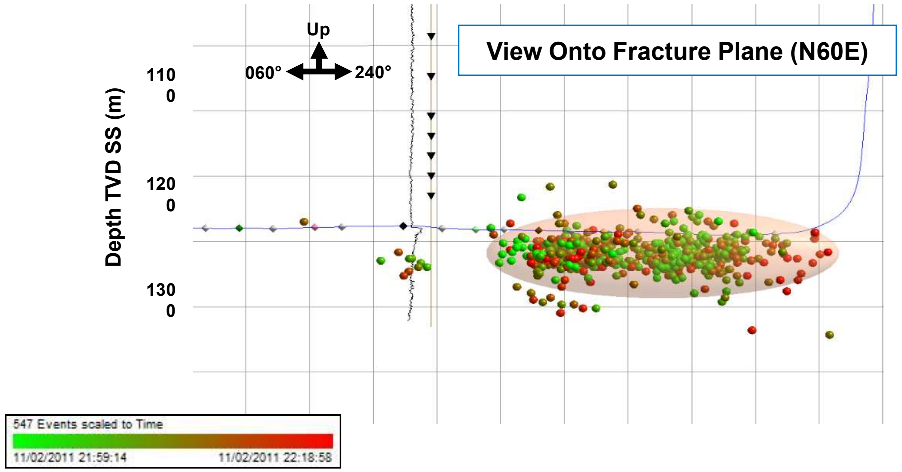
Fracture Geometry



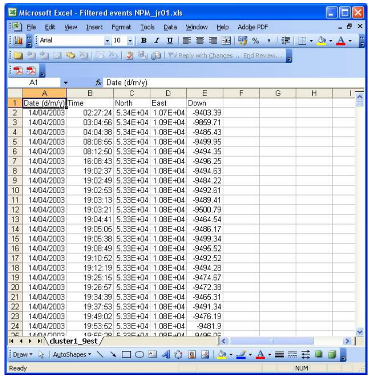


Single Wing	No
Breakthrough	No
Fracture Network Wing Length	135 m (NE-wing)
Fracture Network Length	240 m
Fracture Network Height	70 m
Fracture Network Width	50 m
Fracture Network Top	1,174 m TVDSS
Fracture Network Bottom	1,244 m TVDSS
Fracture Network Azimuth	60 degrees E of N
Fracture Network Plunge	0 degrees
Fracture Network Volume	440x10^3 m^3

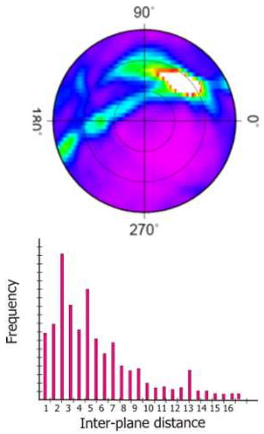
The fractures induced or mobilised due to stress changes (e.g. natural or engineering processes) radiate elastic energy recorded as microseismic events.

The statistical analysis of the locations of the seismic events can be used to interpret the geometry of the fractures.

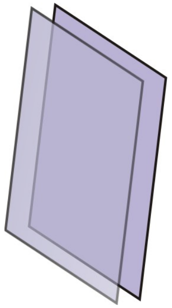
MS catalogue



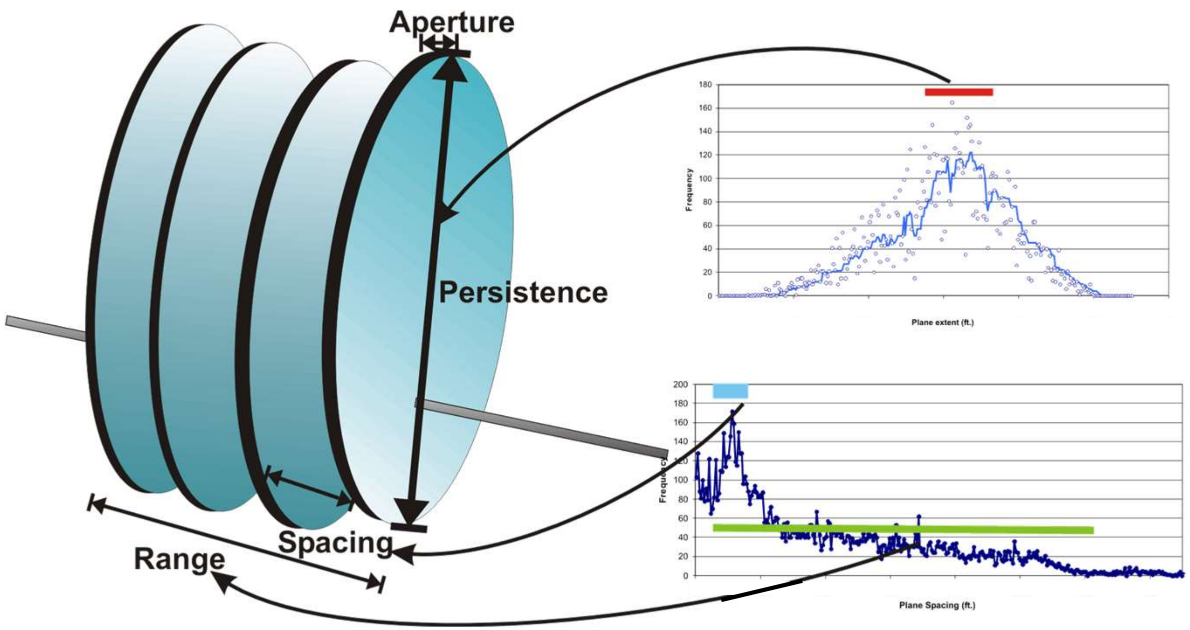
Date (d/m/y)	Time	North	East	Down
14/04/2003	02:27:24	5.34E+04	1.07E+04	-9403.39
14/04/2003	03:04:56	5.34E+04	1.09E+04	-9859.71
14/04/2003	04:04:38	5.34E+04	1.08E+04	-9485.43
14/04/2003	08:08:55	5.33E+04	1.08E+04	-9499.95
14/04/2003	08:12:50	5.33E+04	1.08E+04	-9494.35
14/04/2003	16:08:43	5.33E+04	1.08E+04	-9496.25
14/04/2003	19:02:37	5.33E+04	1.08E+04	-9494.63
14/04/2003	19:02:49	5.33E+04	1.08E+04	-9484.22
14/04/2003	19:02:53	5.33E+04	1.08E+04	-9492.61
14/04/2003	19:03:13	5.33E+04	1.08E+04	-9489.41
14/04/2003	19:03:21	5.33E+04	1.08E+04	-9500.79
14/04/2003	19:04:41	5.33E+04	1.08E+04	-9464.54
14/04/2003	19:05:05	5.33E+04	1.08E+04	-9486.17
14/04/2003	19:05:38	5.33E+04	1.08E+04	-9499.34
14/04/2003	19:08:49	5.33E+04	1.08E+04	-9495.52
14/04/2003	19:10:52	5.33E+04	1.08E+04	-9492.52
14/04/2003	19:12:19	5.33E+04	1.08E+04	-9494.28
14/04/2003	19:25:15	5.33E+04	1.08E+04	-9474.67
14/04/2003	19:26:57	5.33E+04	1.08E+04	-9472.38
14/04/2003	19:34:39	5.33E+04	1.08E+04	-9465.31
14/04/2003	19:37:53	5.33E+04	1.08E+04	-9491.34
14/04/2003	19:49:02	5.33E+04	1.08E+04	-9476.19
14/04/2003	19:53:52	5.33E+04	1.08E+04	-9481.9

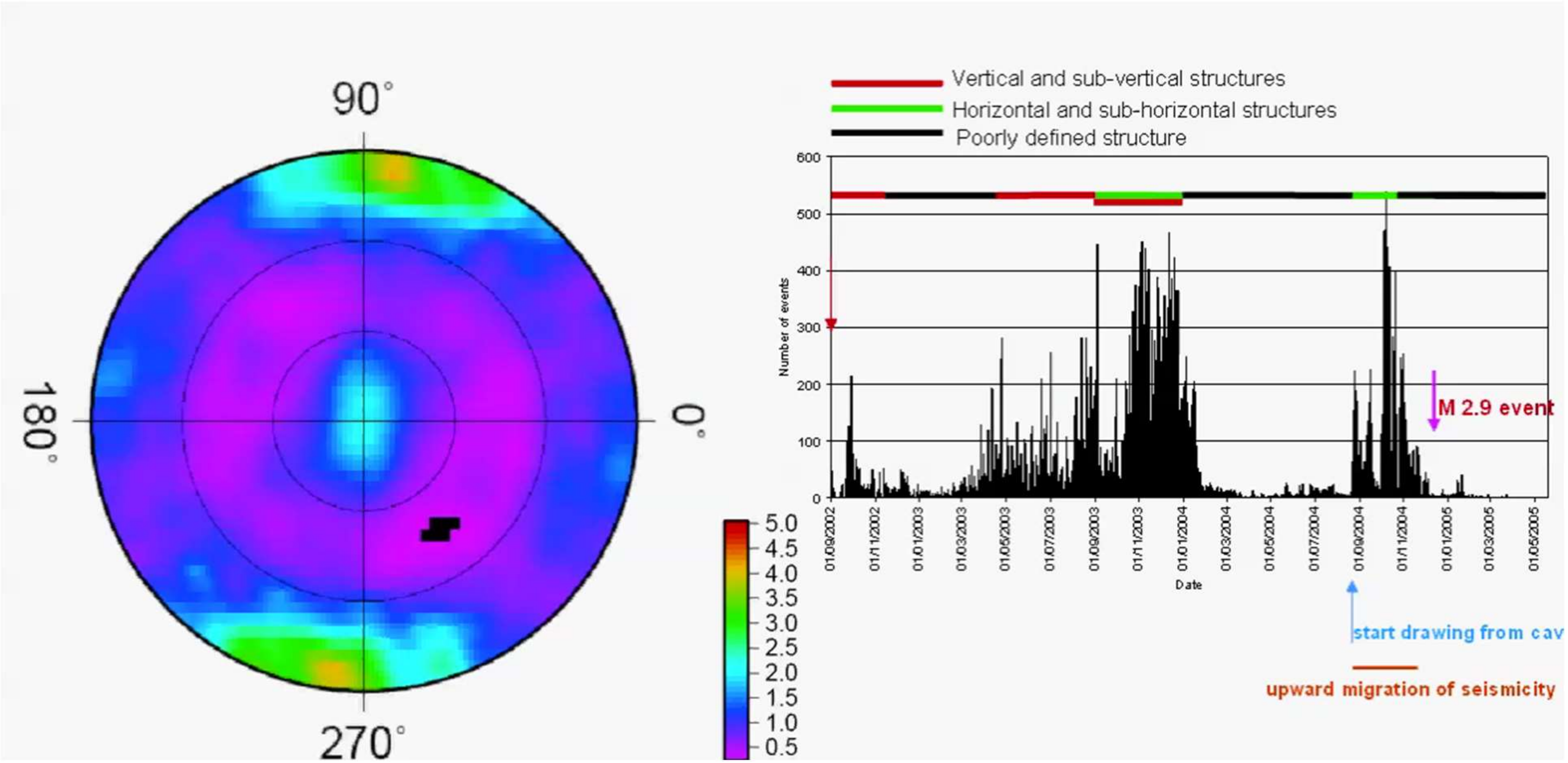


Characterization of induced fracture network

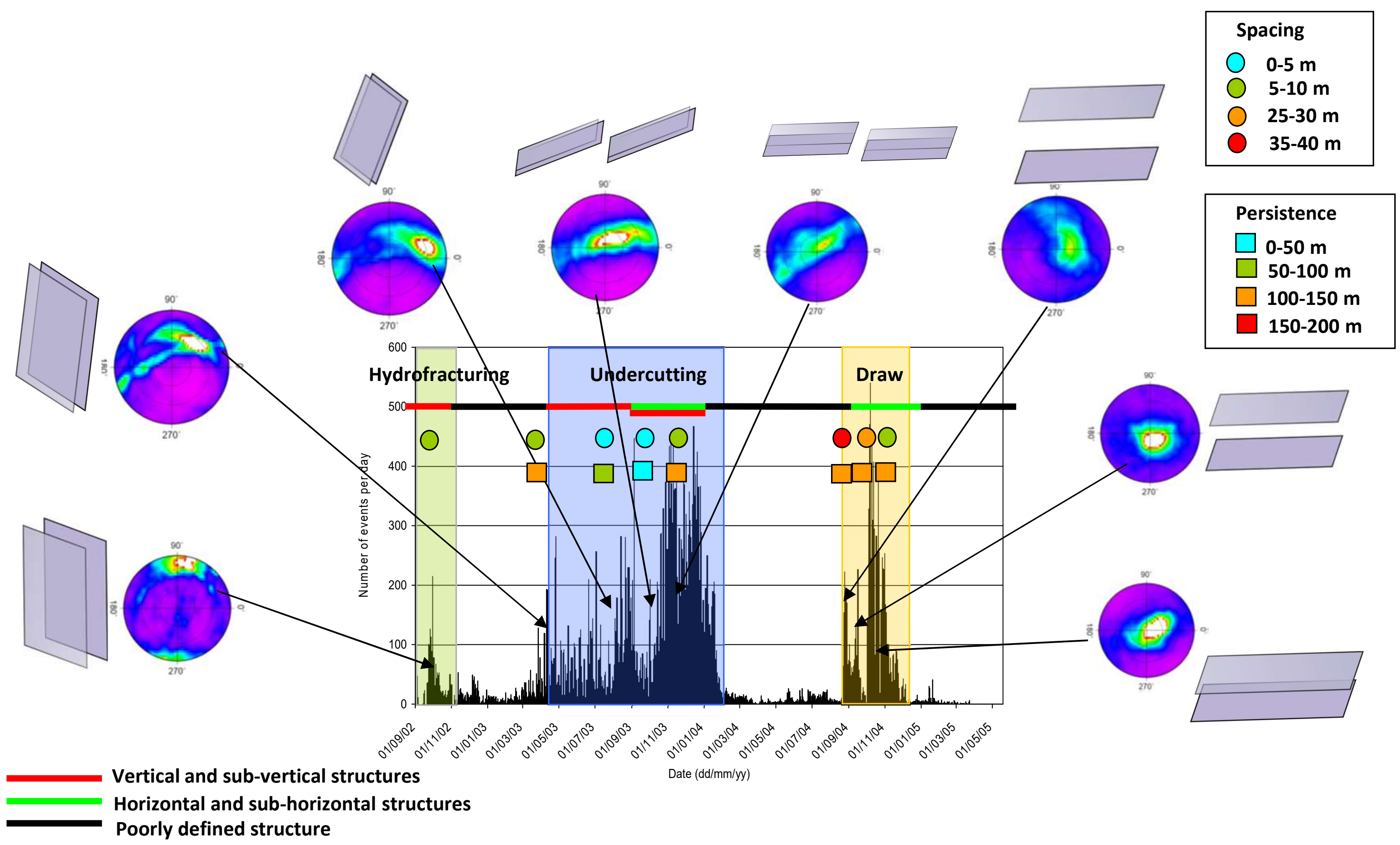


Conceptual diagram showing the interpretation of fracture network spacing and persistence from the inter-plane and inter-event separations within example events fitting planes following the observed dominant orientation.

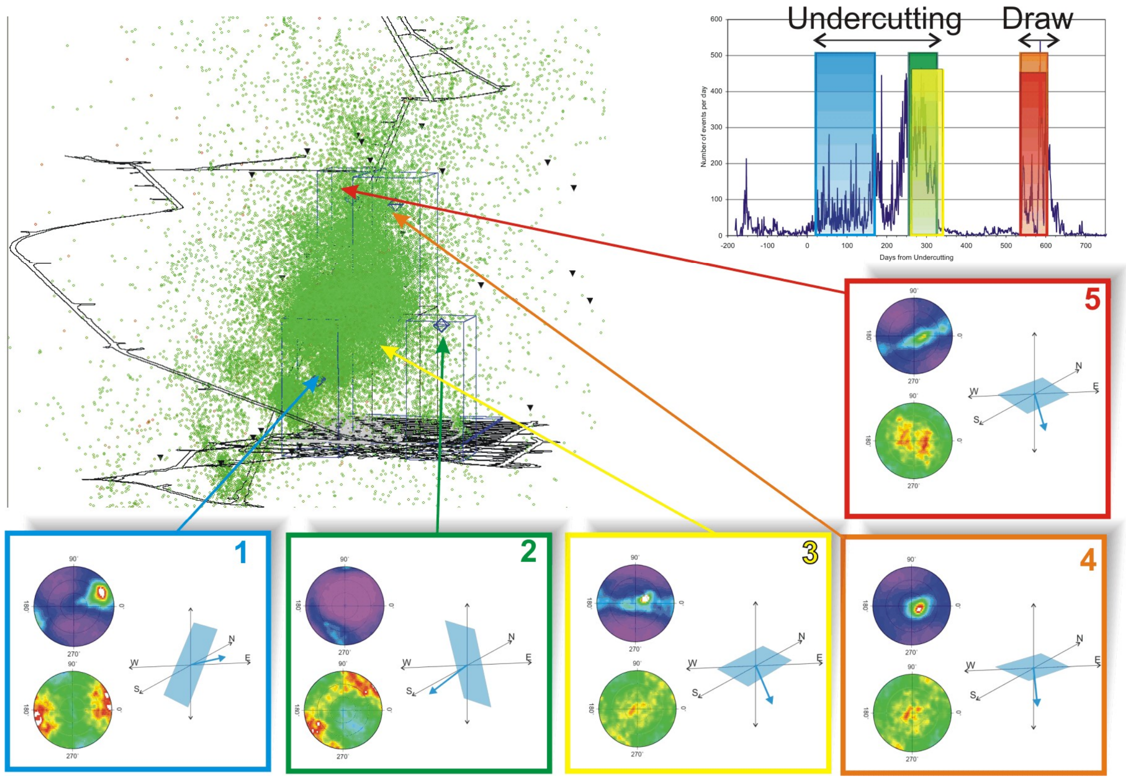



90°
180°
0°
270°
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
Vertical and sub-vertical structures
Horizontal and sub-horizontal structures
Poorly defined structure
Number of events
Date
M 2.9 event
start drawing from cav
upward migration of seismicity

Evolution of slip/fracturing from Microseismic record

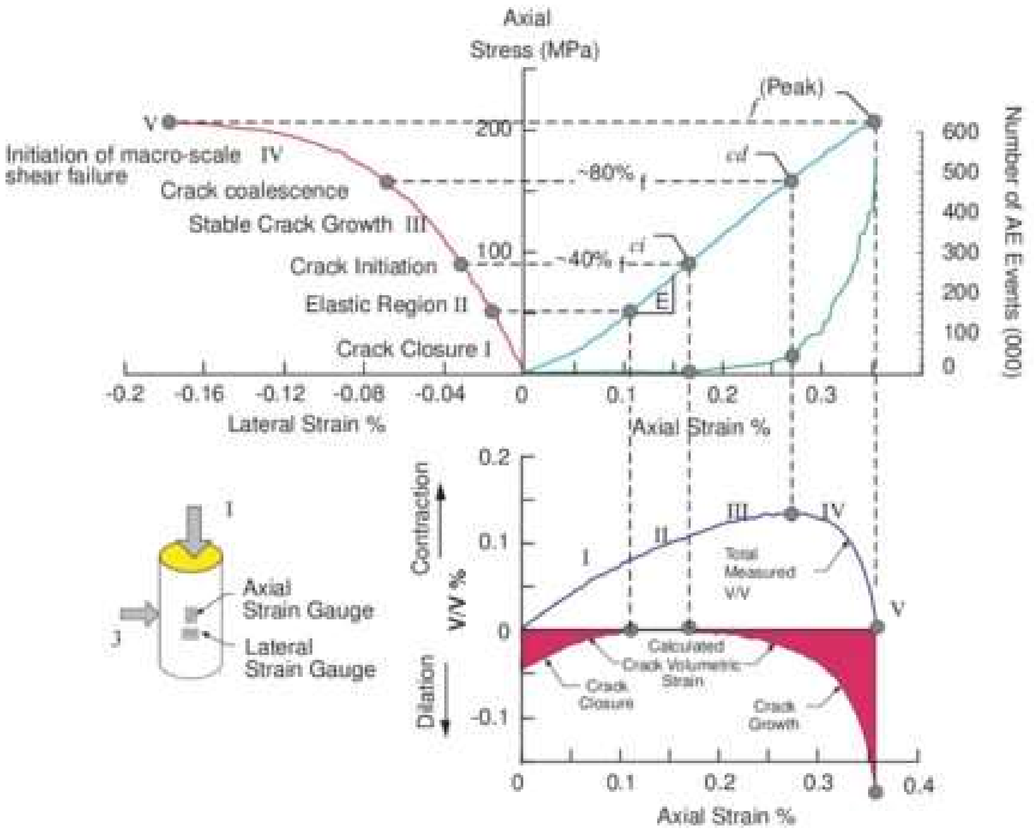


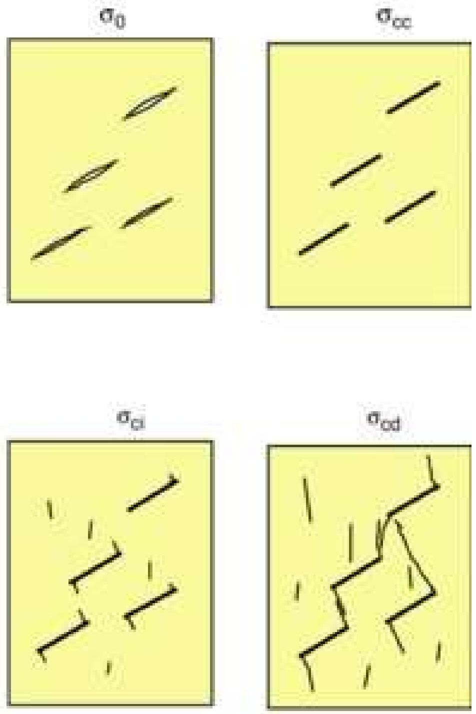
Mining Induced Seismicity



Cave mining: Seismic monitoring is used to image the upward progress of the cave as material is removed from the undercut level

Fracture propagation: Role of interaction and coalescence

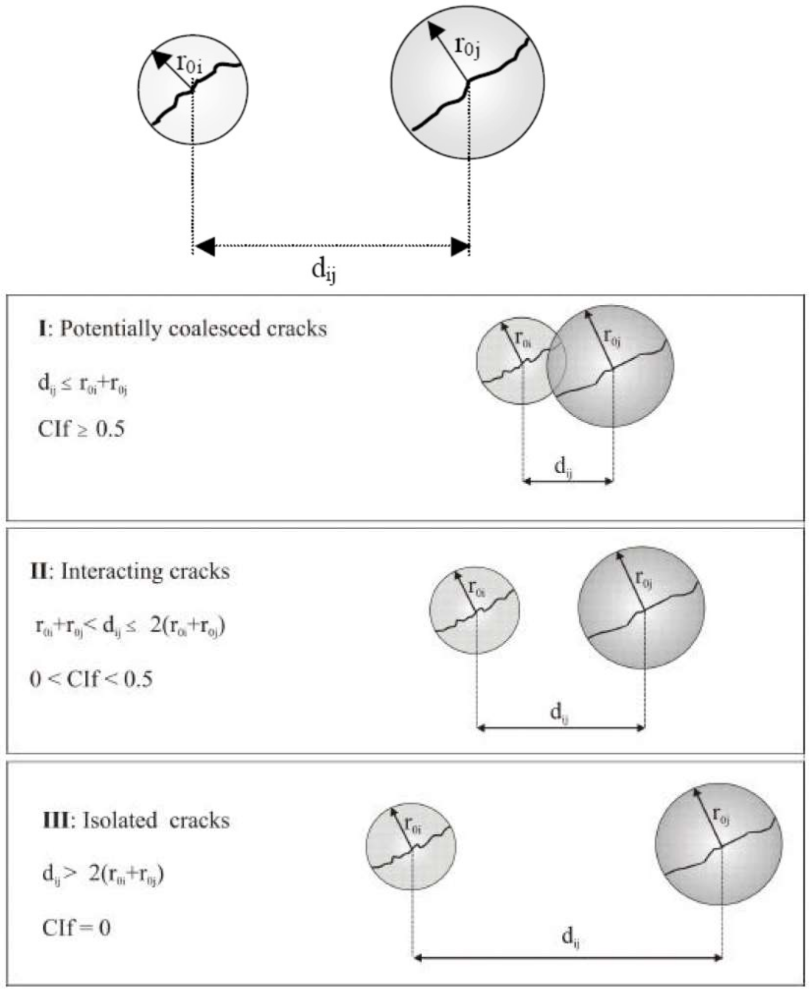




Cai et al., 2004

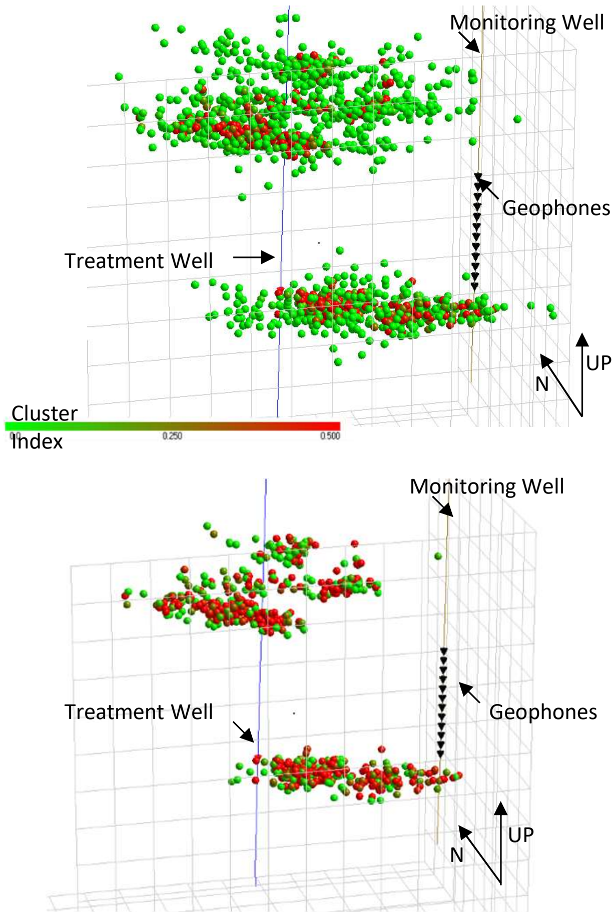
Fracture interaction

- The interaction and eventual coalescence of neighbouring cracks is directly correlated with irreversible damage in the rock mass.
- The Cluster Index (CI) is based on the concepts of critical crack spacing and local crack density (Lockner et al., 1992). It combines source location and effective event size idealizing MS events as representing spheres, with radii equal to their source radii, which contain the source crack.
- This parameter is calculated taking into account all neighbouring events, and can be calculated through time to monitor the degree of damage imposed on the rock mass.

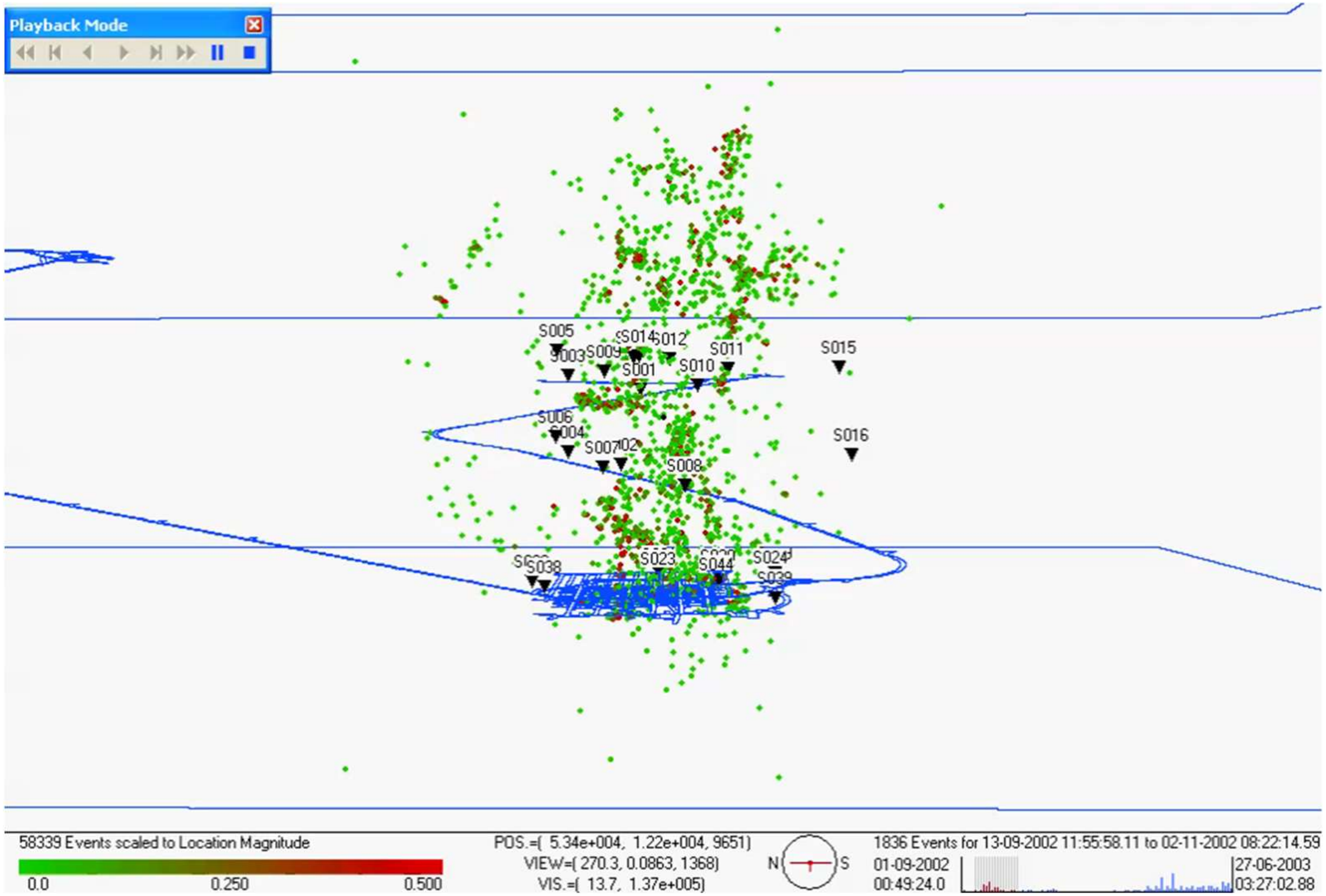


Clustering-coalescence analysis

- Provides better resolution of fracture networks. Identify the volumes where cracks are interconnecting to create potential fluid pathways or unstably growing factures.
- Use of k-means for grouping of events in clusters
- CI is a powerful method for identifying ‘potentially’ interacting or coalescing cracks.
- The higher the CI, the more likely permanent damage is occurring in the rock mass

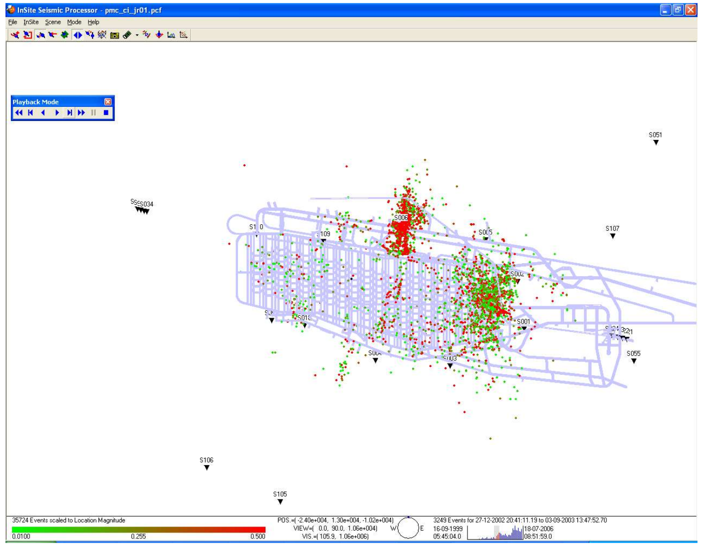


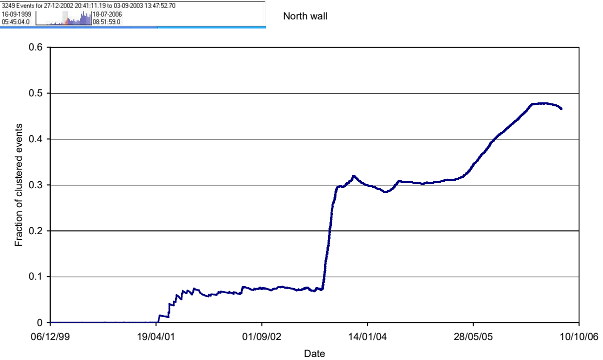
Spatial Clustering



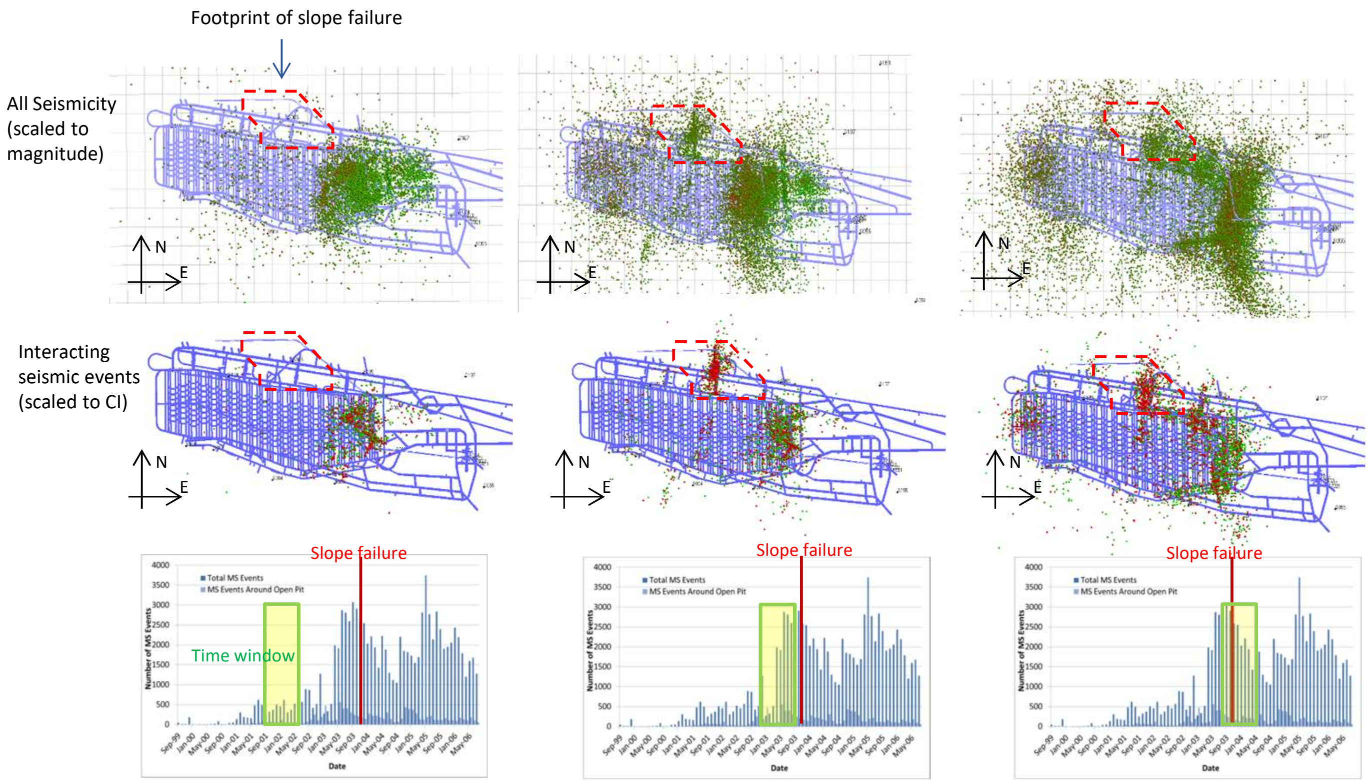
Fracture coalescence as a damage estimator

- Once calibrated, the parameters can be calculated for a series of microseismic catalogues in order to provide a quantitative estimator of the effectiveness of an engineer operation to induce fracturing.
- The use of the damage parameter allows direct comparison between different operations.



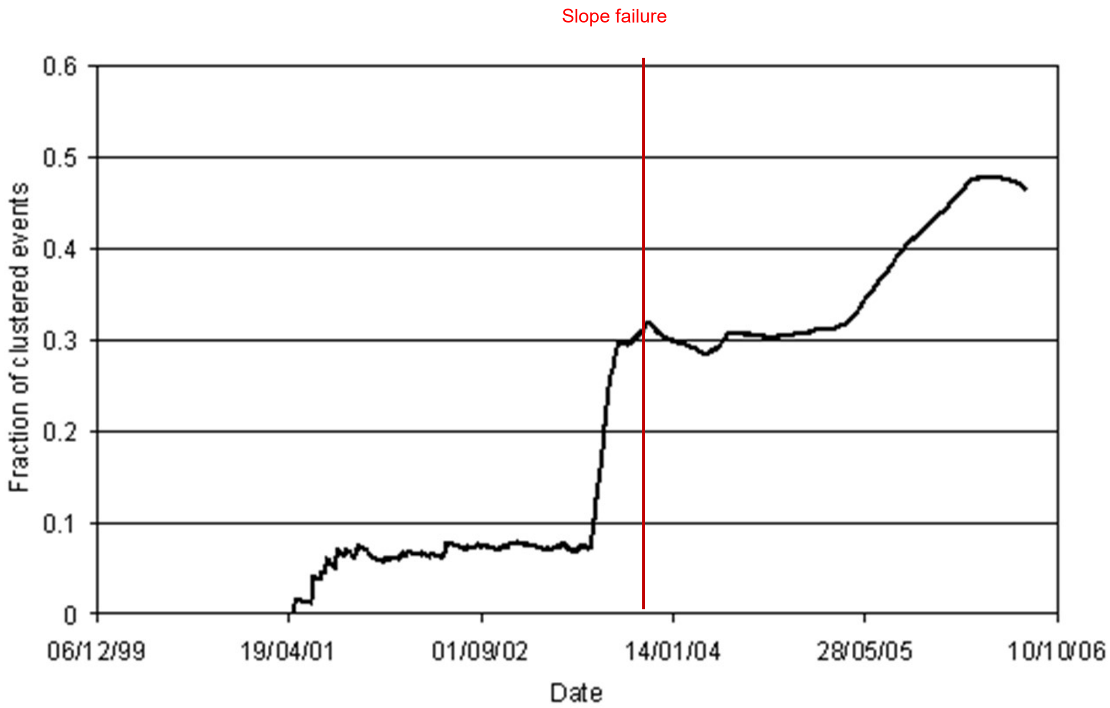


Fracture coalescence: Failure precursor I



Fracture coalescence: Failure precursor II

The relative abundance of clustered events during the undercut and production of Palabora underground cave shows a steep increment in the 2-month period preceding the failure of the open pit's north slope.



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