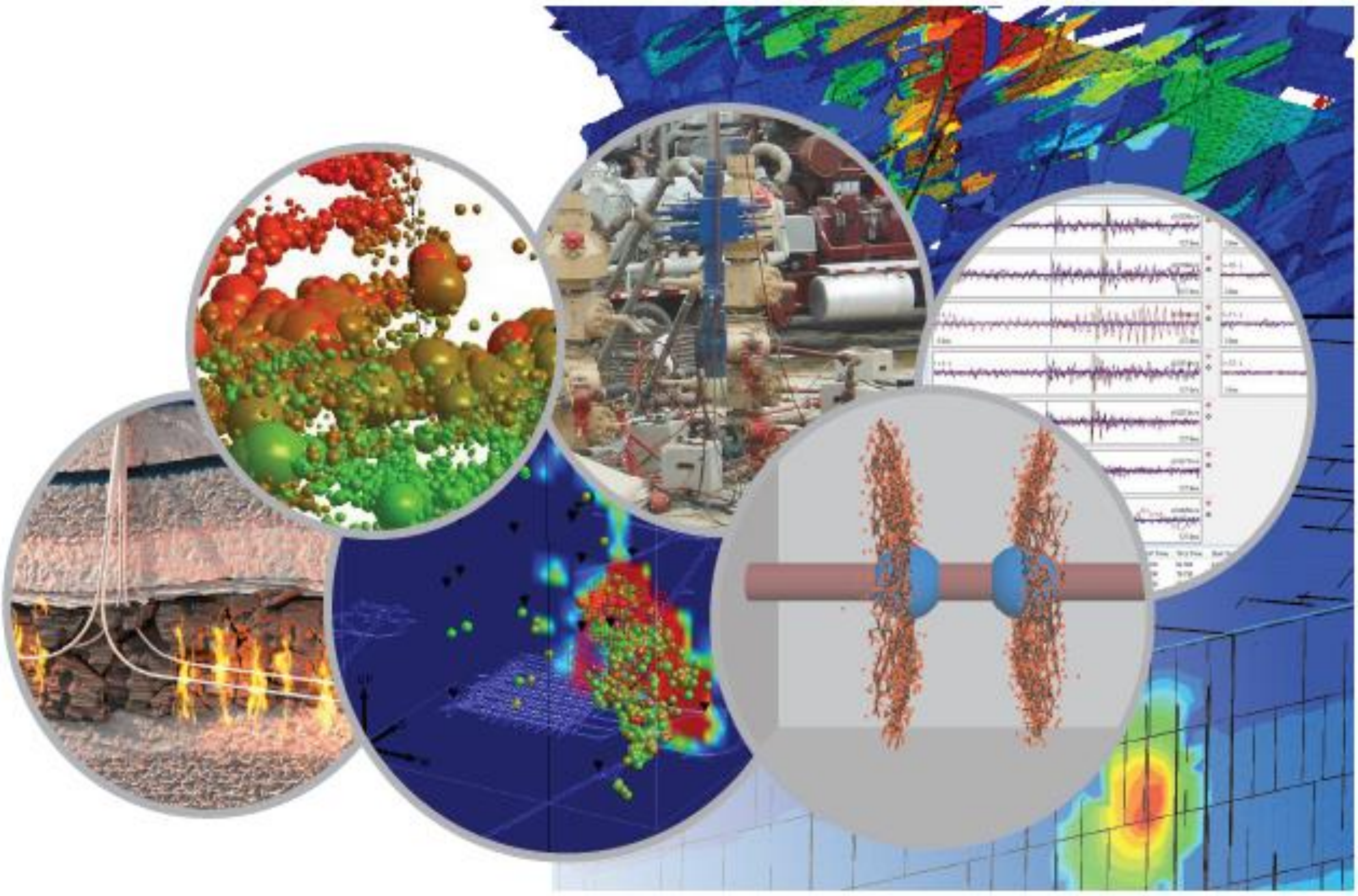
Microseismic and Acoustic Monitoring for the Engineered Environment.



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Contents

1 Microseismic Monitoring of the Engineered Environment: Principles, Objectives and Outcomes

Applied Seismology Consulting (ASC) is specialised in providing consulting, software and acquisition systems for microseismic, acoustic and ultrasonic monitoring of natural and engineered structures. ASC services apply over a wide range of engineering applications from Hydrocarbon extraction, reservoir stimulation, monitoring of geothermal reservoirs, mining, geological storage of RadWaste and CO_2, monitoring of civil infrastructure and rock deformation laboratory testing.

The principles of microseismic monitoring and analysis are basically the same as those employed by seismologists to study earthquake mechanics and the internal structure of the Earth which apply to all engineering-scale problems. These techniques have provided information on the condition of a rock-mass and its response to various types of human intervention. Advances in instrumentation and computing power have broadened the scope of these investigations, and high fidelity microseismic data is now routinely collected as part of a wide range of engineering operations. Microseismicity provides first order information on the impact of the different engineering operations on the host rock, the surrounding volume and infrastructure, delineating the extent and position of any potential induced or mobilised fracturing. Therefore, microseismic monitoring applies to a wide range of industries that involve engineering operations with the potential to induce fracturing in brittle materials:

- **Mining**
- **Geothermal**
- **Geological storage**
- **Oil and gas**
- **Civil engineering**
- **Material testing**

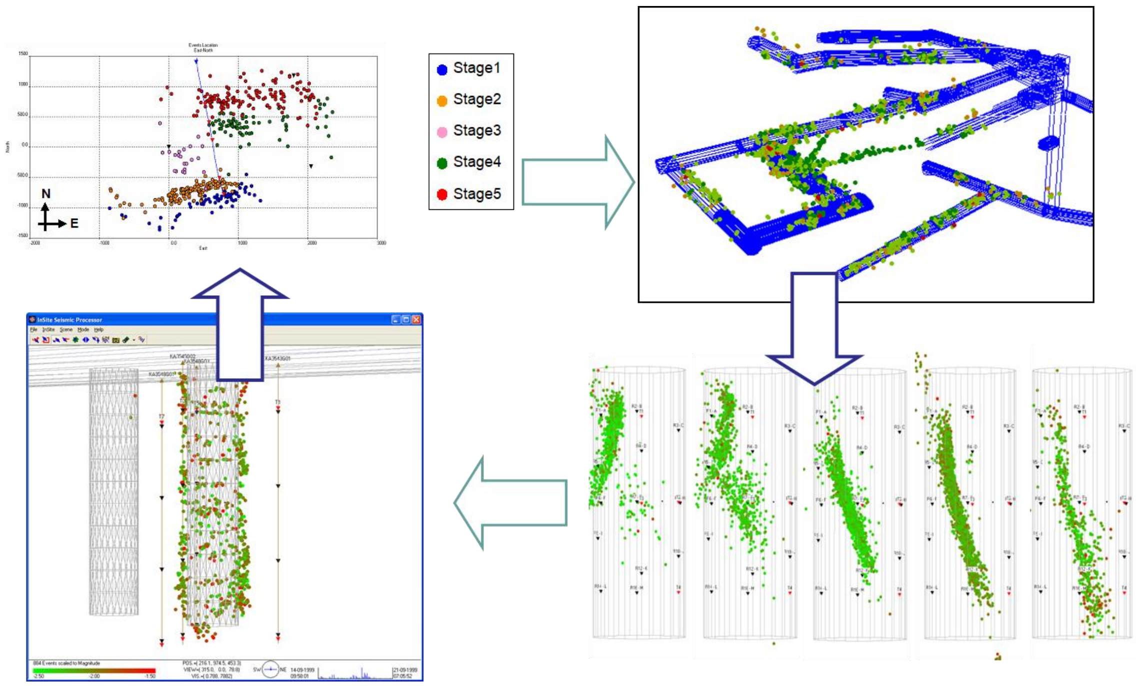


Figure 1: Seismic monitoring across the scales, from laboratory samples to reservoir and regional scale.

A microseismic event, also called micro-earthquake, is simply a smaller-scale version of the same phenomenon. An event is generated by the rapid strain/stress release due to brittle failure when stress conditions in the source volume exceed the envelope of the Mohr-Coulomb criterion for the rock. The energy released travels through the medium as mechanical waves that are recorded by sensors (geophones, accelerometers, piezo-electric crystals, etc.).

At the scales generally associated with engineering applications, acoustic methods can be broadly split into two categories, depending on the frequencies of the mechanical waves under investigation:

- Microseismic (MS) systems monitor energy in the 0.1 to 10 kHz band and are suitable for monitoring large volumes of rock (up to several km^3). These systems are appropriate for monitoring entire mines or the volume round the base of an injection well.
- Acoustic emission (AE) systems record higher frequencies (30 – 250 kHz or greater). These are appropriate for high resolution monitoring of smaller volumes of rock or specific concrete structures (volumes between 1 m^3 and 1 x 10^4 m^3 dependant on the attenuation properties of the material).

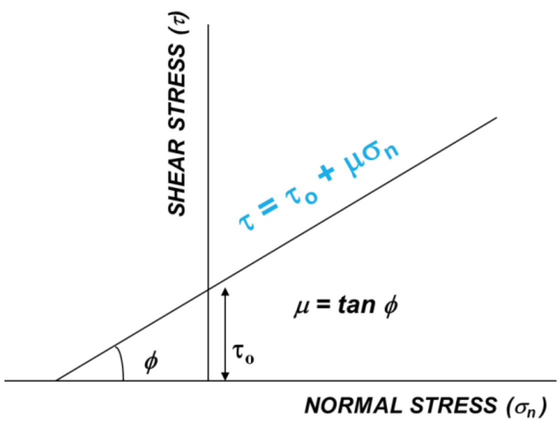


Figure 2: Mohr-Coulomb criterion for brittle failure. When stress state is pushed above the envelope for each material, rupture occurs to return the material to equilibrium.

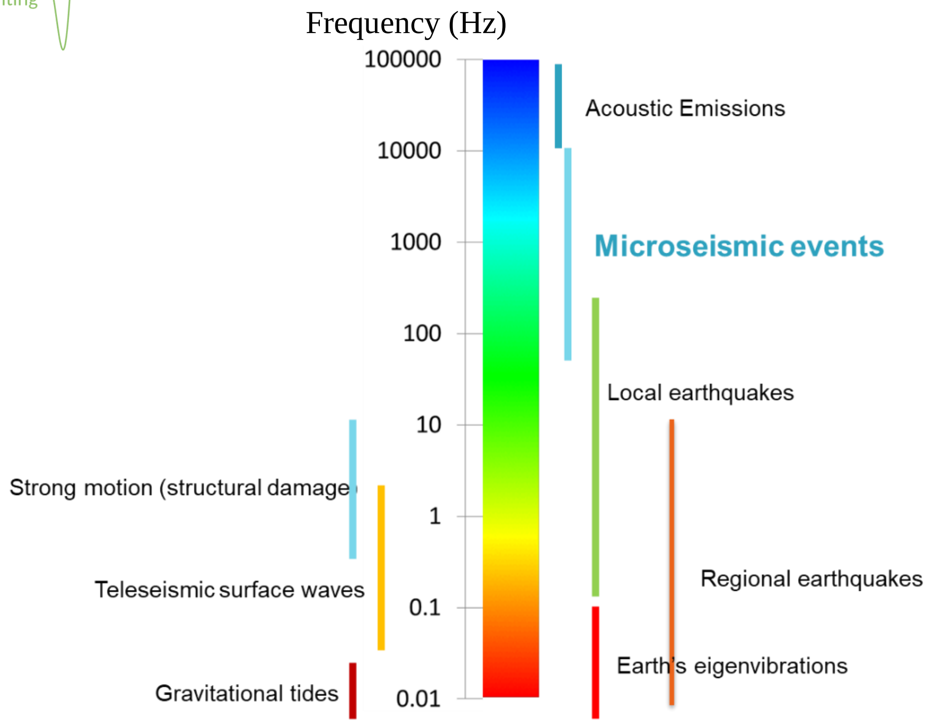


Figure 3: The 'seismic spectrum'.

At any scale, microseismic and acoustic monitoring can provide the following information:

- **Where fracturing is taking place**. Using the arrival times of the seismic phases, the AE/MS events associated with fracturing or slip on existing fractures can be located within the rock with great accuracy.
- **Assess the extent and geometry of the fracture**. The location of events and the event rate can be used to assess the areas within a material where the most fracturing is occurring. Further analysis can provide information on the orientation of the induced or mobilised fracture network. The velocity of seismic waves within the material (derived from passive seismic tomography) can also be used to assess areas of damage as, in general, regions of high damage will show lower velocities when compared to those from intact material.
- **Estimate fracture connectivity and interaction**. Considering the location, source radius and uncertainty, it is possible to quantify the degree of clustering and potential interactivity between induced microseismic events, which translates into the potential for damage and creation of paths for fluid migration.
- **Determine information on the fracture mechanism**. The shape of the waveforms recorded at each sensor is a function of the source mechanism and the path effects experienced by the acoustic energy as it travels from the source to the receiver. From these data it is therefore possible to derive information about the orientation and mechanism (e.g. shear, isotropic) of the failure.
- **Derive information relating to the stress field**. Studies have indicated a relationship between zones with high velocity anomalies and regions of higher stress and, therefore, increased damage potential. These may be identified by passive tomographic imaging and used in conjunction with stress models derived from numerical modelling and/or in-situ measurements. In addition, the orientation of the principal stresses acting at the source of the acoustic activity can be interpreted from waveform processing of the AE/MS activity.

- **Determine material properties of the volume**. As energy travels through rock, concrete or other materials the frequency and amplitude are affected by the material properties. Measurements of seismic velocity, anisotropy and attenuation are therefore sensitive to changes in these material properties.
- **Assess the time-dependent behaviour of the material in response to engineering activities**. The response of the material may vary with time in response to excavation or other engineering activities. The ability of acoustic methods to monitor in a continuous and passive manner is one of their greatest assets.
- **Validation for numerical models.** As geomechanical numerical modelling methods become more powerful and more widely applied, the collection of field data to provide model validation has become a key aspect of this type of engineering study.

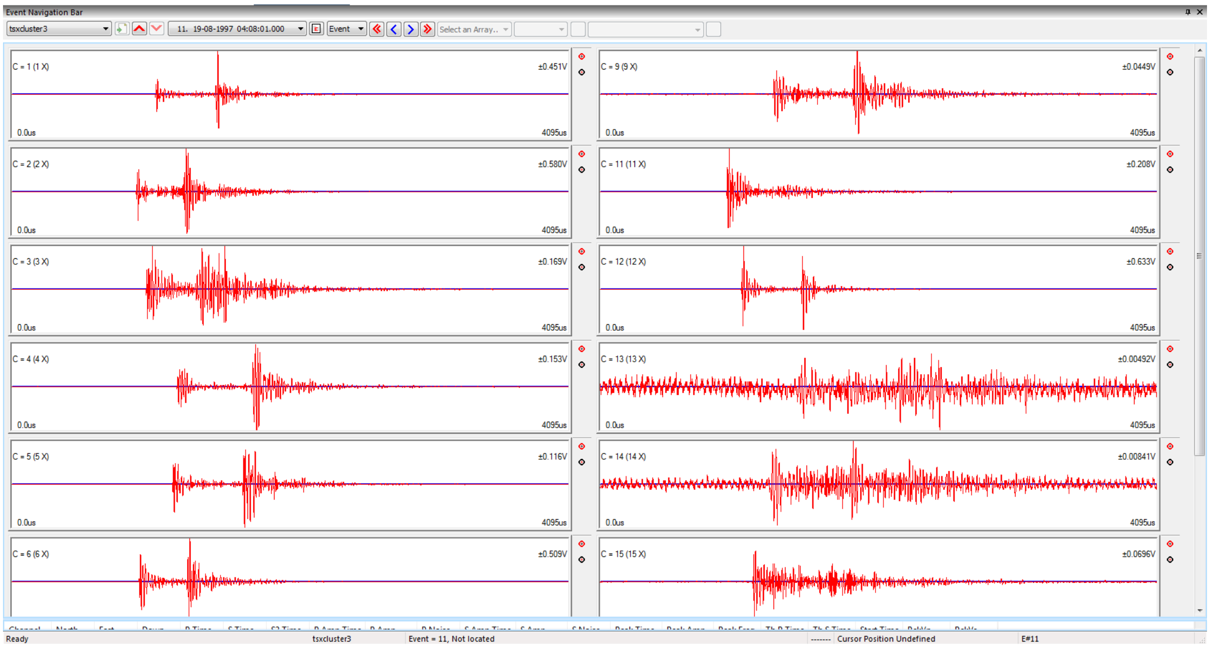


Figure 4: Example seismic record for a microseismic event induced in an underground excavation. The mechanical wave is recorded as a waveform by 16 sensors placed around the monitored volume. The arrival times of the different phases at each sensor are used, together with the transmission velocity of the waves in the rock, for the calculation of the event source location.

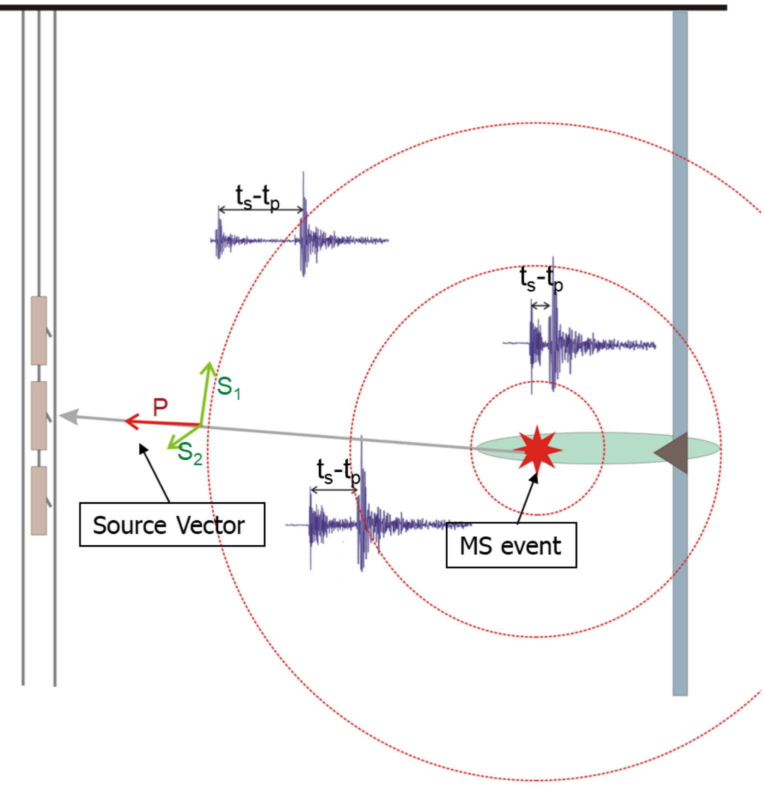


Figure 5: Illustration of the propagation of a seismic wave for an MS event induced from fluid injection. The difference in propagation velocity between the pressure (P) and shear (S) waves, and the different direction of particle motion for each phase (longitudinal for P-waves and transversal for S-waves) is used for the location of source of the MS event.

The combination of microseismic monitoring and analysis applied to field and laboratory observations with state-of-the-art geomechanical simulations, offer a unique and powerful method of understanding in-situ rock mass behaviour. The modelling allows predictions of the rock response to be made based on the properties obtained from laboratory experiments. The microseismic data is then collected in the field to validate the model and appropriate refinements are made to provide a realistic interpretation of the true behaviour. This combination is essential for the concept of Fracture Network Engineering (FNE) which involves the design, analysis, modelling, and monitoring of infield activities aimed at enhancing or minimising rock mass disturbance. FNE relies specifically on advanced techniques to model fractured rock masses and correlate microseismic (MS) field observations with simulated microseismicity generated from these models. Hydrofracture stimulation is an example where FNE is playing a role, with hydraulic treatments now being widely used to optimise production volumes and extraction rates in oil and gas reservoirs, enhanced geothermal systems, and preconditioning operations in caving mines. MS monitoring has become a standard tool for evaluating the geometry and evolution of the fracture network induced during a given treatment, principally by source locating MS hypocentres and visualising these with respect to the treatment volume and infrastructure. The integrated use of synthetic rock mass (SRM) modelling with microseismic analysis provides a feedback loop in which SRM is enhanced and constrained by the information provided by the MS data.

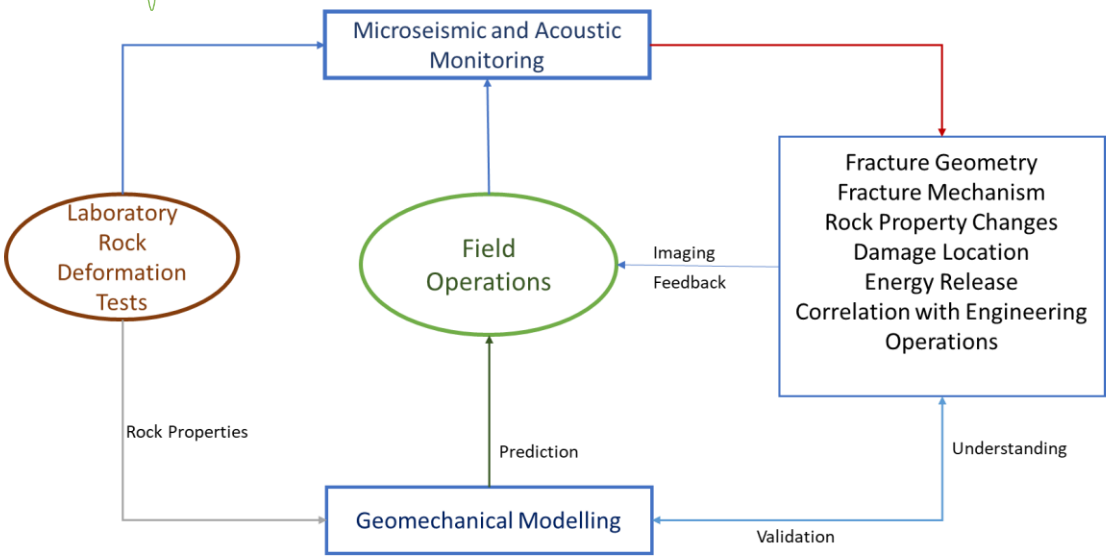


Figure 6: Microseismic monitoring integrated in the understanding of rock mechanics

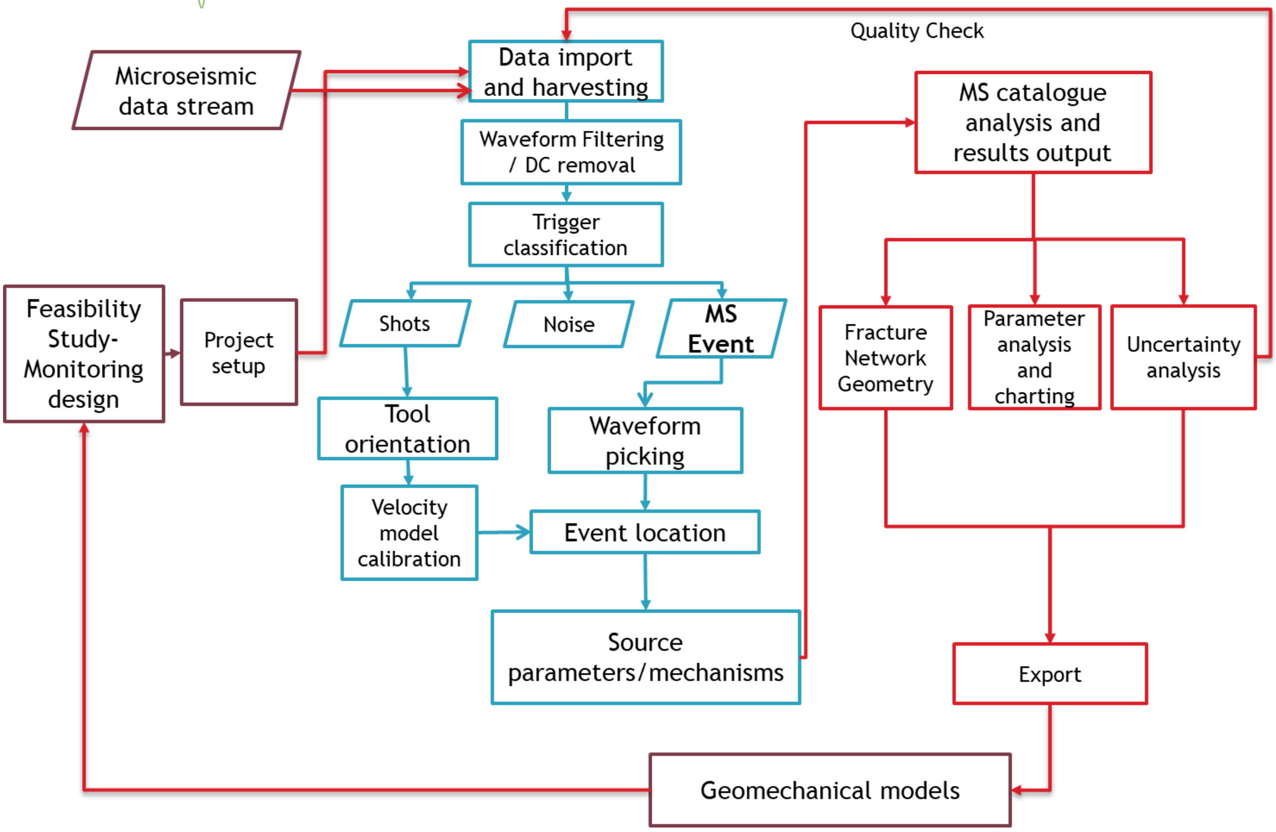
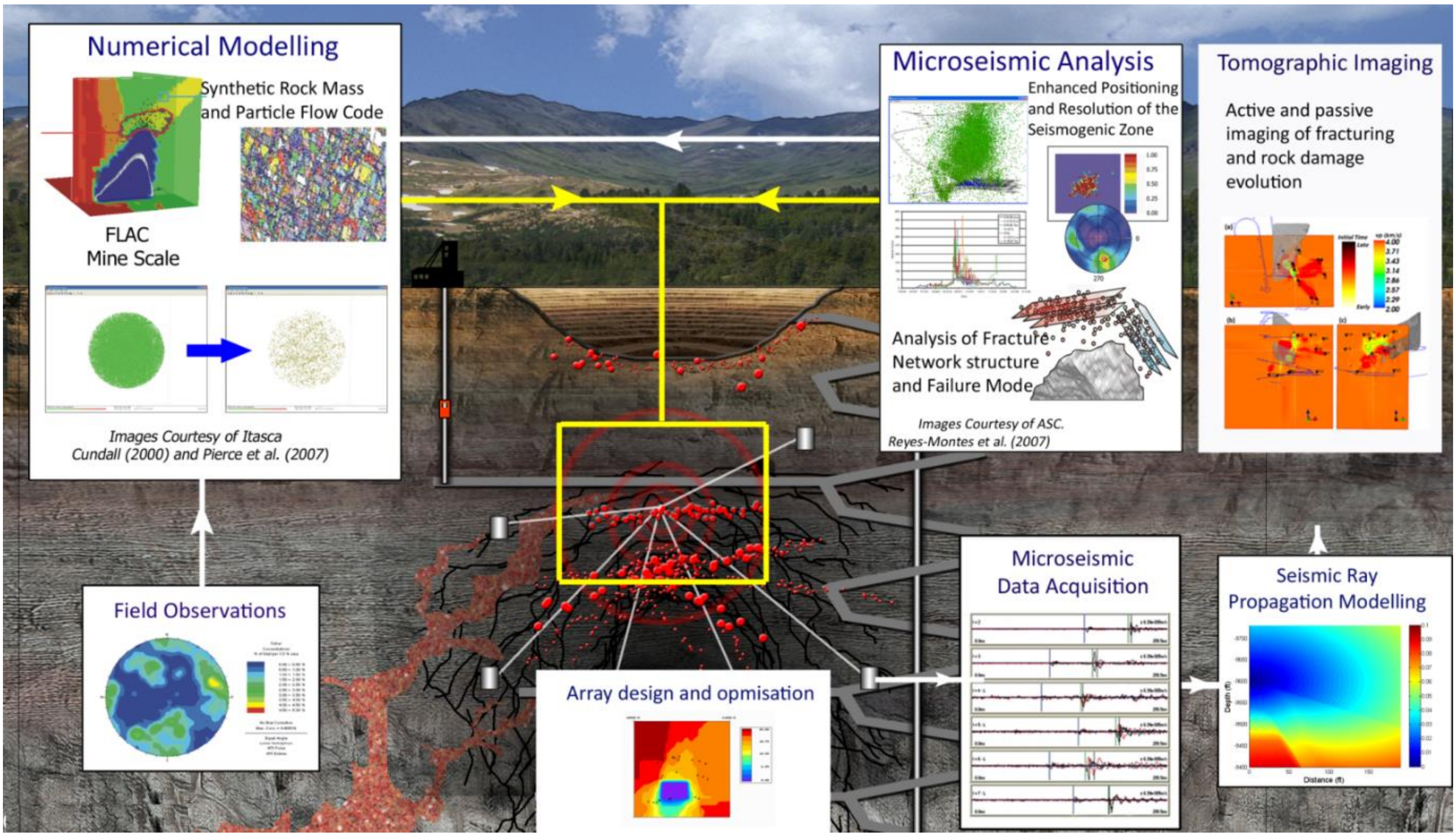


Figure 7: Flowchart for a typical microseismic monitoring job.

2 Seismic and Microseismic Applications for the Mining Industry



Seismic monitoring is an established technology in mines generally applied for safety monitoring, rockburst prediction and imaging the extent of damage induced by the mining operations. Microseismic monitoring, provides an insight into the location and extent of fracturing induced by the stress changes associated to mining processes in general. The spatial characteristics of the observed microseismicity provide valuable validation for the back analysis of fracturing processes such as caving, preconditioning, etc. through numerical models (e.g. Pierce et al. 2006; Sainsbury et al., 2008). It also provides a tool for the future validation of forward cave models that predict the extent and location of the seismogenic zone and the transmission properties of the damaged rock.

The post-process analysis of seismic catalogues or seismic record or real-time analysis can provide feedback for:

- Early warning on localised induced damage to mine infrastructure.
- Slope stability in open-pit mines
- Extent and positioning of damage zones in underground operations
- Imaging the cave progress and extent in underground caving mines
- Imaging the persistence, spacing and mechanism of induced and mobilised fractures
- Progress of subsidence zones above underground operations
- Effectiveness of preconditioning operations

ASC has developed a series of novel analyses that enhance the information provided by existing microseismic catalogues to monitor the evolution of the fracturing processes and provides the following services for mining stakeholders:

- Advanced post-processing, analysis and interpretation of client data using a range of techniques and software functionality developed in-house to identify fracturing modes, the fraction of newly opened and reactivated fractures and provide a full geometrical characterisation of fracturing.
- Active and passive source tomography for imaging of damage induced by mining operations
- Acquisition system-independent seismic processing software for automatic, real-time processing of induced seismicity
- In-depth understanding of fracture mechanisms through the integration of acquired data and “Synthetic Rock Mass” models built with Itasca’s Particle Fluid Code (PFC) and site-scale degradation models.
- Structure imaging and velocity inversion combining the illumination capability of controlled seismic sources and passive seismic events.

- P- and S-wave time-lapse tomography to image the degradation of host rock and structures in terms of elastic modulus and fracture density.
- Temporal and spatial clustering of microseismic events to quantify damage accumulation and identify areas of localised fracturing.
- Fully-featured microseismic training courses focussed on the principles behind the technology, processing algorithms and hands-on experience of using processing software.
- Design, optimisation and quality check of seismic monitoring arrays.

2.1 Case studies

2.1.1 Mass Mining Technology Project: Validation of SRM models

ASC participated in phases I and II of the Mass Mining Technology Project (MMT), an International Collaborative mining research project coordinated by the University of Queensland focused on critical reviews of conventional caving design approaches, collation of common caving practice, and advancing the understanding of the caving fundamentals. ASC role focused on enhancing the information extracted from MS data collected from case study mine to use MS events in the imaging of the fracture network as an essential validation tool for geomechanical models.

Innovative processing methodologies were developed to improve the understanding of the evolution of the fracture network as the rock mass undergoes undercutting and caving.

SRM (Synthetic Rock Mass) experiments were used to model the effects of undercutting and caving on the rock mass using the results from case studies (Northparkes mine, Palabora mine, Kiruna mine, Ridgeway mine) as a basis for the validation of the SRM approach.

The analysis of the evolution of the spatial distribution of MS events to was correlated to mining operations in the different identified domains to test the validity of using SRM tests as a means to predict rock mass response to undercutting and caving.

The statistical approach presented by Reyes-Montes (2005) was used to investigate the distribution of MS events along non-random planar structures. This method made use of the three-point method to identify preferential fracture orientations.

The mine was categorised into geomechanical domains, the seismic behaviour of each of the domains was used to characterise the difference in the nature fracturing and degree of yielding.

SRM's from each domain underwent tests resulting in the sample exhibiting over 100,000 cracks each. Two different techniques were used to study the macroscopic cracks, the first used examination of contiguous blocks to see how the initial rock disintegrates, visualising the fractures that lead to the disintegration.

The second technique used the three-point method to fit planes to clouds of cracks in a similar way to its use on the mine data. Individual cracks were grouped into PFC seismic events, events consisting of less than four cracks were filtered out before the three-point method was employed.

The second technique allowed easy comparison of the fractures inferred from seismicity in the mine and those predicted by the SRM as a way of validating the predictive capabilities of SRM tests.

The results from the SRM investigations agreed well with the dominant structure inferred from seismic data analysis indicating that SRM testing may be used for prediction of rock mass response to undercutting and caving.

The study allowed to track the fragmentation of each SRM sample as it fractured which was similar to average fragmentation observed in the mine.

Further exploration of the SRM approach could be undertaken as a potential means to estimate primary fragmentation.

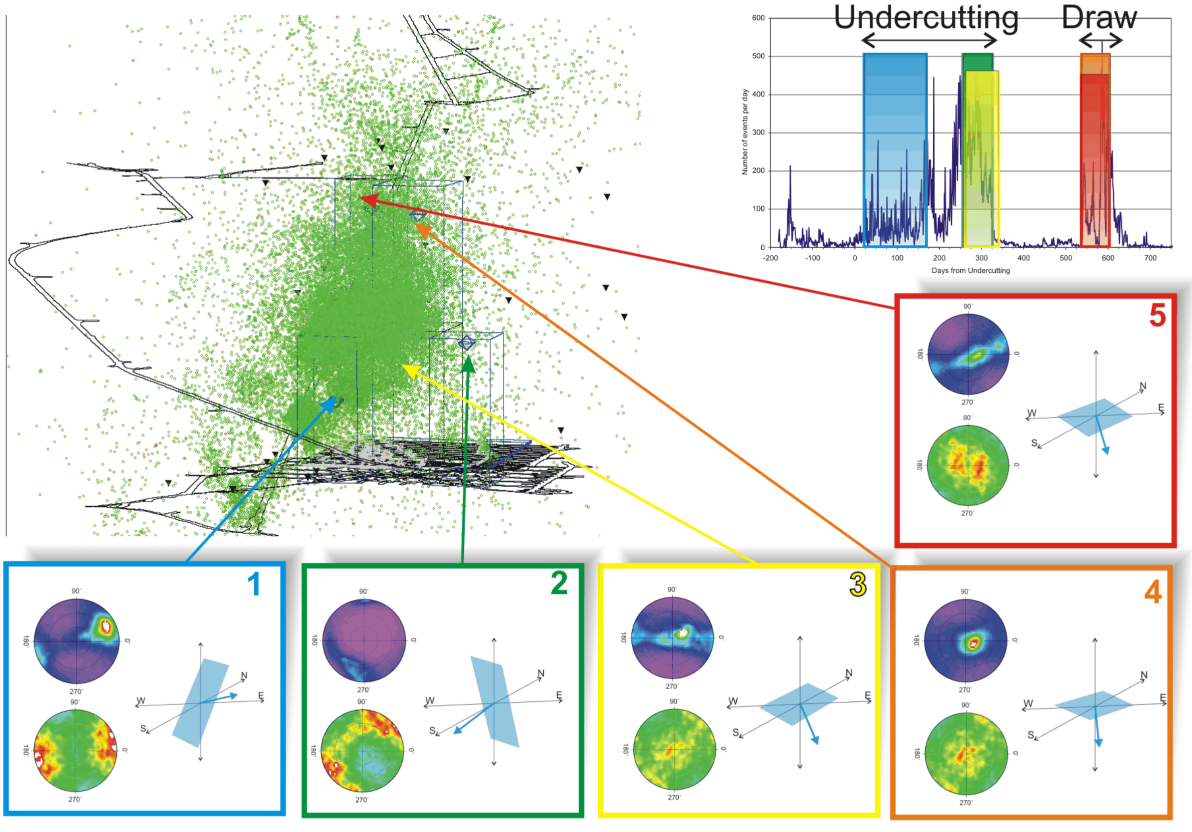


Figure 8: Stereographs showing the relative density of poles to the planes fitting the microseismic events induced at different stages of cave development at Northparkes Mine. The time period and the corresponding mining operation are shown in the histogram of daily seismic activity rate shown in the top-right corner. In each pane, the upper stereograph represents the density plot calculated for in-situ induced microseismicity while the lower stereograph is calculated for the synthetic model constructed for the corresponding geomechanical domain. The

results show a good correspondence between in-situ and synthetic seismicity. The diagrams show the interpreted dominant planar structures.

2.1.2 Microseismic tools for the analysis of the interaction between open pit and underground developments

As part of the Mass Mining Technology project, the seismic catalogue from different mines, representing different challenges in cave development were analysed, in order to enhance the information extracted from the seismic record. A case study consisted on the seismicity recorded during undercutting and production at Palabora Mine leading which lead slope failure in the open pit above the cave. The transition from surface to underground mining presents a series of technical and operational challenges, in particular those arising from the interaction between the cave and the overlying pit. Seismic monitoring provides a unique means to obtain near real-time information about the development of the fracturing process induced by the mining operations. The temporal, spatial and source size patterns in the seismicity recorded during undercutting and production at Palabora Mine were investigated in order to identify associations between seismic parameters and the subsequent slope failure that could serve as a forecast tool in other mines.

The analysis made use of b-values and the cluster index (CI), a parameter quantifying the degree of interaction and clustering in events. The results showed a good correlation between high degrees of clustering, changes in the slope of b-value distribution and the development of major failure in the area above those areas with highly clustered seismicity. The conclusions showed that the back analysis of the seismic data provides a prediction technique that could now be employed during the planning stages of a mining operation. It is hoped that by employing these techniques it would be possible to incorporate results from predicted fracture network behaviour into engineering designs in similar future mining operations and thus provide a means to predict and mitigate against large scale failure as observed at the Palabora Mine.

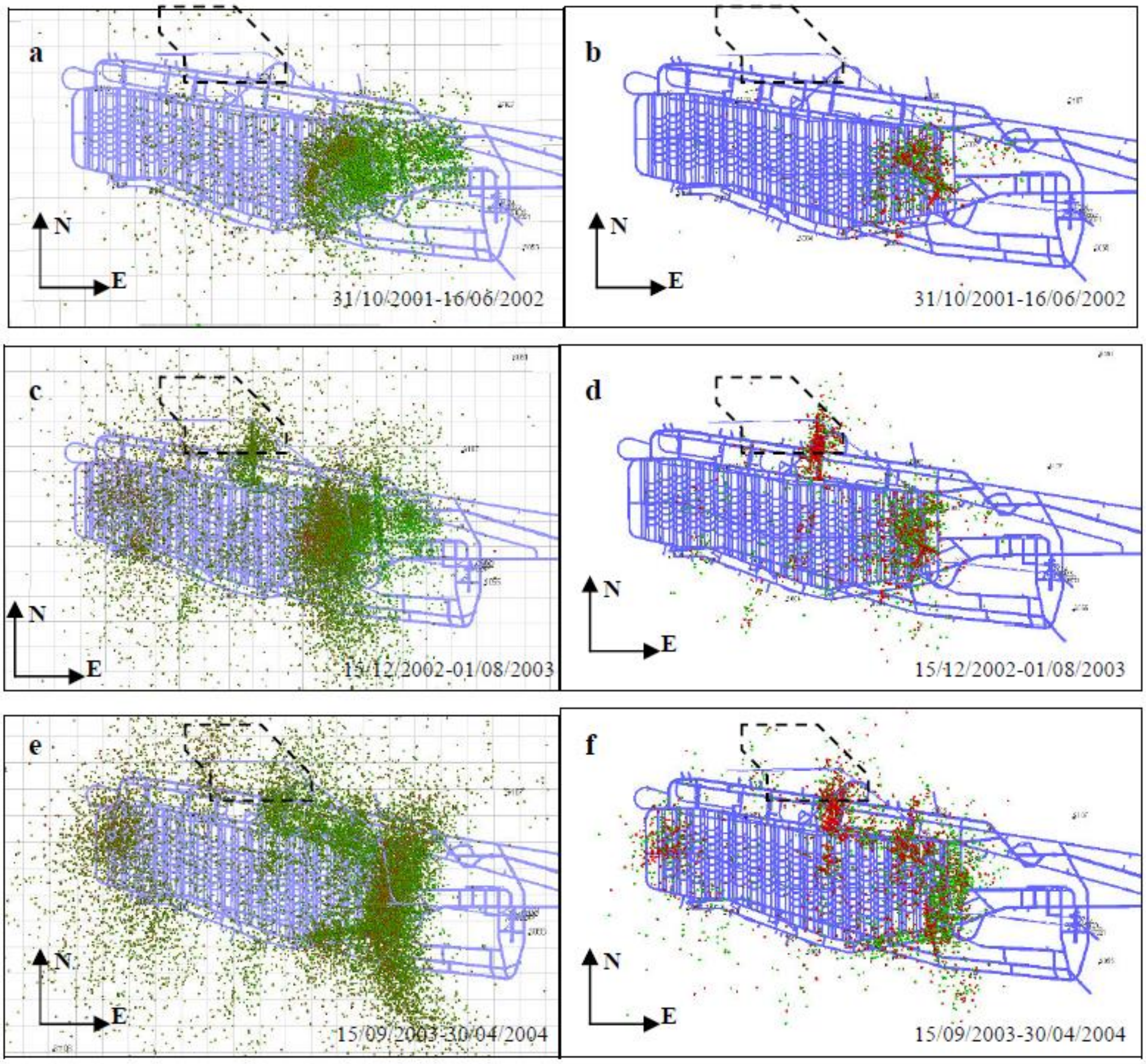


Figure 9: Plan view of the seismicity at Palabora mine in different periods preceding the Open pit North wall failure in November 2003 (a-d) and post failure (e-f). Left column (a,c,e) shows all events scaled to moment magnitude, Right column (b,d,f) shows only events with CI>0 scaled to CI. The dashed outline represents the projection of the open pit mobilised zone.

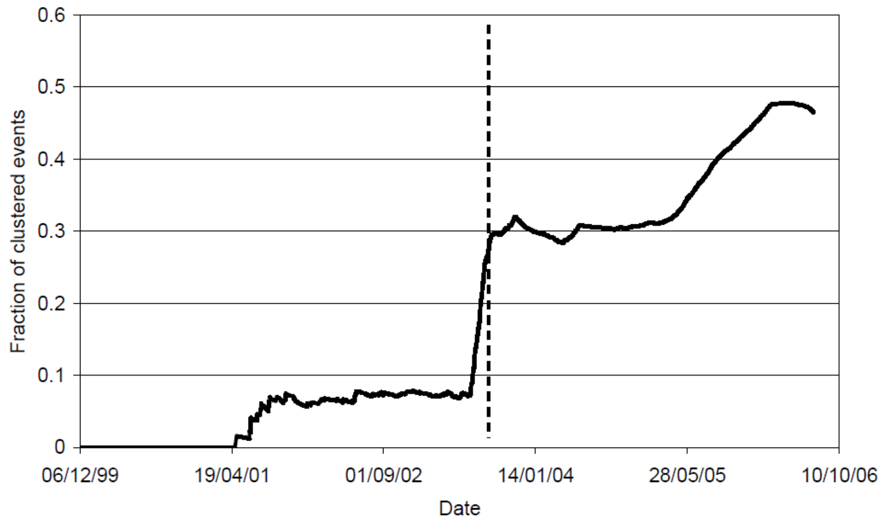


Figure 10: Evolution of the relative abundance of clustered events during the undercut and production of Palabora underground cave. The vertical dashed line marks the time of the slope failure in the open pit initiated at upper levels.

Figure 11: Evolution of b-values for the seismicity recorded

2.1.3 Quantification of preconditioning efficiency in cave mining

Hydraulic fracturing preconditioning has been applied as a means to induce cave propagation into unfractured rock volumes within underground caving mines. ASC analysed the processed microseismic events induced during preconditioning of an area within Northparkes mine to evaluate the effectiveness of the process and quantify the damage imposed by the hydraulic fracturing treatment. By combining the location of induced microseismic events with their source dimension, interpreted from the frequency content, it is possible to interpret and quantify the damage and degree of interaction between the induced fractures. The spatial and temporal evolution of the degree of interaction is provided by the cluster index, which allows the characterisation of events in terms of their potential interactivity.

The patterns of damage accumulation in different geomechanical domains of a caving production were analysed through a series of Synthetic Rock Mass samples subject to the same stress disturbance expected in the field and the analysis of the induced microseismicity. The analysis focuses on the comparison of damage and fracture propagation in caved volumes and a domain that failed to cave following the removal of the undercut and was subject to hydraulic pre-conditioning in order to stimulate cave development into the volume. In particular, the cluster index was calculated for sets of microseismic events induced during the hydraulic treatment of a non-caved rock volume and volumes previously caved. The degree of interaction between microseismic events and the evolution of source parameters such as moment magnitude and P and S-wave energy ratio appear to correlate with different behaviour in terms of cave propagation in the different rock volumes monitored in this study and can therefore provide feedback on the effect achieved on a preconditioned rock volume.

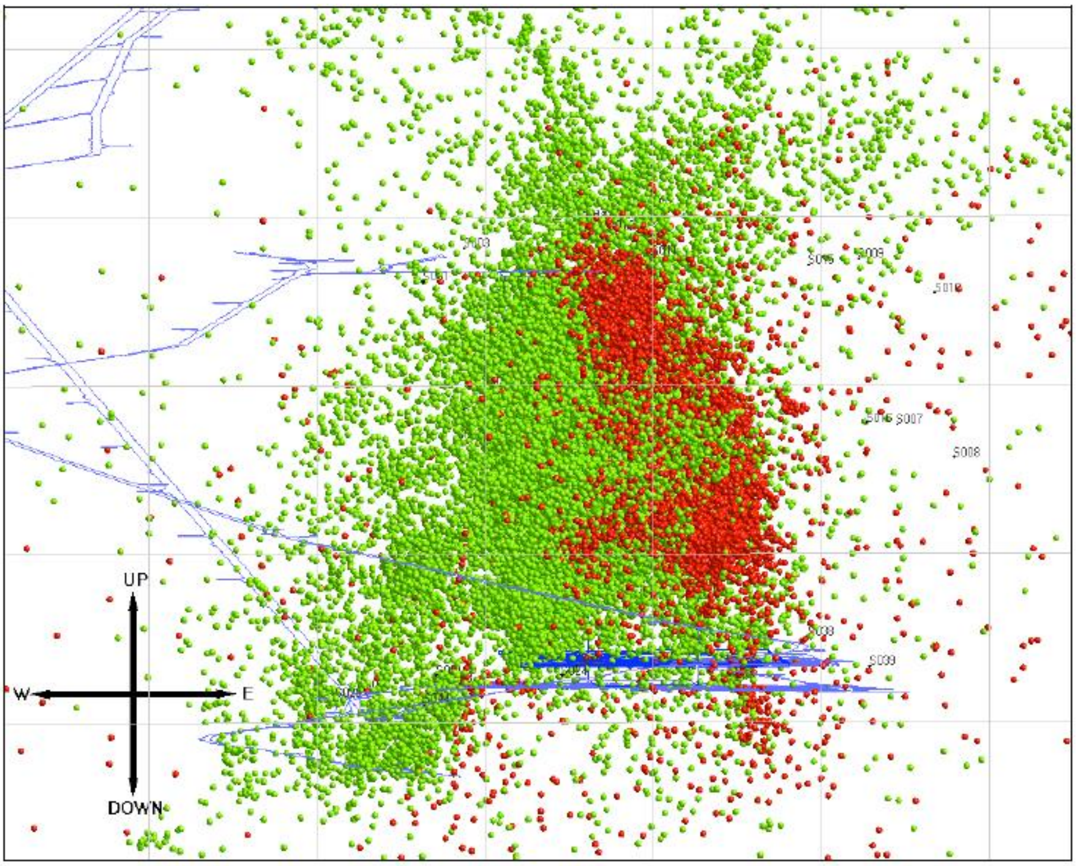


Figure 12: Microseismic events induced during the caving of volume E26 of Northparkes Mine. In green, events induced during the caving of the volume, in red, events induced during the preconditioning of the uncaved volume.

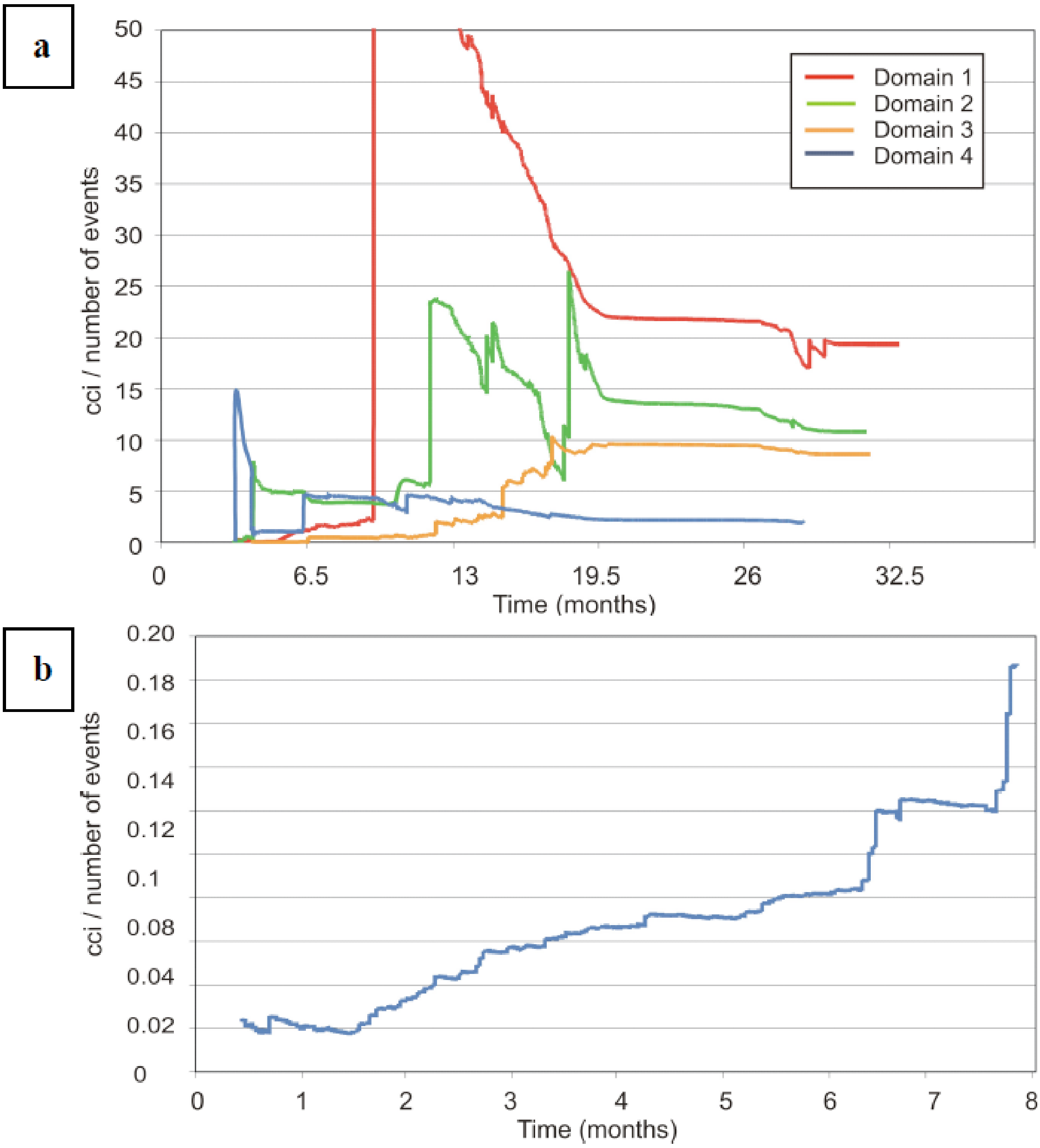


Figure 13: Evolution of the cumulative cluster index normalised to the number of events and cumulative number of located MS events for the events induced during the caving of four example domains (a) and the preconditioning of the uncaved volume (b).

2.1.4 Application of cave-scale rock degradation models in the imaging of the seismogenic zone

Microseismic monitoring provides insight into the location and extent of rock-mass fracturing induced by cave mining, enabling interpretation of the cave profile and validation of predictive numerical models. Source location uncertainties can lead to misinterpretation of the inferred characteristics of the fracture network. One principal source of uncertainty is the velocity model used to invert the location algorithm. Large-scale 3D numerical models of modulus changes across a caved mass can represent such complexities in the location algorithms, allowing more accurate interpretation of the microseismic activity. A Northparkes mine case study applies this advanced approach to microseismic data interpretation. The implementation of a nonlinear modulus-softening relation in a large-scale caving analysis was conducted at Northparkes mine. The model results were used to process the microseismic data and locate the seismogenic zone during cave propagation. A comparison of the predicted and observed microseismic events was completed to validate the seismic location and ray-tracing algorithms outlined herein.

Wavefront construction was used to forward-model travel times through a velocity model discretised as voxels that reproduce the damage distribution due to mining activities. This method can use predictive cave-scale numerical models of moduli distribution interpreted in terms of elastic wave-transmission velocities. Location of microseismic events using a cave-scale modulus model provides a more realistic description of the velocity structure and, hence, allows a higher resolution and level of confidence in the location and definition of the seismogenic zone. Model fit quality was assessed by comparing measured and modelled travel times. The quality of the fit between measured and modelled travel times for high-quality seismic events provides a means of validating cave-scale moduli-distribution predictions.

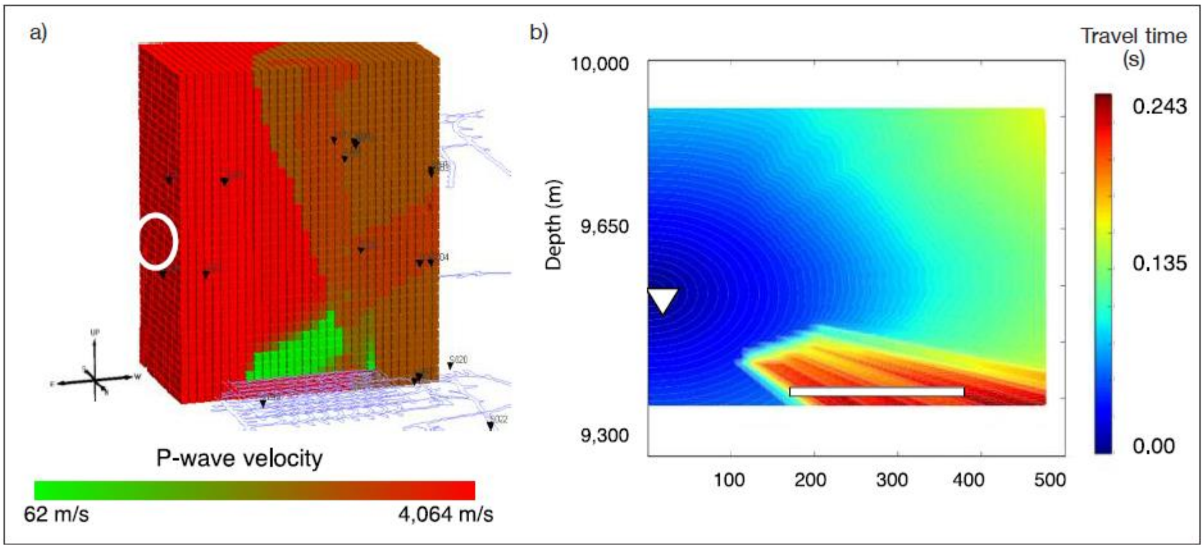


Figure 14: Example vertical section of the wave-transmission model built from the FLAC3D™-based predictions of modulus/density variability for early drawing stages at Northparkes lift 2. Voxels are colour scaled to P-wave–transmission velocity. b) Contour plot of travel times calculated through ray-tracing from the station circled in a) a white triangle in b) to the points in the chosen east-west section. The colour scale represents the travel time, with warm colours indicating higher travel time values. The white box shows the approximate position of the undercut.

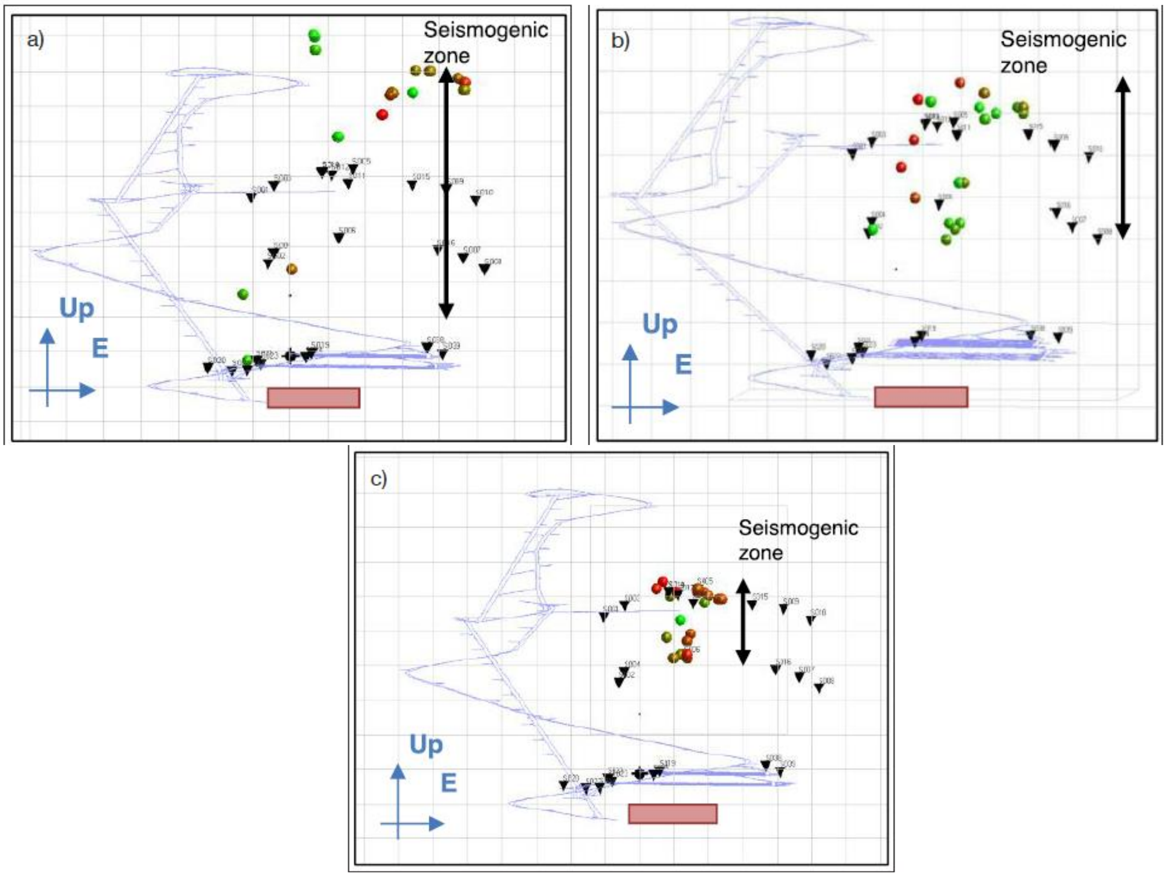


Figure 15:Location of sample high-magnitude microseismic events from early undercut development of volume e26 at Northparkes mine. Events were located using three velocity models: a) a homogeneous-isotropic velocity model, b) a coarse damage model (model 1), and c) a velocity model using the cave-scale yield predictive model (model 2). grid size is 50 m. Note: The red box represents the progress of the undercut at this stage

2.2 Clients

RioTinto

The University Of Queensland AUSTRALIA

AngloGold Ashanti

bhpbilliton

CODELCO

NEWCREST MINING LIMITED

LKAB

2.3 Publications

Reyes-Montes, J.M., Sainsbury, B.L., Andrews, J.R., and Young, R.P. (2016) 'Application of cave-scale rock degradation models in the imaging of the seismogenic zone'. *CIM Journal*, Vol. 7, No. 2, 2016

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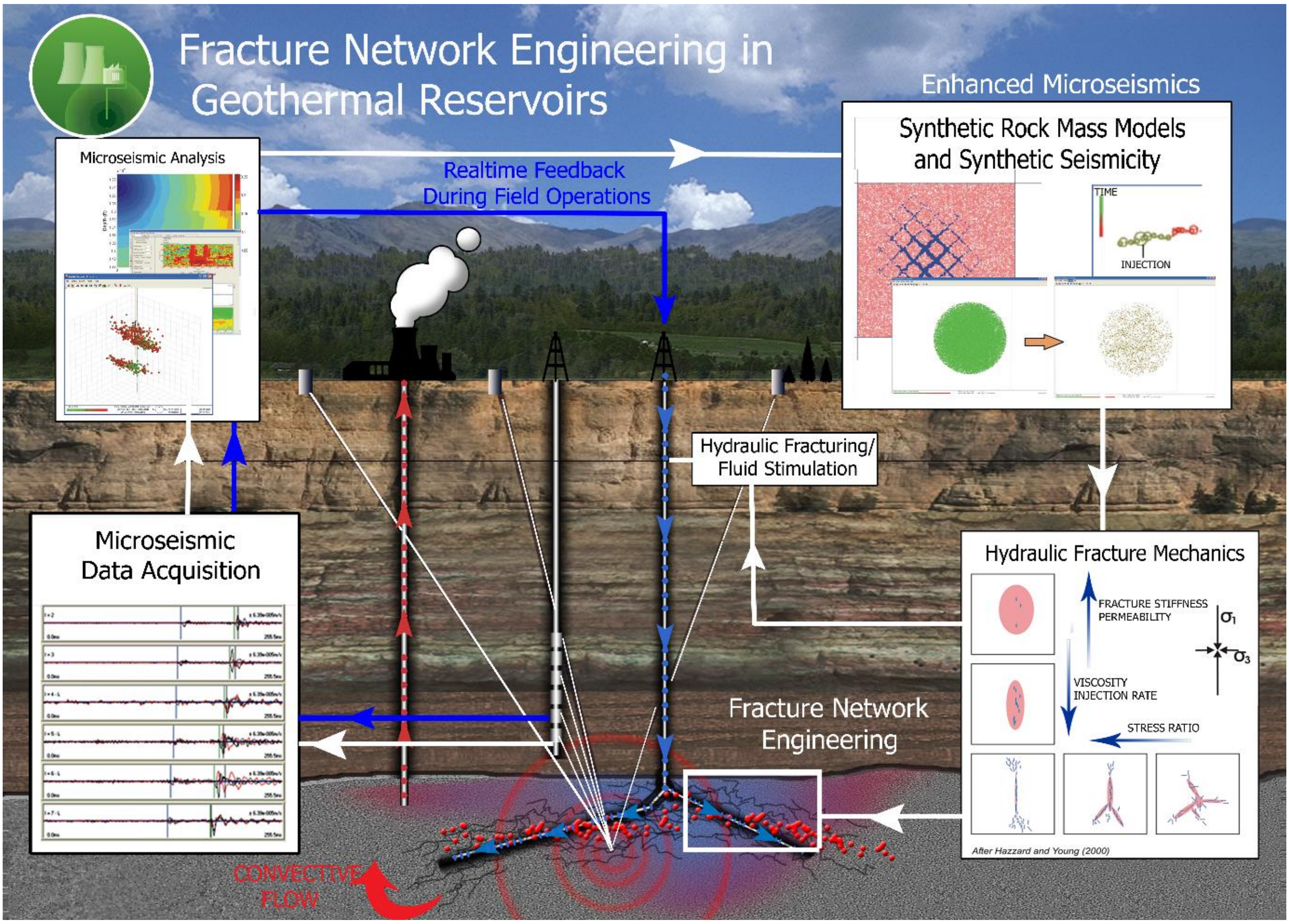
3 GEOTHERMAL



ASC was involved in the first commercial Enhanced Geothermal System (EGS) project in the EU and for over 15 years has undertaken international research programs for the monitoring of rock damage at reservoir scale. ASC's seismic processing software InSite is used for the processing of induced microseismicity and regional seismicity by commercial companies and research institutions managing geothermal projects in the U.S., Australia, Germany and the Republic of Korea.

Microseismic monitoring allows engineers to image and visualise active fracture networks within developing or producing geothermal fields, providing the following outcomes:

- Real-time monitoring and optimisation of hydraulic, chemical or thermal stimulation of geothermal fields. The location and characteristics of induced event provide feed-back of information to engineers on the position, growth and effectiveness of a hydrofracture stimulation, or can map extraction and injection paths in a producing field.
- Post-processing yields a greater understanding of the treatment history and fluid migration. Analysis of microseismic parameters and clustering yields treatment hot zones and provides for an assessment of the completion objectives
- 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

ASC provides a full integrated processing service from array design, through data management, processing and reporting to advanced interpretations with dynamic numerical models to better understand the growth and activation of the fracture structures. ASC's advanced analysis of microseismic data yields information on fracture networks such as distribution, persistence and orientations, and can describe the mechanisms behind the fracture growth leading to a better understanding of stimulation of geothermal fields. ASC provides the following services for stakeholders of the geothermal energy sector:

- Advanced post-processing, analysis and interpretation of client data using a range of techniques and software functionality developed in-house.
- Analysis of baseline regional seismicity.
- Seismic processing software for manual and automatic processing of induced and natural seismicity, incorporating customisable alarm systems adapted to local traffic-light-system regulations for induced seismicity.
- Design, optimisation and quality check of seismic monitoring arrays.

- Active and passive source tomography for imaging of fractured reservoir volumes.
- Acquisition system-independent seismic processing software for automatic, real-time processing of induced seismicity
- In-depth understanding of fracture mechanisms through the integration of acquired data and “Synthetic Rock Mass” models built with Itasca’s geomechanical models.
- Structure imaging and velocity inversion combining the illumination capability of controlled seismic sources and passive seismic events.
- P- and S-wave time-lapse tomography to image the degradation of reservoir and host rock and structures in terms of elastic modulus and fracture density.
- Fully-featured microseismic training courses focussed on the principles behind the technology, processing algorithms and hands-on experience of using processing software.

3.1 Case studies

3.1.1 Optimised EGS reservoir stimulation using microseismic and numerical methods

Passive microseismic (MS) monitoring provides a unique tool to monitor the evolution of fluid injection around the treated geothermal rock reservoir and seismic source mechanisms can yield information about the nature of deformation. However, the conflict between induced tensile fractures suggested by theory and shear failure observed from recorded waveforms is still the subject of much debate. Furthermore, the triggering mechanism for seismicity with a large magnitude has yet to be clearly understood, as well as the fluid migration in EGS. For these reasons ASC developed a project to integrate and correlate microseismic field observations with simulated microseismicity from numerical models using discrete element methods.

On the one hand, data acquisition and microseismic processing were used to map a disturbed or enlarging fracture network in space, magnitude and evolution. The feedback provides "first order" information to engineers, potentially in real time, so that decisions on project design can be made and revised effectively and efficiently. On the other hand, a Synthetic Rock Mass (SRM) numerical model was developed. SRM samples model the movement and interaction between stressed assemblies of bonded non-uniform-sized spheres (intact rock) with an embedded discrete network of disc-shaped flaws (Discrete Fracture Network) that reproduce the pre-existing joint fabric (represent joints, faults or other pre-existing fractures as smooth, frictional (or cohesive) planar features) (Pierce et al., 2007; Pierce, 2010). SRM models employed Itasca's *PFC2D*/*PFC3D* codes to create an assembly of bonded particles that represent the rock mass on a large scale (e.g. 10-100m). SRM samples that are subjected to the same mechanical or fluid disturbance expected in the field produce synthetic seismicity that can be compared directly with microseismic data collected in the field.

This approach can effectively monitor the rock mass disturbance as it is developed on site and has two principal objectives: (1) to use the models to better interpret the causal effects of the microseismicity by analysing the micromechanics occurring within the numerical model framework (recognising that in the model we observe all activity within the configured boundary conditions, whereas field observations record only a portion of the activity depending on the sensitivity of the monitoring system); (2) to use the observed microseismicity to feed back into the development of the models and so validate their results, in order to develop robust predictive models for engineering the reservoir and the induced or mobilised fracture network (both for the project in hand or for future projects).

The results showed similar MS propagating patterns between field and model:

- Event locations with time
- Linear orientations
- Truncation or arrestment of events in the N-E and S-W directions

The numerical results qualitatively agreed with field observations and revealed the possible interaction between new fractures and natural fractures indicated by recorded microseismic events.

The validated numerical models can help elucidate our understanding of the mechanics underlying seismicity, and examine in detail the interaction between fluid pressure, rock deformation and slip on existing fractures.

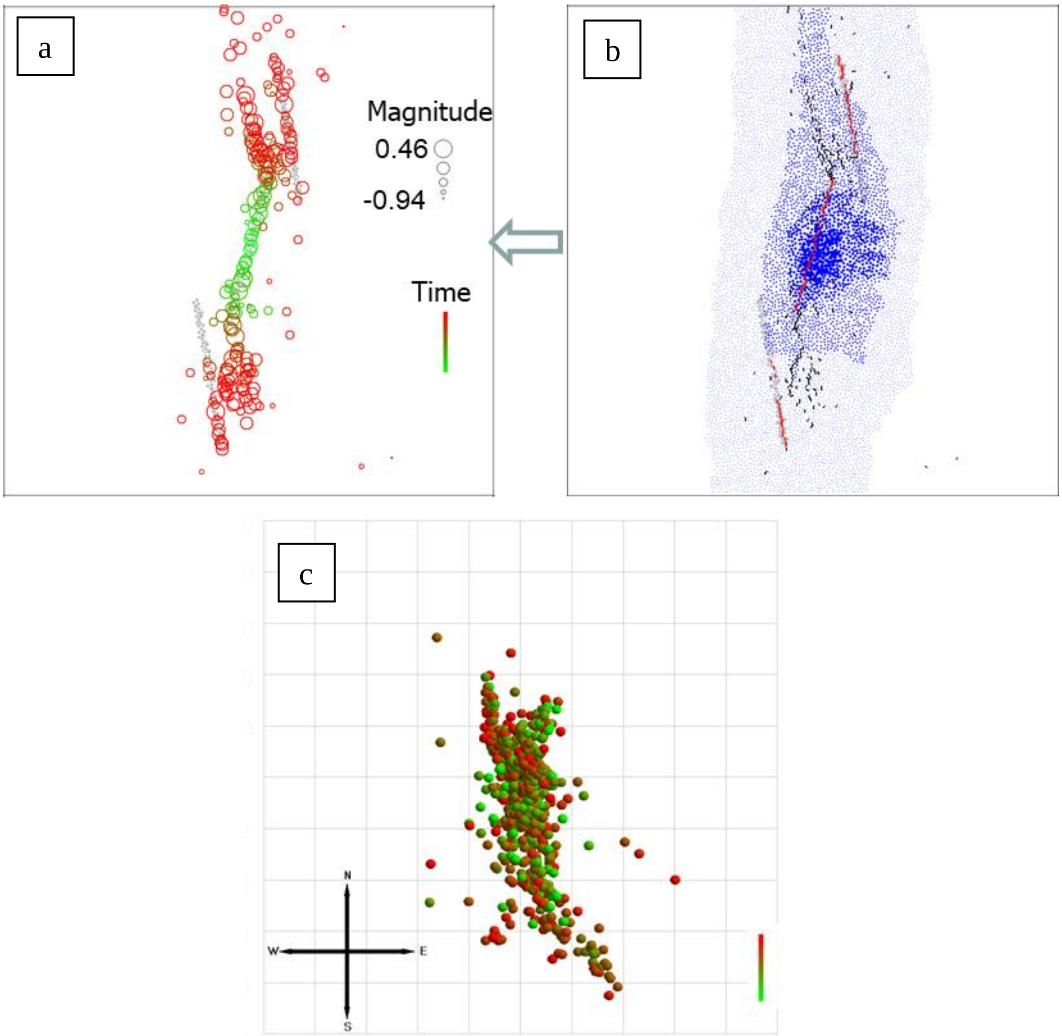


Figure 16: a) synthetic MS events induced in an SRM sample subject to fluid injection for 63.8 hours. b) Fluid flow and induced cracks in the SRM sample subject to hydraulic injection. c) MS events induced during the EGS treatment at Soult-sous-Forêts.

3.2 Clients

3.3 Publications

Pettitt, W.S., Damjanac, B., Hazzard, J.F., Han, Y., Sanchez-Nagel, M., Nagel, N., Reyes-Montes, J.M. and Young, R.P. (2012). 'Engineering Hydraulic Treatment of Existing Fracture Networks'. *SPE Annual Technical Conference and Exhibition*, 8-10 October 2012, San Antonio, Texas, USA. DOI 10.2118/160019-MS

Pettitt, W.S., Pierce, M., Damjanac, B., Hazzard, J., Lorig, L., Fairhurst, C., Sanchez-Nagel, M., Nagel, N., Reyes-Montes, J.M., Andrews, J. and Young, R.P. (2012) 'Fracture Network Engineering: Combining Microseismic Imaging and Hydrofracture Numerical Simulations'. *Proceedings 46th US Rock Mechanics/Geomechanics Symposium, ARMA 2012*. Chicago, June 2012.

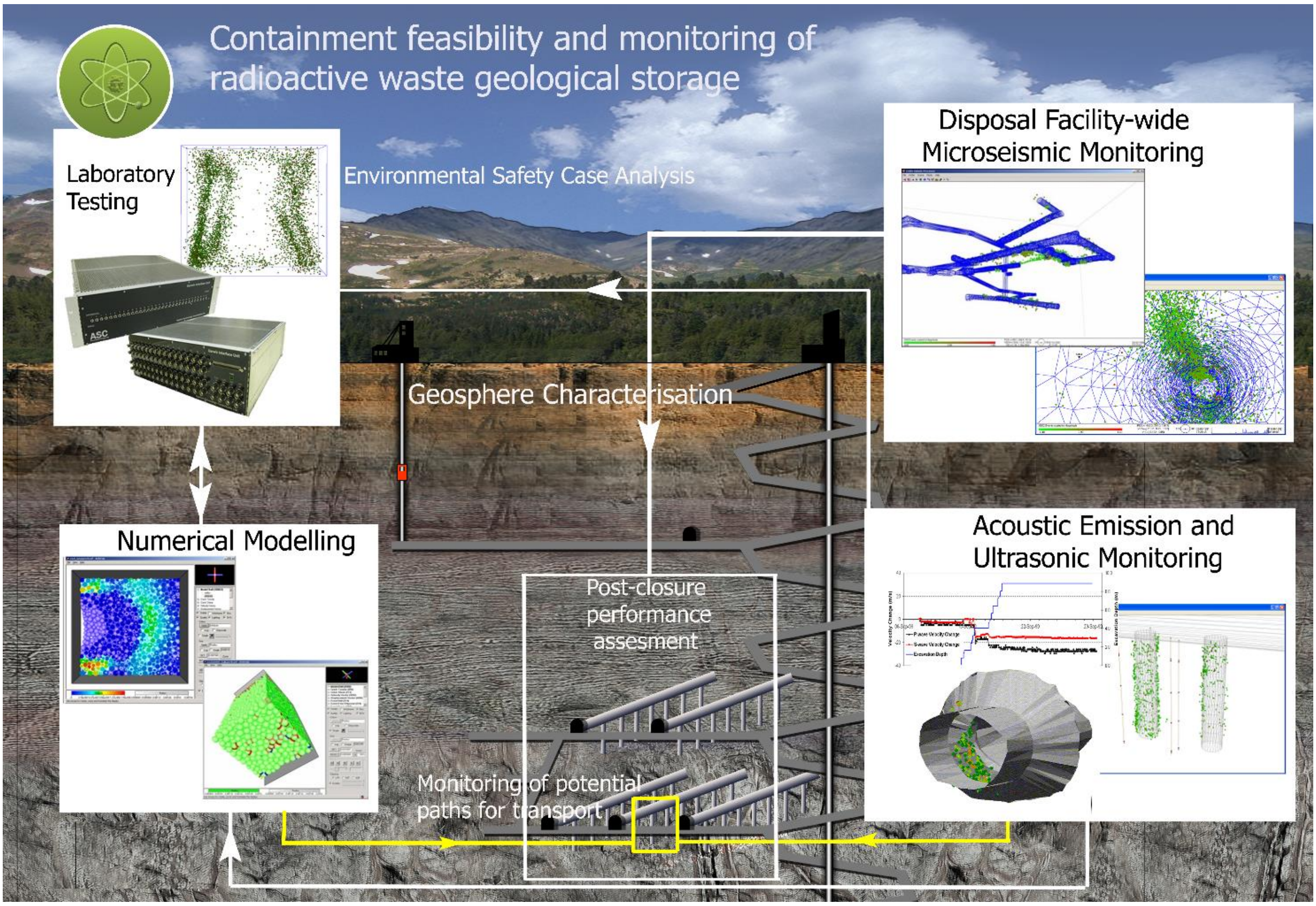
Zhao, X.P., Reyes-Montes, J.M. and Young, R.P. (2012) 'The role of pre-existing fracturing in enhanced reservoir treatments'. *Proceedings 46th US Rock Mechanics/Geomechanics Symposium, ARMA 2012*. Chicago, June 2012.

Zhao, X.P., Reyes-Montes, J.M., Andrews, J.R. and Young, R.P. (2011) 'Optimised EGS Reservoir Stimulation using Microseismic and Numerical Models'. In *Proceedings, GRC Annual Meeting (San Diego, USA*).

Andrews, J.R., Reyes-Montes, J.M. and Young, R.P. (2011) 'Continuous Microseismic Record Analysis for Reservoir Hydrofracture Treatments'. In *Proceedings, GRC Annual Meeting (San Diego, USA*).

Pettitt, W., Pierce, M., Damjanac, B., Hazzard, J., Lorig, L., Fairhurst, C., Gil, I., Sanchez, M., Nagel, N., Reyes-Montes, J.M. and Young, R.P. (2011) 'Fracture Network Engineering for Hydraulic Fracturing'. *The Leading Edge*, ***30***(8), 844-853, doi 10.1190/1.3626490.

4 GEOLOGICAL STORAGE OF RADIOACTIVE WASTE



ASC provides cutting-edge research, consultancy and tailor-made technological solutions for local geosphere characterisation, remote monitoring of critical rock excavations and engineered structures in radioactive waste disposal. In the past 20 years, ASC has been involved in the monitoring of major international projects for the feasibility of underground geological storage for the permanent disposal of high level radioactive waste. Projects include the characterisation and quantification of the EDZ in crystalline rock (Posiva, Finland; CNL, Canada), long-term baseline site monitoring (CNL, Canada), the impact of thermal loads on the host rock around canister deposition holes (SKB, Sweden; Posiva, Finland) and monitoring of sealing properties of engineered barriers (CNL, Canada).

ASC was a partner in three major EU-funded research projects addressing the permanent disposal of radioactive waste:

- **Safeti**: Seismic validation of 3D thermo-mechanical models for the prediction of the rock damage around radioactive spent fuel waste.
- **Omnibus**: Development of the tools and interpretation techniques for ultrasonic surveys to monitor the rock barrier around radioactive waste packages.
- **Timodaz**: Thermal impact on the damage zone around a radioactive waste disposal in clay host rocks.

ASC provides the following service to the radioactive waste storage industry:

- Seismic monitoring at all scales from regional earthquake site characterisation to micro seismic and acoustic emission studies.
- Repository-wide 3-D seismic array design, installation and operation from consultancy and post-processing data analysis, to project management.
- Three-dimensional ultrasonic surveys to quantify damage and disturbance accumulation.
- Embedding of sensors within structures, such as concrete bulkheads, to assess integrity.
- Validation and development of numerical models for predictive modelling of repository behaviour.
- Acoustic Emission and microseismic monitoring to detect fractures around engineered structures and delineate potential fluid pathways

4.1 Case Studies

4.1.1 **Timodaz: Investigating effects of the thermal impact on the EDZ and the host rock around a radioactive disposal site.**

The TIMODAZ project was a 4-year project that involved monitoring SCK-CEN's PRACLAY gallery to understand the effects of the EDZ (Excavation Disturbed Zone) and heat on the gallery and the damaged zone surrounding it. The test gallery was excavated in Boom Clay and Bentonite seals were used to seal the gallery for the pressurisation tests.

During this project ASC developed seismic processing techniques for assessing the characteristics and behaviour of the rock mass around the PRACLAY heater test using ultrasonic and acoustic data. Using these techniques ASC processed the collected data to explain the evolution of the host rock fabric and fracture network.

To develop the seismic processing technique to be used, two different inversion methods were applied to two different experimental data sets. The chosen data set was then used for validation of the inversion method to be used for the TIMODAZ project.

P-wave transmission velocities were calculated from the daily ultrasonic surveys; the changes in transmission properties between transmission-receiver pairs were interpreted as changes in the material properties. By cross-correlating the p-wave transmission velocities for each ray-path with a reference survey a velocity resolution of ±2 $m \cdot s^{-1}$ was achieved. The Kachanov effective medium theory for transversely isotropic symmetry was then used on these velocities to model the crack density for the rock.

A strong 3D anisotropy was observed, the evolution of which show the changes in the host rock fabric and fracture geometry due to excavation of the test tunnel. The anisotropy is interpreted as a result of sub-horizontal fabric of microcracks.

A decrease trend in crack density was observed towards the end of the study period indicating self-healing of host clay rock.

After excavation, damage was dominated by microcracks that developed normal to the radial direction.

Changes in P-wave velocities fit modelled transmission velocities corresponding to a fabric of microcracks well indicating no connectivity between induced or pre-existing crack.

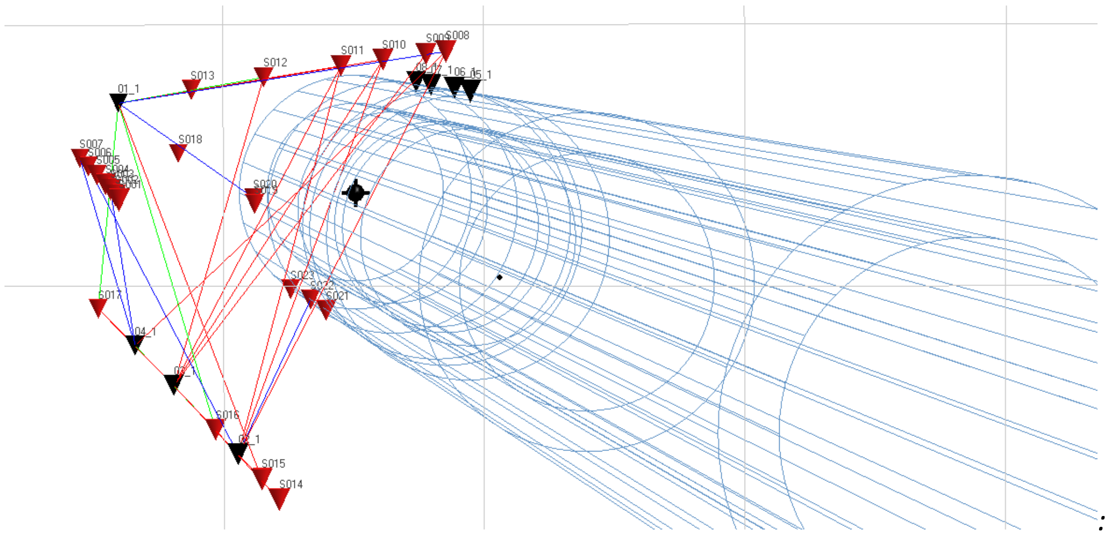


Figure 17: Raypaths for P-wave velocity surveys shown crossing different regions in the Boom Clay host rock neighbouring the PRACLAY test gallery.

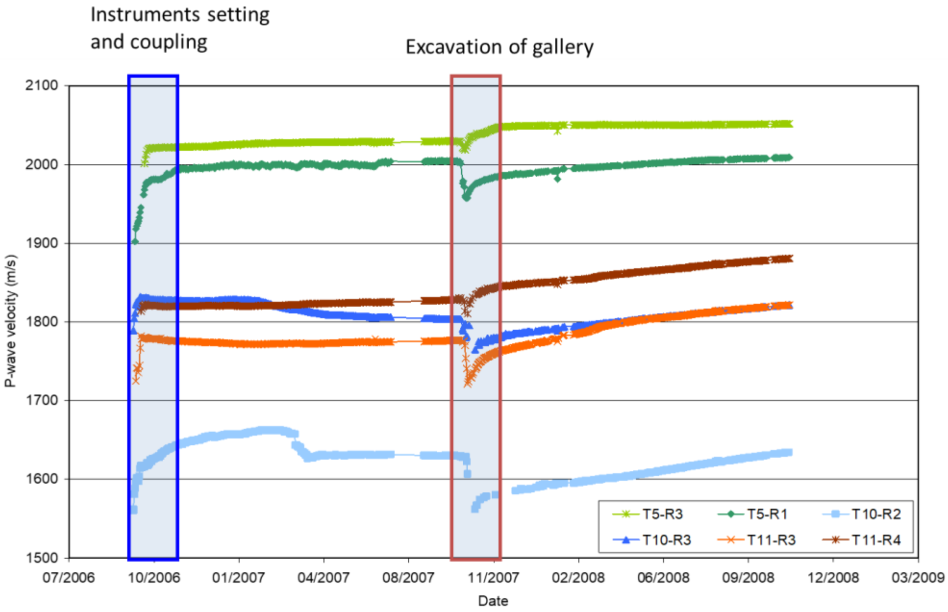


Figure 18: P-wave velocity along sample raypaths crossing different regions in the Boom Clay host rock neighbouring the PRACLAY test gallery. Showing microcrack healing or matrix compaction induced by excavation of gallery.

4.1.2 **Äspö Pillar Stability Experiment**

ASC carried out the acoustic monitoring of a series of tests at SKB's Äspö Hard Rock Laboratory to demonstrate effect of confining pressure in a nuclear repository deposition hole on the propagation of micro-fractures, assess spalling prediction capability and investigate the effect of thermal loads on the EDZ. The overall objective was determining an optimal deposition hole density in the design of a permanent storage for high-level radioactive waste.

Different monitoring methodologies were used, combining passive and active Acoustic Emission monitoring.

In particular for the Pillar Stability Experiment, ASC ASC designed a 24-piece ultrasonic acquisition system, with ray paths skimming the borehole EDZ, in four vertical arrays providing acoustic emission (AE), ultrasonic surveys and data processing via InSite. Two 1.8m diameter vertical deposition holes, of 5m depth, were drilled in isotropic, fractured diorite, forming a pillar, one confined with a 0.8MPa internal pressure and both were subjected to heating in two phases.

Pre-excavation testing established the velocity profile and calibration of the receiver array allowed passive monitoring, data acquisition and auto-processing. Data was leached and parsed for noise before locating events spatially and temporally. Manual picking as part of waveform analysis allowed more detailed data interpretation.

Outcomes:

- Assessing the effects of drilling and heating on the micro-fracturing of the pillar
- Identifying possible reduction in fracturing due to the confining pressure
- Optimal deposition hole density constrained.
- Spalling prediction model re-evaluated.

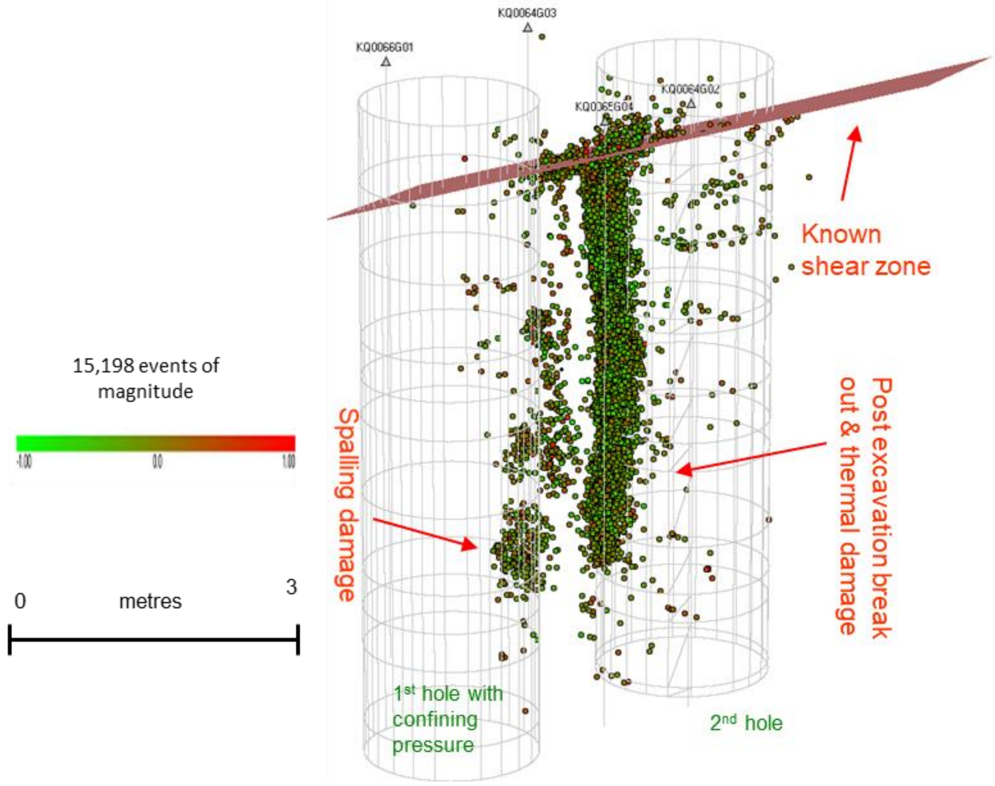


Figure 19: AE locations of all 17,360 AE events induced during the Pillar Stability Experiment.

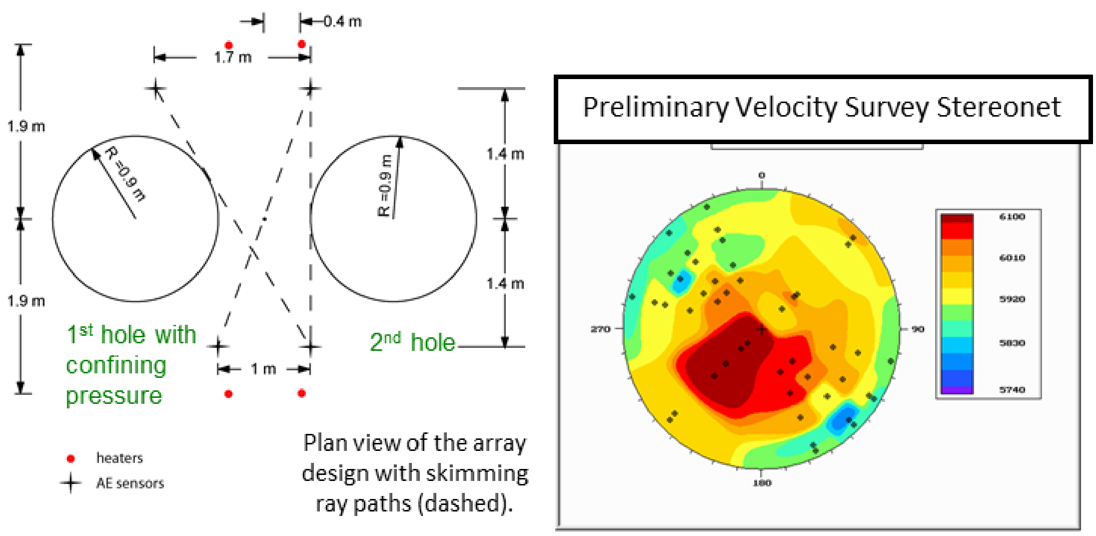


Figure 20: Sample P-wave velocity survey carried out through the Pillar between the test deposition holes

4.1.3 AECL’s Underground Research Laboratory

The Underground Research Laboratory (URL) is a facility established in 1987 by Atomic Energy of Canada Ltd. (AECL, now CNL) in Manitoba to investigate the rock mechanical and geotechnical aspects of the safe geological disposal of radioactive waste. It represented a unique facility to study the fundamental behaviour of initially unfractured granite in-situ. The facility consisted of a network of tunnels that have been excavated at a depth of 420 m below the surface. ASC was involved in the monitoring of the microseismic activity and acoustic emission activity induced during and after the excavation of different galleries and during the heating and pressurisation of the Tunnel Sealing eXperiment chamber, focusing on the EDZ and the sealing properties of the engineered barriers.

The monitoring of induced seismicity at AECL’s URL was performed over a 20-year period, during a number of Experiments between 300-440 metres depth, including rock behaviour immediately following gallery excavation using different techniques and changes in fluid pressure.

Analysis of the seismic data has helped to provide a fundamental understanding of how the initially unfractured Lac du Bonnet granite responds to stresses induced by excavations, as well as the secondary effects of thermal pressure and confinement:

- Overlapping seismic arrays, have shown microseismic scale events (-4<M<-1) to be spatially associated with clusters of precursory higher frequency acoustic emissions (-7<M<-5).
- The damage zones around excavations are concluded to be in metastable equilibrium, with small stress changes (associated with nearby excavations, temperature change or confinement) to cause new crack initiation and development.
- The effect of temperature on the EDZ was imaged using the located MS events.
- The temporal correlation allowed an interpretation of the EDZ evolution
- Considering a short lag time, increases in the rate of temperature rise correlated with increases in MS event rate. The first lag time is 31 days and corresponds to a temperature change of 6°C. Subsequent lag times are shorter suggesting that smaller temperature changes are required at higher temperatures to induce microcracking

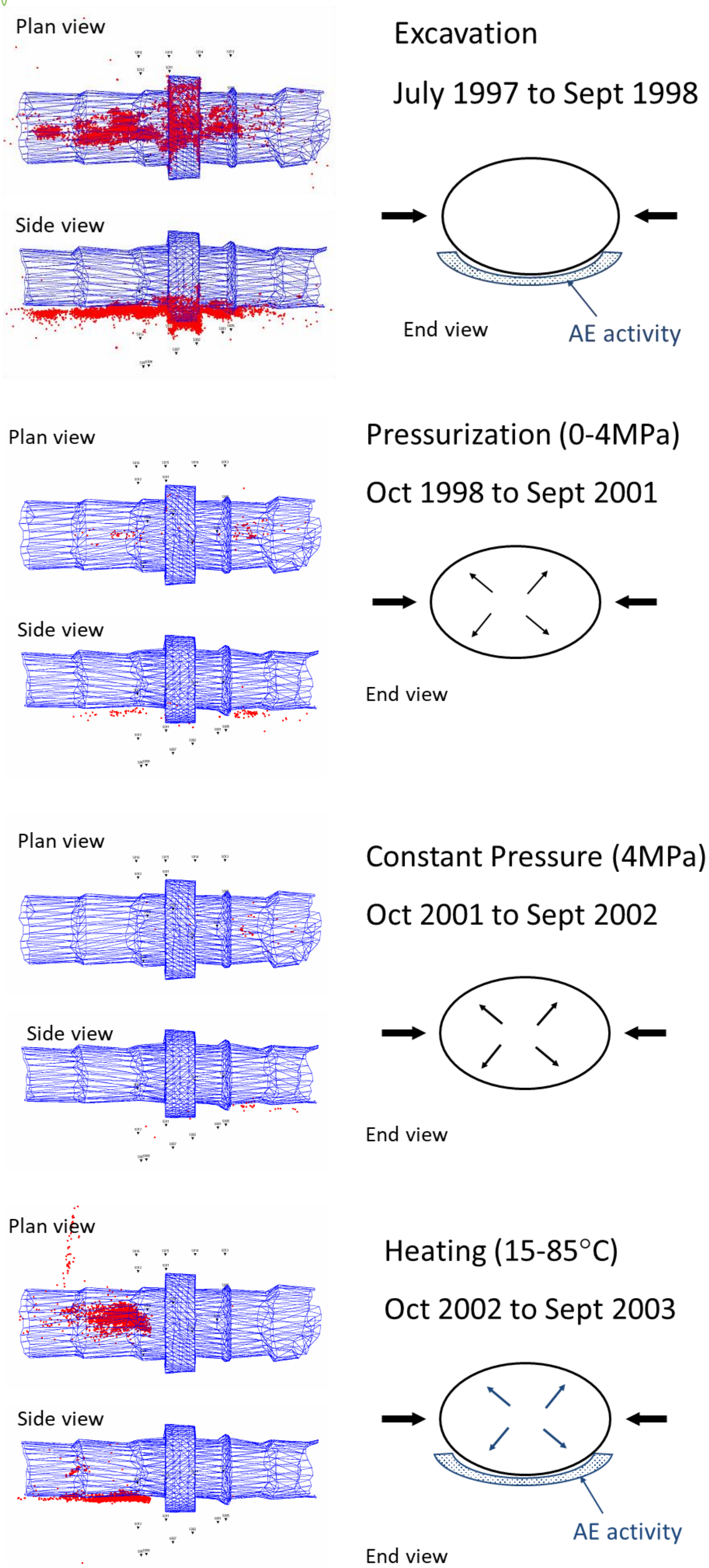
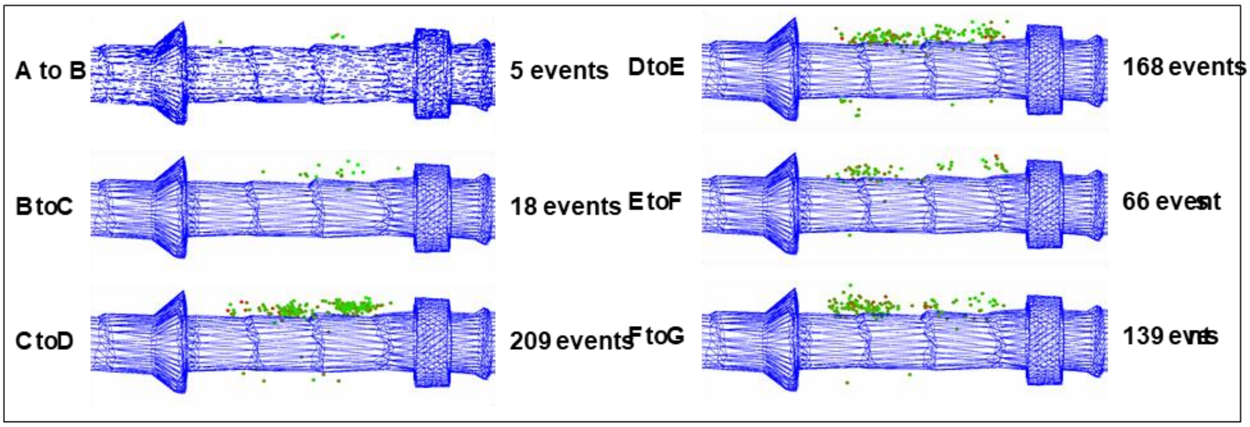


Figure 21: High-frequency AE response recorded by a local sensor array around the lower half of the Tunnel Sealing eXperiment test chamber.



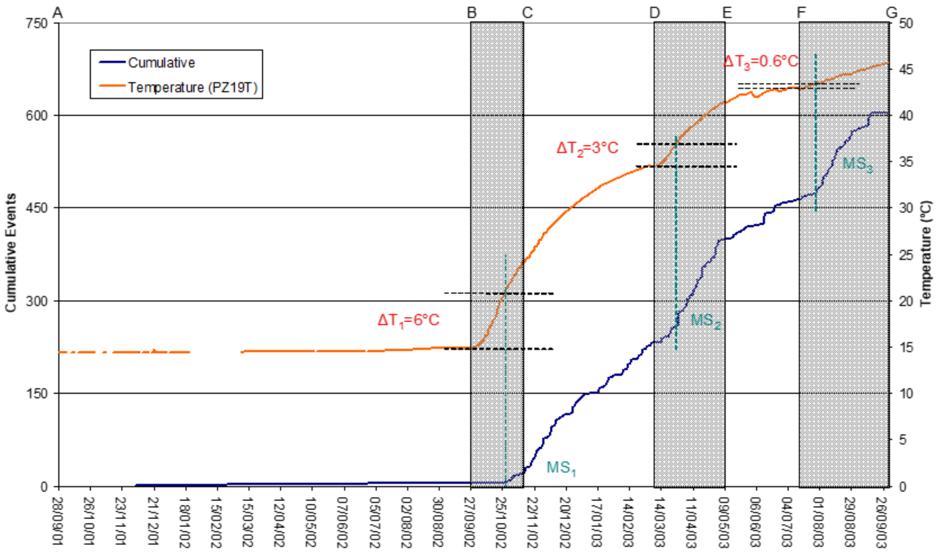


Figure 22: MS response of the Tunnel Sealing eXperiment gallery during the heating and pressurisation of the test gallery.

4.1.4 **Tomographic imaging of the Excavation Damage Zone**

Ultrasonic tomography is an active imaging technique that utilises the ultrasound to image the velocity variation beneath the excavation surface. This can provide a map of damaging through the structure based on the spatial variation of velocity images.

The combination of tomography with other geophysical measurements can characterise the rock deformation and provides better evaluation of the long-term safety and integrity of the rock mass.

ASC carried out the design and data processing for imaging the Excavation Damage Zone (EDZ) of the ONK-TKU-3620 niche at Posiva's Onkalo Underground Disposal Facility, excavated through drill and blast, to obtain a P-wave tomographic image of the top 0.8 m of the tunnel floor. The P-wave tomography covered a three-dimensional volume of the EDZ field sampled by multiple two-dimensional planes defined by drill-holes, providing 30 2-D sections along the North-South, East-West, North West-South East and North East-South West directions.

The results showed that the P-wave velocity varies between 4,800 $m\cdot s^{-1}$ and 6,500 $m\cdot s^{-1}$, with higher velocities at the northern end of the EDZ field. A general trend of increasing velocities with depth was observed, with lower velocities confined to the top 0.5 m associated with a higher degree of fracturing or damage. The modest variation of velocity with direction also indicates weak anisotropy. The higher velocities in the NE-SW direction may suggest oriented fracturing developed in its normal direction NW-SE. Some low velocity anomalies near a number of drill-holes can also be observed in the tomographic image and may be associated with local damage around the drill-holes. The combination of tomography surveys with other geophysical measurements can characterise the rock deformation in the EDZ and provides better evaluation of the long-term safety and integrity of the rock mass around engineered openings in the nuclear disposal facility.

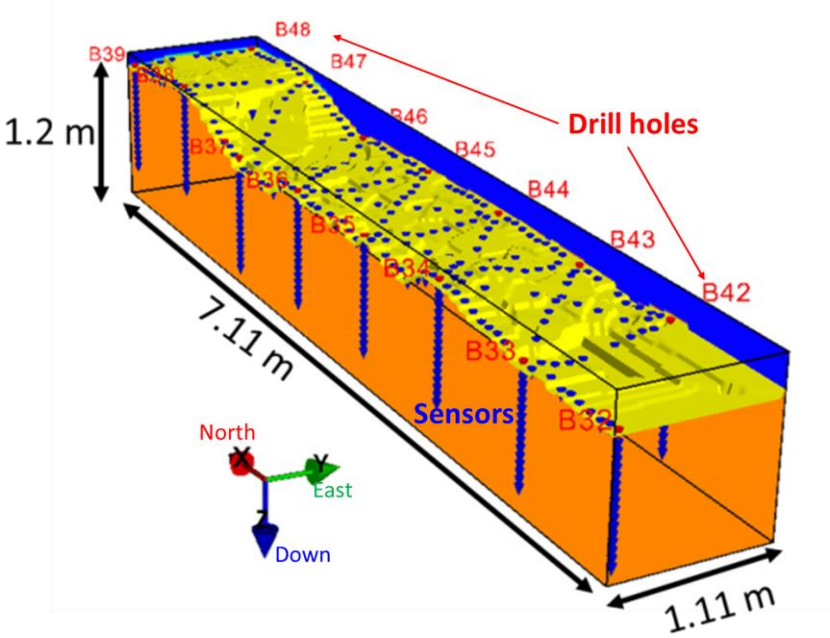


Figure 23: Configuration of the array designed for the tomographic imaging of a sample section of the EDZ

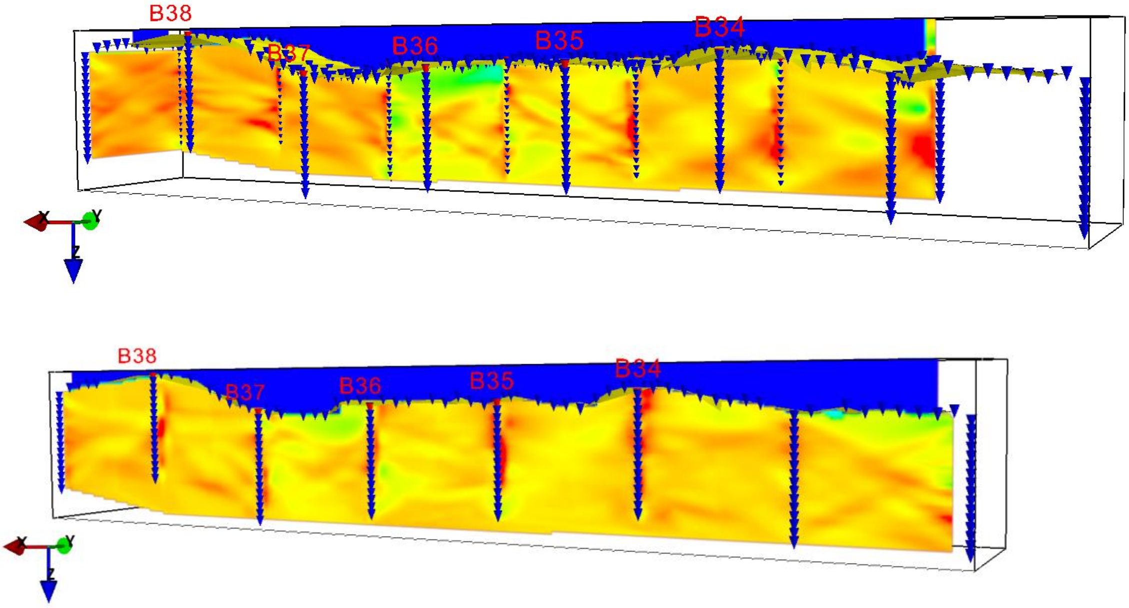


Figure 24: Summary of tomographic planes using all available surveys in 3D viewing the east side (top) and the west side (bottom) N-S planes

4.1.5 Posiva's Olkiluoto Spalling Experiment (POSE)

Posiva's Olkiluoto Spalling Experiment (POSE) main objectives are to predict the stress state around a deposition hole both before and during heating and also to find the time at which expected spalling begins. As part of the monitoring methodologies for the experiment, Acoustic Emissions and Ultrasonic surveys were used during the different phases of the experiment,

Continuous acoustic emission (AE) monitoring is a passive technique that records the acoustic energy emitted from the structure over an array of sensors. This can provide a map of fracturing through the structure based on the source locations of the acoustic emissions recorded.

Ultrasonic velocity surveys are employed at regular intervals to monitor changes in the material properties of the structure more specifically the changes in P- and S-wave velocities

ASC designed the acoustic monitoring array and processed the continuous data recorded over the three-month period of the heating and cooling phase of the experiment. An array of 24 piezoelectric AE transducers mounted on 4 borehole frames (6 transducers per frame) were installed to carry out both passive and active ultrasonic monitoring. The monitoring array was configured to allow for all transducers to switch between active and passive modes, maximising the azimuthal coverage of acoustic emission and the number of raypaths surveying the volume around the test hole.

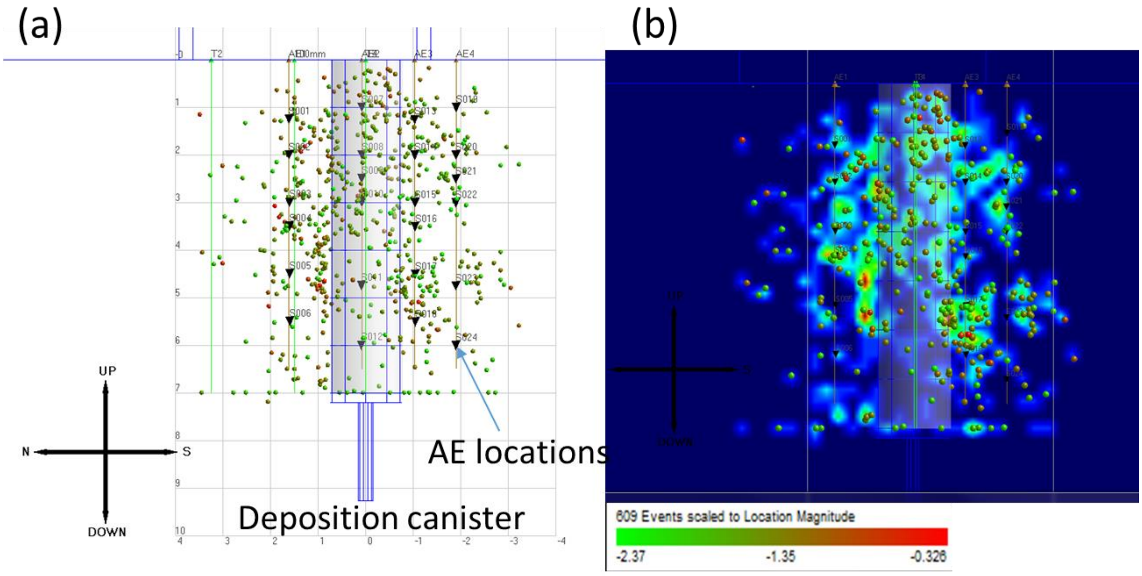


Figure 25: a) Located AE events during the monitoring period along the POSE 3 test hole. b) event density for the complete monitoring period

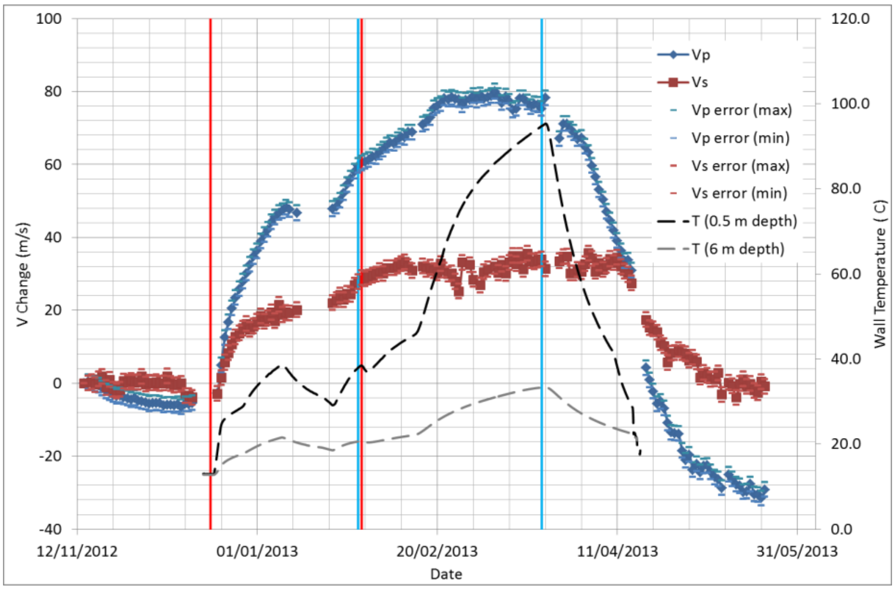


Figure 26: Changes in average transmission velocities relative to the ultrasonic survey performed on 14/11/2012. Horizontal lines above and below each data point indicate the error margin. Vertical solid lines indicate dates when heaters were switched on (red) and off (blue).

4.2 Clients

4.3 Publications

Huang, J.W., Flynn, J.W., Haycox, J.R., Reyes-Montes, J.M., Mustonen, S., Young, R. P., and Maxwell, S.C. (2016) 'Ultrasonic Tomography of the Excavation Damage Zone at the Onkalo Nuclear Waste Repository Facility, Finland'. *ISRM International Symposium on In-Situ Rock Stress*, 10-12 May 2016, Tampere, Finland.

Reyes-Montes, J.M., Pettitt, W.S., Haycox, J.R., Lopez-Pedrosa, M. and Young, R.P. (2015) 'Microseismic, Acoustic Emission and Ultrasonic monitoring in radioactive waste disposal and feasibility studies'. *Proceedings 77th EAGE Conference and Exhibition*. Madrid, Spain 1-4 June 2015.

Moretti, H.C., Reyes-Montes, J.M., Haycox, J.R. and Young, R.P. (2013) 'Temporal analysis of fracturing using acoustic emissions at the Äspö Pillar Stability experiment'. *Rock Mechanics for Resources, Energy and Environment- Proceedings of EUROCK 2013 - The 2013 ISRM International Symposium* Wroclaw, Poland, 23-26 Sept 2013, pp 627-631.

Goodfellow, S.D., Nasseri, M.H.B., Young, R.P., Flynn, J.W., and Reyes-Montes, J.M. (2013). 'Analysis of continuous Acoustic Emission waveform records from rock fracturing experiments'. *47th US ARMA Rock Mechanics/ Geomechanics Symposium* held in San Francisco, CA, USA, 23-26 June 2013

Zhao, X.P., Reyes-Montes, J.M., and Young, R.P. (2013) 'Time-lapse velocities for locations of microseismic events - A numerical example'. *Proceedings 75th EAGE Conference and Exhibition* London, UK, 10-13 June 2013.

Turichshev, A., Hadjigeorgiu, J., Brzovic, A., Reyes-Montes, J.M., and Nasseri, M.H.B. (2012). 'Behaviour of Veined Rock under Triaxial Compression'. *Proceedings 6th Int. Conference and Exhibition on Mass Mining, Massmin 2012*. Sudbury, Ontario, Canada, June 10-14, 2012.

Haycox, J.R., Moretti, H.C., Reyes-Montes, J.M. and Young, R.P. (2012) 'Enhanced interpretation of fracturing from acoustic emissions and ultrasonic monitoring at the Äspö Pillar Stability Experiment'. *Proceedings, EUROCK 2012 — Rock Engineering and Technology for Sustainable Underground Construction*. ISRM International Symposium. Stockholm, Sweden, May 2012.

Mas Ivars, D., Pierce, M.E., Darcel, C., Reyes-Montes, J.M., Potyondy, D.O., Young, R.P. and Cundall, P.A. (2011). 'The Synthetic Rock Mass Approach for Jointed Rock Mass Modelling'. *Int. J. Rock Mech. Min. Sci.*, *48*, 219-244 (2011).

Reyes-Montes, J.M., Pettitt, W.S., Haycox, J.R., Andrews, J.R. and Young, R.P. (2009). 'Characterisation of Rock Mass Crack Damage Using Ultrasonic Surveys'. In *Proceedings, EURADWASTE '08 — Community Policy & Research and Training Activities (Luxembourg, October 2008)*, European Commission, EUR 24040, 2009, http://cordis.europa.eu/fp7/euratom-fission/euradwaste2008_en.html.

Reyes-Montes, J.M., Rietbrock, A., Collins, D.S. and Young, R.P. (2005) 'Relative Location of Excavation Induced Microseismicity at the Underground Research Laboratory (AECL, Canada) Using Surveyed Reference Events'. *Geophys. Res. Lett.*, *32,* L05308, doi:10.1029/2004GL021733 (March 2005).

Reyes-Montes, J.M. (2004) *Enhanced Spatial Resolution of Microseismicity in the Investigation of In-Situ Crack Interaction and Coalescence*, Ph.D. Thesis, University of Liverpool, November 2004.

Young, R.P., Collins, D.S., Reyes-Montes, J.M. and Baker, C. (2004) 'Quantification and Interpretation of Acoustic Emission and Microseismicity at the Underground Research Laboratory, Canada'. *Int. J. Rock Mech. Min. Sci.*, *41*(8), 1317-1327 (December 2004).

Young, R.P., Collins, D.S. and Reyes-Montes, J.M. (2004) '10 Years of Research at the Underground Research Laboratory'. *AGU Fall Meeting*, San Francisco, December 2004.

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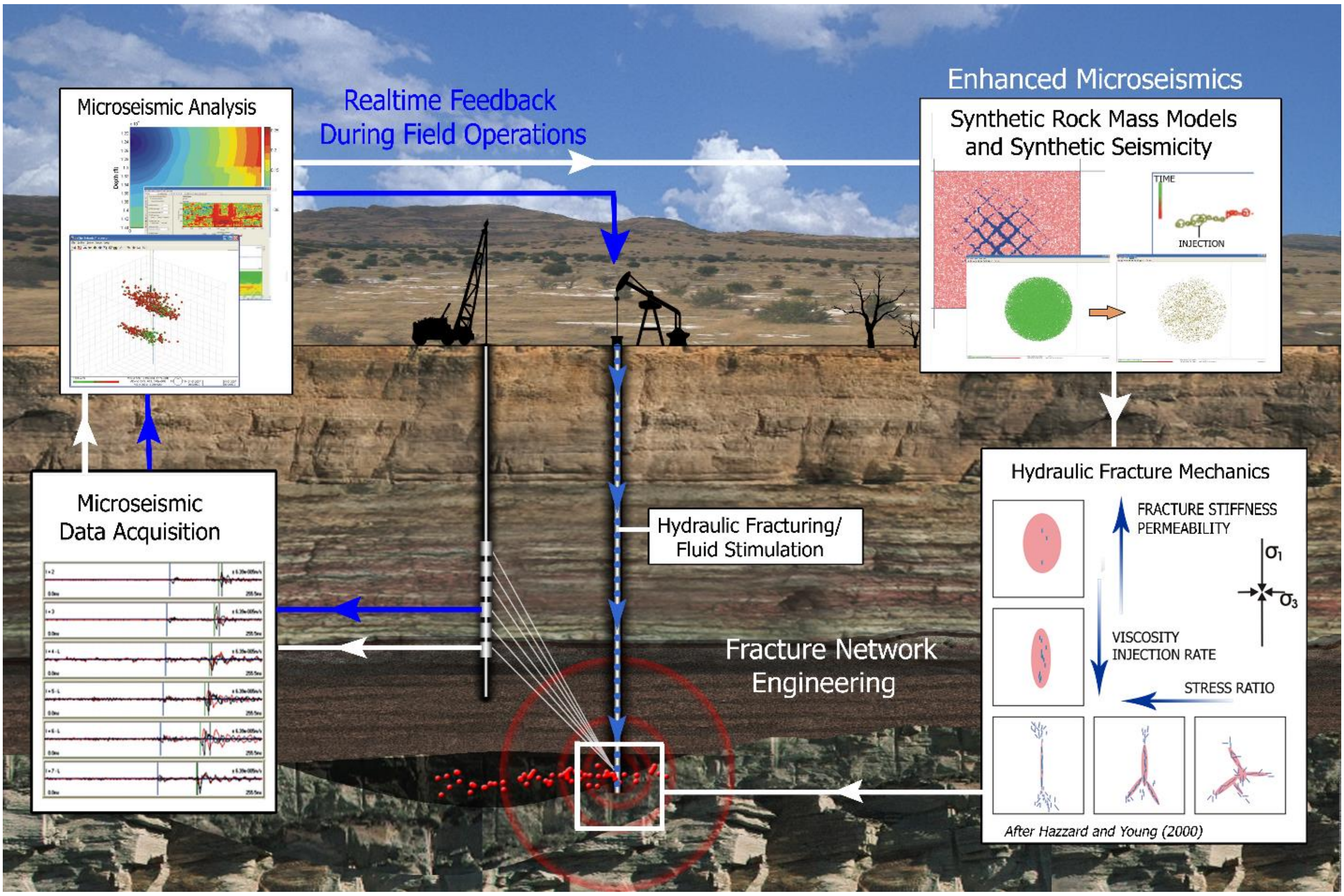
Reyes-Montes, J.M., Collins, D.S. and Young, R.P. (2002) 'An Investigation of Fracture Interaction and Coalescence at the URL (AECL, Canada)'. *NARMS-TAC 2002: Mining and Tunnelling Innovation and Opportunity*, Toronto, July 2002.

5 OIL AND GAS



Microseismic Analysis
Realtime Feedback
During Field Operations
Enhanced Microseismics
Synthetic Rock Mass Models
and Synthetic Seismicity
TIME
INJECTION
Microseismic
Data Acquisition
Hydraulic Fracturing/
Fluid Stimulation
Fracture Network
Engineering
Hydraulic Fracture Mechanics
FRACTURE STIFFNESS
PERMEABILITY
σ_1
σ_3
VISCOSITY
INJECTION RATE
STRESS RATIO
After Hazzard and Young (2000)

ASC has been involved in the real-time monitoring, post-processing and quality assurance of enhanced oil recovery projects using single and multi-stage hydraulic fracturing. Our experience covers a wide variety of completions, acquisition geometries and treatments, employing novel processing techniques where necessary to improve the quality of information fed back to oil and gas reservoir stimulation design. As part of these services to the energy sector, ASC runs a research and development program which has produced the development of advanced location algorithms to locate seismic sources using geometrically limited arrays, such as geophone strings in a single borehole, and under low signal-to-noise conditions, using wave polarisation analysis, point-to-point raytracing, wavefront construction and advanced filters for signal processing.

MS monitoring is now becoming a standard tool for evaluating the geometry and evolution of the fracture network induced during a given treatment, principally by source locating MS hypocentres and visualising these with respect to the treatment volume and infrastructure.

The combination of microseismic monitoring and analysis applied to field and laboratory observations with state-of-the-art geomechanical simulations, offer a unique and powerful method of understanding in-situ rock mass behaviour. The modelling allows predictions of the rock response to be made based on the properties obtained from laboratory experiments. The microseismic data is then collected in the field to validate the model and appropriate refinements are made to provide a realistic interpretation of the true behaviour. This combination is essential for the concept of Fracture Network Engineering (FNE) which involves the design, analysis, modelling, and monitoring of infield activities aimed at enhancing or minimising rock mass disturbance. FNE relies specifically on advanced techniques to model fractured rock masses and correlate microseismic (MS) field observations with simulated microseismicity generated from these models.

ASC's full integrated microseismic processing service provides:

- Real-time processing of microseismic data to provide feed-back of information to engineers on the position, growth and effectiveness of a hydrofracture simulation, and mapping extraction and injection paths in a producing field.
- Real-time imaging of the position, growth and effectiveness of hydrofracture stimulation to assess completion objectives.
- Post-processing of MS data for a greater understanding of the treatment history and fluid migration. Analysis of microseismic parameters and clustering yields treatment hot zones and provides for an assessment of the completion objectives.
- Alarm system for customised magnitude and rate thresholds
- Full integrated processing service from array design, through data management, processing and reporting to advanced interpretations with dynamic numerical models to better understand the growth and activation of the fracture structures.

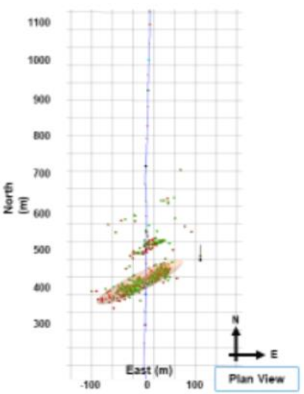
- Advanced analysis of microseismic data yields information on fracture networks such as distribution, persistence and orientations, and can describe the mechanisms behind the fracture growth leading to a better understanding of reservoir behaviour.
- Site and regional seismic characterisation
- Design and optimisation of monitoring arrays
- Quality control of acquisition settings and microseismic dataset
- Microseismic processing Software with full training and support

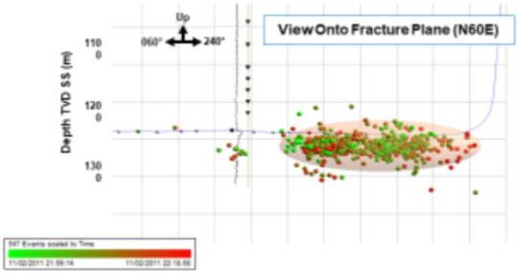
.

5.1 Example HF monitoring job

Output from Real-Time and post-processing operations provide a full characterisation of the geometry of the induced fracture network, as well as its correlation with the treatment engineering parameters. The following slides show an example of a typical report for the monitoring of a stage of hydraulic fracturing stimulation

Fracture Geometry: Sample Stage

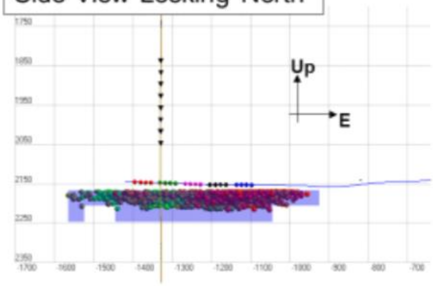




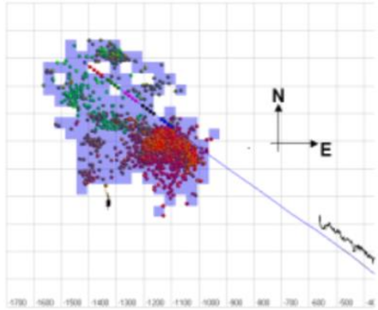
Single Wing	No
Breakthrough	No
Fracture Network Wing Length	135 m (NE-wing)
Fracture Network Length	240 m
Fracture Network Height	70 m
Fracture Network Width	50 m
Fracture Network Top	1,174 m TVDSS
Fracture Network Bottom	1,244 m TVDSS
Fracture Network Azimuth	60 degrees E of N
Fracture Network Plunge	0 degrees
Fracture Network Volume	440x10³ m³

Stimulated Volume

Side View Looking North



Plan View



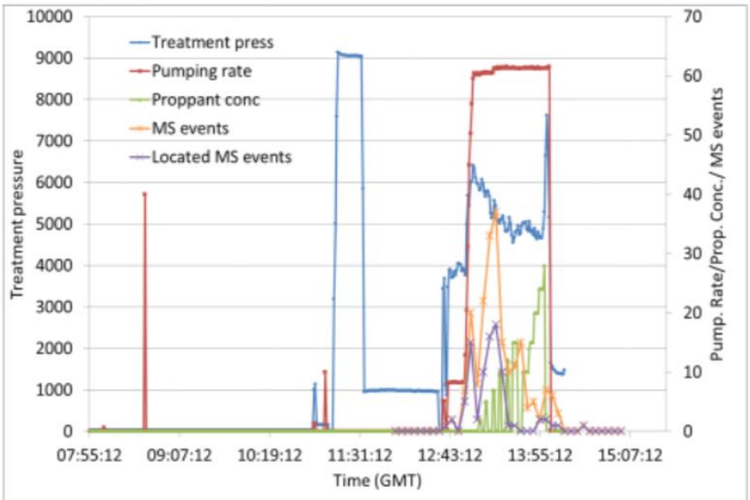
Fracture Network Length	640 m
Fracture Network Height	40 m
Fracture Network Width	640 m
Stimulated Volume	10.11×10^{6} m^3

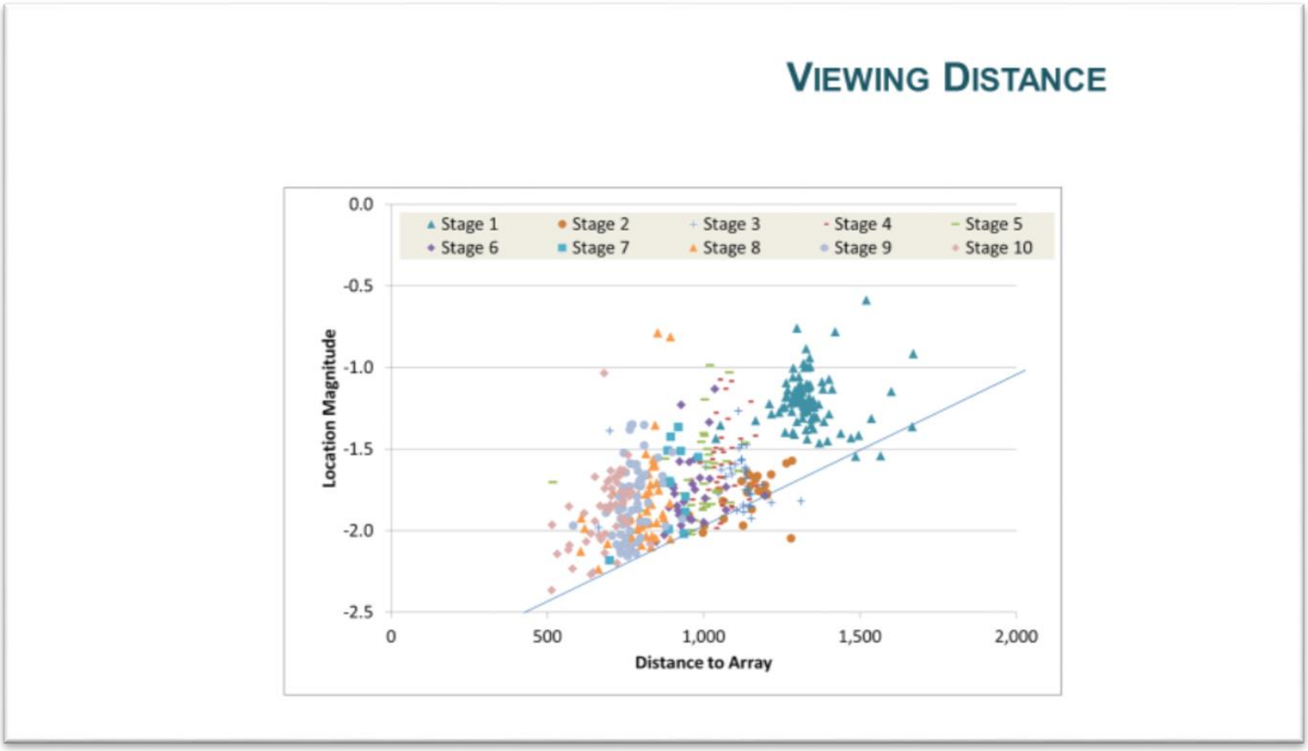
Depth shown as TVD

Grid-spacing = 100 m

Correlation with Engineering Data

- **Seismicity compared with Treatment Procedure**





5.2 Case Studies

5.2.1 Analysis of Hydraulic Fracturing-induced Microseismic Event Location Using S-wave Polarisation

Microseismic (MS) monitoring of hydraulic fracture reservoir treatments typically result in a significant number of events displaying a relatively high energy S-wave arrival but with a P-wave that is close to or below the ambient noise level. These events have been interpreted as associated to the mobilisation of pre-existing structures rather than tensile opening of new fracture pathways.

Hydraulic fracturing jobs are normally monitored using a geophone string installed along a single borehole in the vicinity of the treatment. This limited azimuthal coverage prescribes the use of source direction information additionally to travel time in order to uniquely determine MS event locations. Traditional location methods, relying on P-wave polarisation information to determine the source vector, would fail to determine a source location for events where only S-waves were observed. Such analyses would not image the full fracture history, particularly the activity relating to in-situ structures within the reservoir, giving an incomplete picture of treatment efficacy and fluid movement.

ASC developed tools for the use of full information from S-wave phases in order to enhance the number of located events and the imaging of the induced fracture network. A sensitivity study was carried out using the MS activity induced during the hydraulic stimulation of tight sand reservoirs in USA and China to evaluate the efficiency and robustness of a methodology developed to locate MS events with low-amplitude P-wave arrivals based on the calculation of source vectors from S-wave polarisation.

The results from the example data sets proved the efficiency and robustness of the method for calculating source vector information from either P- or S-wave polarisation. This method has the potential for significantly increasing the number of located MS events in typical hydraulic fracturing monitoring jobs, where events with only S-wave triggers form in certain cases 80% of the record. As observed in most MS records, S-wave events dominate the record following the first stages of fluid injection. The enhanced number of located events has numerous implications in the interpretation of the monitored results, providing a more complete image of the induced fracture network and enabling a more robust interpretation of the effect of the hydraulic treatment.

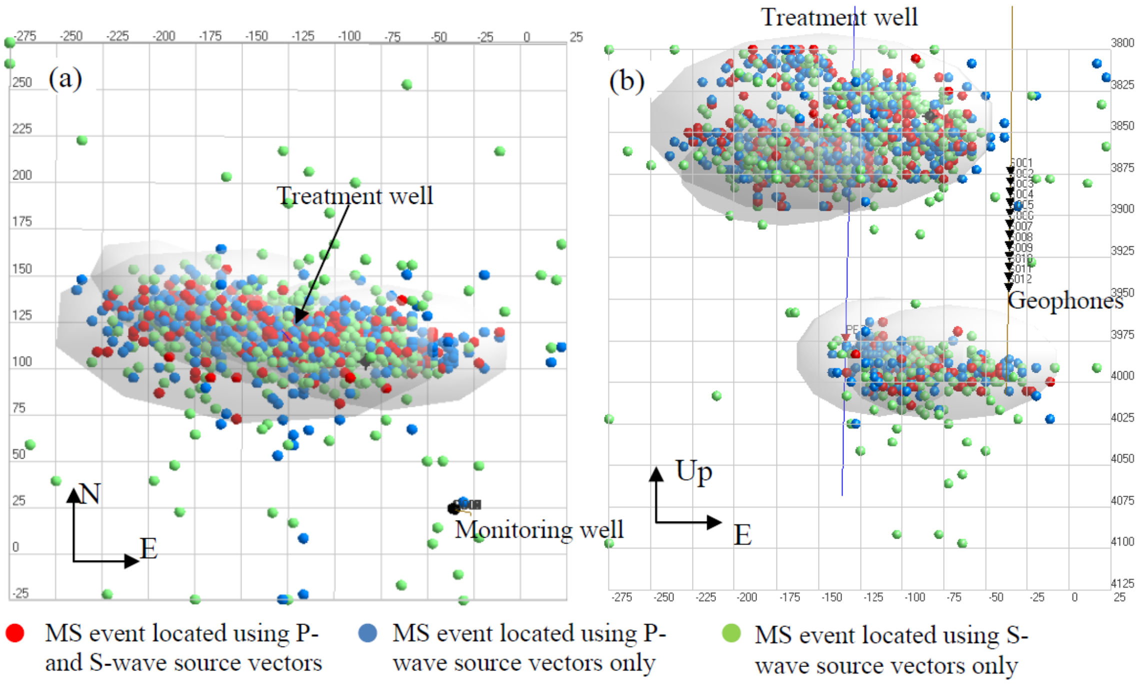


Figure 27: Plan view (a) and side view looking North (b) of the determined locations of the sample MS events induced in the hydraulic stimulation of a tight gas sand reservoir in USA. MS locations were processed using three different approaches, i.e. full P- and S-wave information (red dots), source vectors calculated using only P-wave arrivals (blue dots), and source vectors calculated using S-wave arrivals only (green dots). The shaded ellipsoids show the volume of the different fractured zones identified using full P- and S-wave information. Grid size is 25 m.

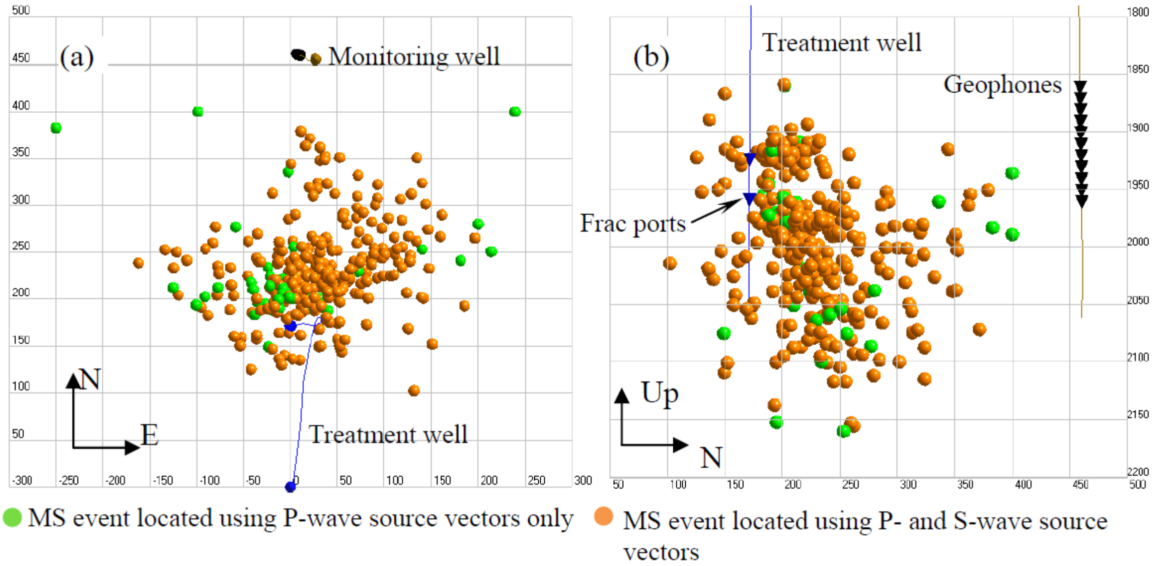


Figure 28: Plan (a) and side (b) view of the locations of the sample MS events induced in the hydraulic stimulation of a tight gas sand reservoir in China. MS locations were processed using P-wave polarisation only (green dots) and S-wave polarisation only (brown dots). Grid size is 50 m.

5.2.2 **Microseismic Quality Control using synthetic seismograms**

A downhole microseismic array was used to monitor a Woodford Shale hydraulic fracture treatment. The initial processing resulted in events being located significantly above the horizontal treatment well and laterally offset from the initiation point, along with a lack of microseismicity at the initiation points. Interpretation of the microseismic image was therefore compromised and undermined the value of information to confidently interpret the fracture geometry. A quality control evaluation was performed to assess the location patterns, including the use of synthetic microseismic signals computed from different origin points.

The method employed in this case study involves several steps to help identify the presence, cause, and solution for the apparent processing artefact. The workflow is outlined in the following steps:

1. **Assess the velocity model calibration –** Perform an initial assessment of the velocity model, including QC of the sonic logs, method for calibrating the model, and calibration shot relocations.
2. **Evaluate waveform complexity with synthetics –** Select/relocate a subset of calibration events and compare recorded signals for stages that may appear problematic, as well as those which do not to identify potential for systematic mis-picks.

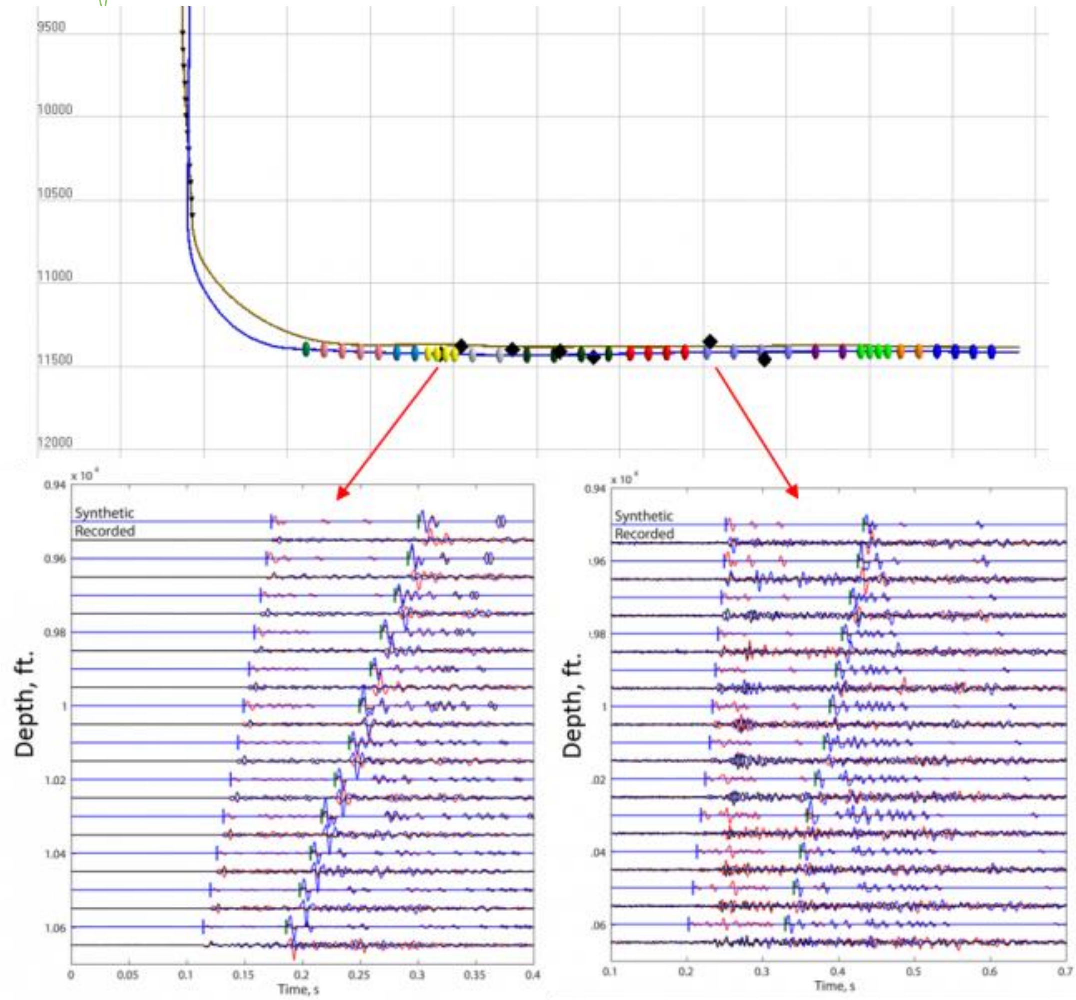


Figure 29

3. **Compare synthetics of original processing and reprocessing to the observations – **Select events from both the original data and reprocessed calibration subset and generate synthetic waveforms for each. Compare the results to the recorded data to determine the adequacy of the fit throughout the waveform. If the fit is appropriate for both waveforms, the data may be deemed adequate in the original processing. If notable deviations from the recorded signal are observed in the original processing, the data may require a reprocess. Repeat the calibration process using the synthetics as a guide if necessary to improve the fit.

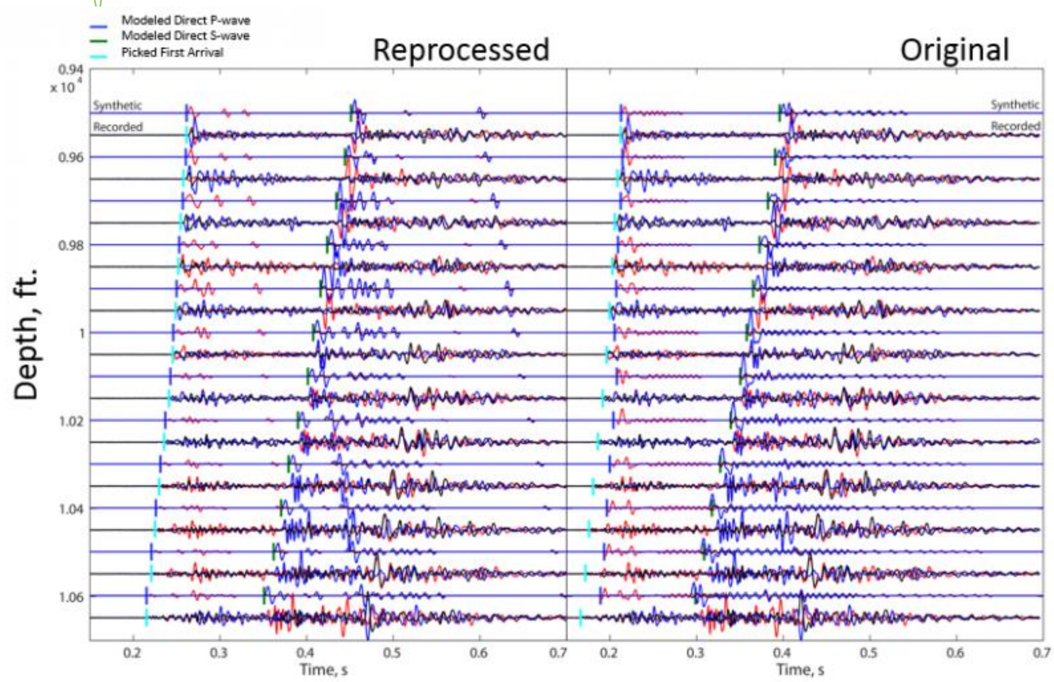


Figure 30

4. **Reprocess entire dataset –** Continue processing the dataset using the knowledge obtained in previous steps.

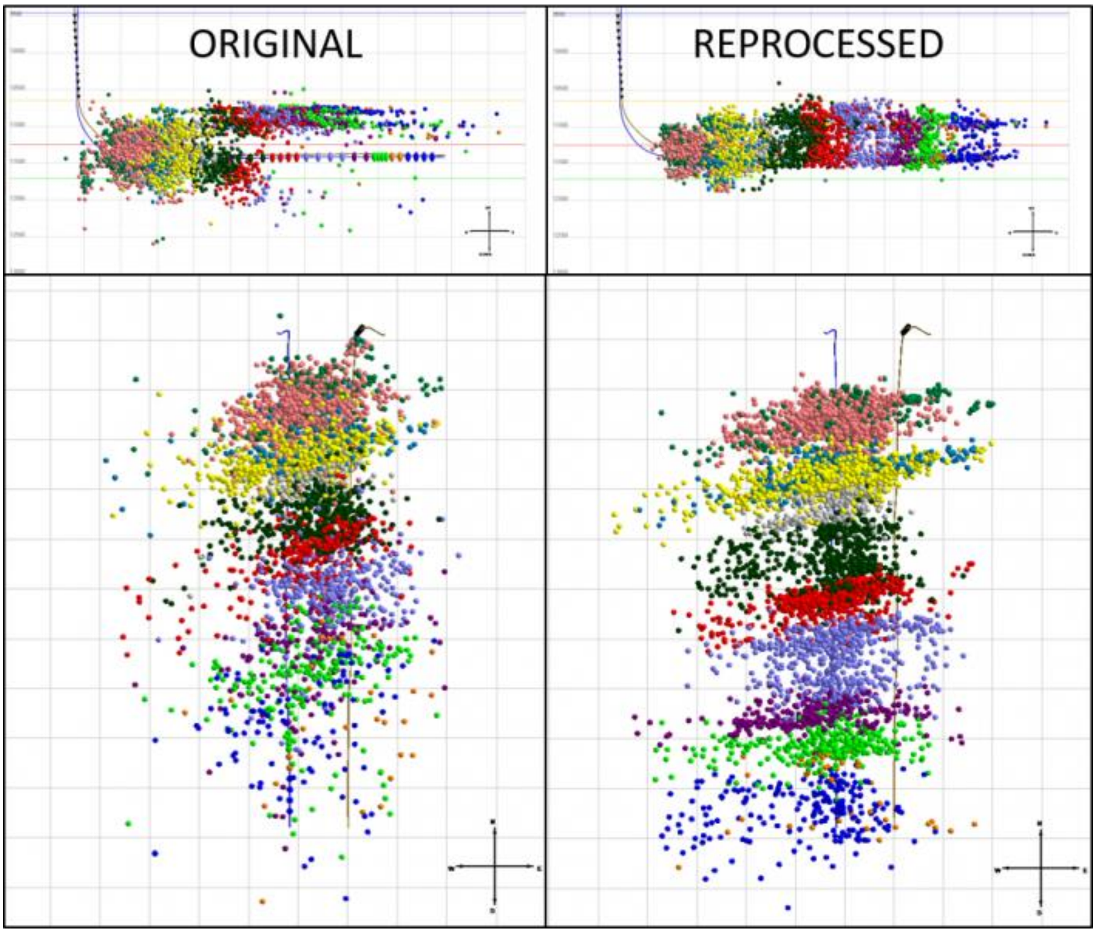


Figure 31

5. **Validate reprocess result with synthetic comparisons –** If any artefacts are still suspected, QC of the reprocessed result can be continued with the questionable events using synthetic signals similarly to step 3.

A cross correlation of the waveform kurtosis can be used to obtain a quantitative measure of the fit of the synthetic waveforms to the recorded data. The comparison is done for both event locations and both synthetics, with the cross correlation performed 4 times to assess the match. The figure below shows the stacked correlation for all sensors in the bold black line, as well as the individual sensor correlations (dashed coloured lines).

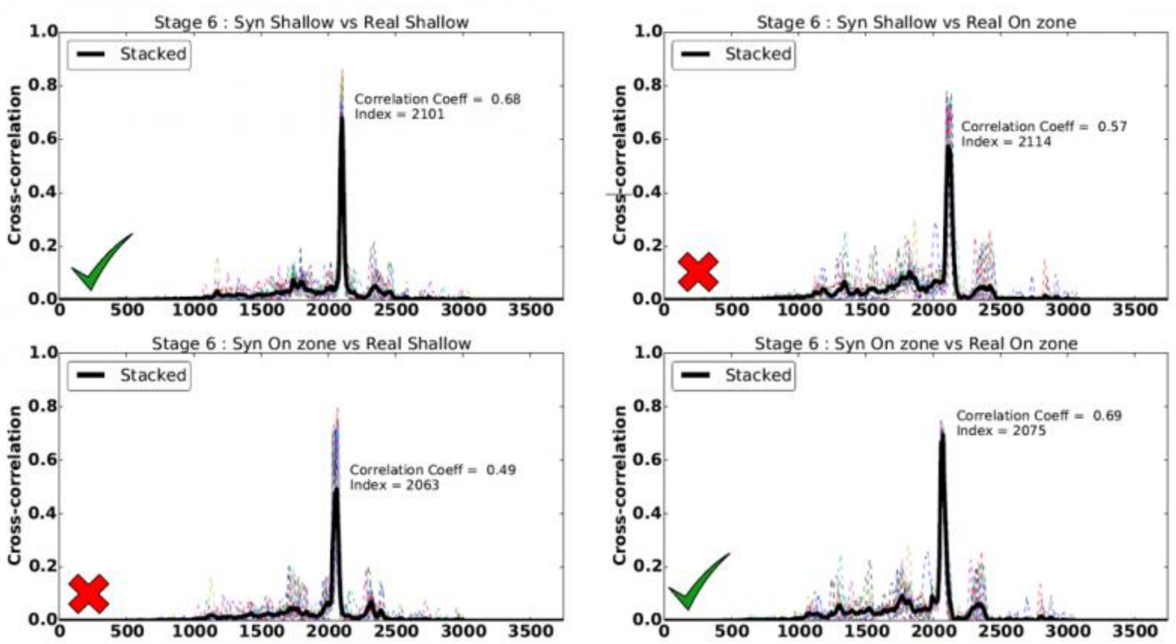


Figure 32

The stages with the suspected processing artefacts were found to suffer from significant signal complexity. The microseismicity was relocated using the synthetic signals to guide phase interpretation, which resulted in locating microseismicity much closer to the fracture initiation points. Discrepancies between the original and reprocessed results were assessed by correlating synthetic waveforms from the corresponding locations with the recorded signals. The reprocessed results were shown to better correlate with the recorded waveforms than the original, disperse locations.

The presence of waveform complexity in the recorded microseismic often creates a significant challenge for accurate event processing and location. The generation of synthetic seismograms may also add value to pre-survey modelling by predicting the presence of such complexities to assist in selection of sensor placement before acquisition. Finally, industry-sanctioned synthetic microseismic data sets could be a useful resource to benchmark different processing strategies.

5.3 Clients

5.4 Publications

Huang, J.W., Reyes-Montes, J.M., Maxwell, S.C. and Young, R.P. (2015) 'A new Finite Difference Eikonal Equation solver for anisotropic medium'. *Proceedings 77th EAGE Conference and Exhibition*. Madrid, Spain 1-4 June 2015

Zhao, X.P., Reyes-Montes, J.M., and Young, R.P. (2014) 'Analysis of the stability of source mechanism solutions for microseismic events from different receiver configurations'. *Proceedings 76th EAGE Conference and Exhibition* Amsterdam, Netherlands 16-19 June 2014

Huang, J.W., Reyes-Montes, J.M., and Young, R.P. (2014) 'Locating microseismicity from surface monitoring arrays using symmetry-based grid search and hypocentre inversion — A case study'. *Proceedings 76th EAGE Conference and Exhibition Amsterdam*, Netherlands 16-19 June 2014

Huang, J.W., Reyes-Montes, J.M., Zhao, X.P., Chun, F., and Young, R.P. (2014) 'Quantifying reservoir stimulation using passive traveltime tomography'. *Proceedings 76th EAGE Conference and Exhibition* Amsterdam, Netherlands 16-19 June 2014

Reyes-Montes, J.M., Zhao, X.P., Chun, F. and Young, R.P. (2014) 'Analysis of hydraulic fracturing-induced microseismic event location using S-wave polarisation'. *Proceedings 76th EAGE Conference and Exhibition* Amsterdam, Netherlands 16-19 June 2014

Huang, J.W., Reyes-Montes, J.M., and Young, R.P. (2013) 'Symmetry-based automated microseismic location from data streams of surface monitoring arrays - A numerical study'. *SEG Technical Program Expanded Abstracts 2013*: pp. 2167-2172. doi: 10.1190/segam2013-0945.

Zhao, X.P., Reyes-Montes, J.M., and Young, R.P. (2013) 'Time-lapse velocities for locations of microseismic events - A numerical example'. *Proceedings 75th EAGE Conference and Exhibition.* London, UK, 10-13 June 2013.

Huang, J.W., Reyes-Montes, J.M., and Young, R.P. (2013) 'Automated microseismic event location using finite difference traveltime calculation and enhanced waveform stacking'. *Proceedings 75th EAGE Conference and Exhibition.* London, UK, 10-13 June 2013.

Pettitt, W.S., Damjanac, B., Hazzard, J.F., Han, Y., Sanchez-Nagel, M., Nagel, N., Reyes-Montes, J.M. and Young, R.P. (2012) 'Engineering Hydraulic Treatment of Existing Fracture Networks'. *SPE Annual Technical Conference and Exhibition*, 8-10 October 2012, San Antonio, Texas, USA. doi 10.2118/160019-MS

Pettitt, W.S., Pierce, M., Damjanac, B., Hazzard, J., Lorig, L., Fairhurst, C., Sanchez-Nagel, M., Nagel, N., Reyes-Montes, J.M., Andrews, J. and Young, R.P. (2012). Fracture Network Engineering: Combining Microseismic Imaging and Hydrofracture Numerical Simulations. *Proceedings 46th US Rock Mechanics/Geomechanics Symposium, ARMA 2012*. Chicago, June 2012.

Zhao, X.P., Reyes-Montes, J.M. and Young, R.P. (2012) 'The role of pre-existing fracturing in enhanced reservoir treatments'. *Proceedings 46th US Rock Mechanics/Geomechanics Symposium, ARMA 2012*. Chicago, June 2012.

Pettitt, W., Pierce, M., Damjanac, B., Hazzard, J., Lorig, L., Fairhurst, C., Gil, I., Sanchez, M., Nagel, N., Reyes-Montes, J.M. and Young, R.P. (2011). 'Fracture Network Engineering for Hydraulic Fracturing'. *The Leading Edge*, ***30***(8), 844-853, doi 10.1190/1.3626490.

Pettitt, W.S., Reyes-Montes, J.M., Andrews, J.R. and Young, R.P. (2010) 'Enhanced Imaging of Hydraulic Fracturing through Induced Seismicity'. In *Proceedings, 44th U.S. Rock Mechanics Symposium (5th U.S.-Canada Rock Mechanics Symposium, Salt Lake City, Utah, June 2010)*, Paper No. 10-274. Alexandria, Virginia: ARMA, 2010.

Reyes-Montes, J.M., Pettitt, W.S and Young, R.P. (2010) 'The More We Listen the More We See: Microseismic Monitoring of Induced Seismicity is Coming of Age'. *CSEG Recorder*, *35*(9), 38-40,42-43 (November).

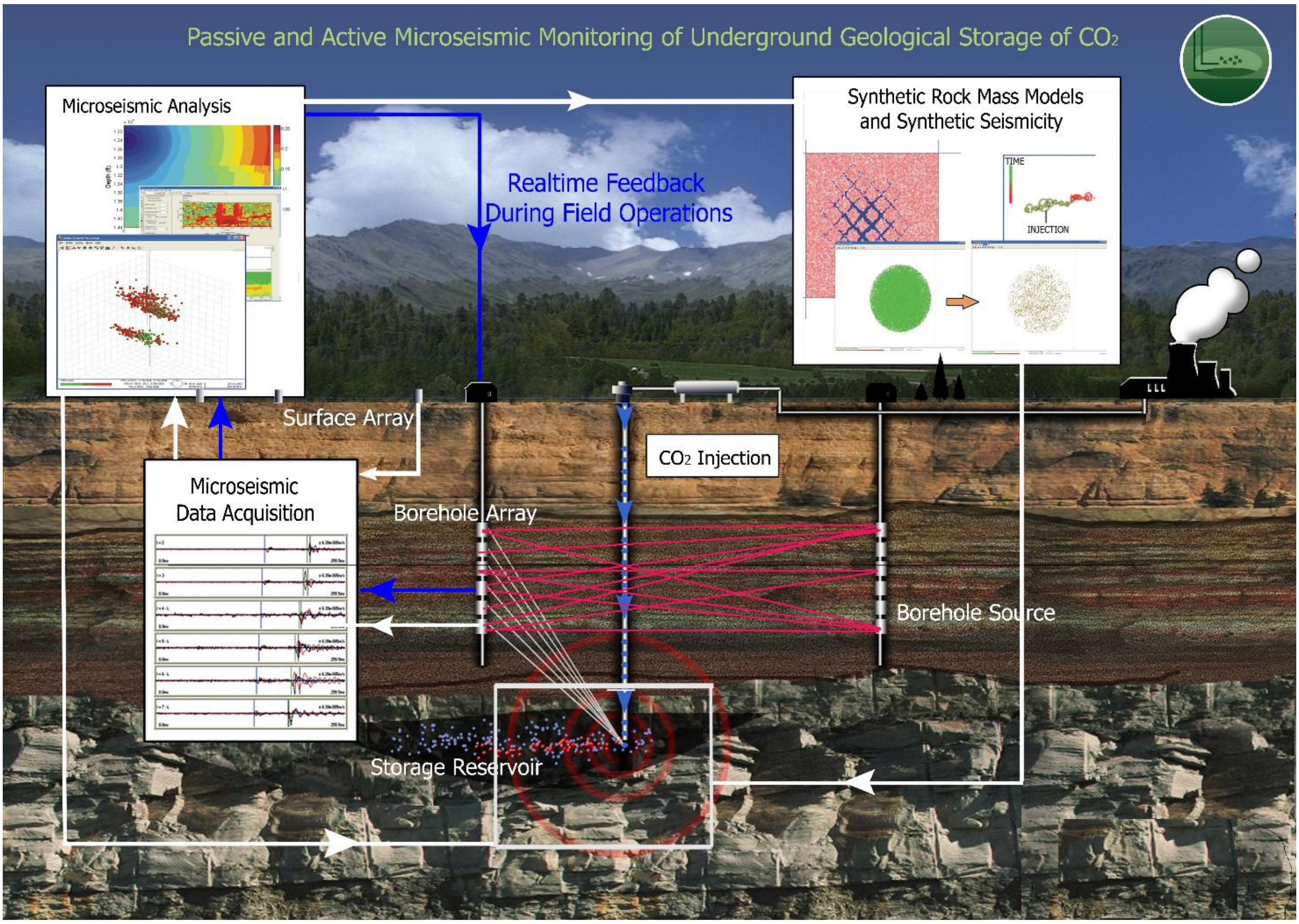
Pettitt, W.S., Reyes-Montes, J.M., Hemmings, B., Hughes, E. and Young, R.P. (2009) 'Using Continuous Microseismic Records for Hydrofracture Diagnostics and Mechanics'. In *Proceedings, SEG International Exposition and 79th Annual Meeting, Houston, October 2009*, pp. 1542 -1546.

Reyes-Montes, J.M., Pettitt, W.S., Haycox, J.R., Hemmings, B. and Young, R.P. (2009) 'Microseismic Analysis for the Quantification of Crack Interaction during Hydraulic Stimulation'. In *Proceedings, SEG International Exposition and 79th Annual Meeting, Houston, October 2009*, pp. 1652-1656.

Reyes-Montes, J.M., Pettitt, W.S., Hemmings, B., Haycox, J.R., Andrews, J.R. and Young, R.P. (2009) 'Application of Relative Location Techniques to Induced Microseismicity from Hydraulic Fracturing'. In *ATCE2009: Proceedings, SPE Annual Technical Conference and Exhibition, New Orleans, 2009*. Paper No. 124620.

Reyes-Montes, J.M., Pettitt, W.S., and Young, R.P. (2009) 'Enhancement of Fracture Network Imaging from Microseismic Monitoring of Hydraulic Fracturing Treatments'. *Canadian Society of Exploration Geophysicists Microseismic Workshop*, Calgary, November 2009.

6 UNDERGROUND CO_2 STORAGE



The objective of reducing the total CO_2 emissions in short and medium term requires the safe disposal of CO_2 separated and compressed to a sub-critical state from single point high producers (e.g. fossil power generation stations or metals and cement processing plants). A proposed solution for the permanent disposal of the compressed gas is its geological storage in deep saline aquifers, oil and gas reservoirs or deep unmineable coal seams. It is crucial for the operational implementation of this solution to be able to assess the integrity of the geological reservoir before, during and following the injection of the gas.

CO_2 is currently used as a flooding medium for enhanced oil and natural gas recovery and used to form emulsions used as acidizing systems for well stimulation in depleted oil bearing reservoirs. Microseismic monitoring is routinely used in hydraulic fracturing stimulation campaigns for the petroleum and geothermal industries as a means to map the growth of the induced fracture network and the connectivity between different geological units and to evaluate the changes in the fluid conductivity properties of the reservoir rock induced by the hydraulic fracturing.

ASC has been involved in the monitoring, post-processing and quality assurance of enhanced oil recovery projects using single and multi-stage hydraulic fracturing and has pioneered the application of microseismic monitoring to commercial enhanced geothermal systems.

As in the case of well stimulation for oil and gas production, microseismic monitoring can provide a unique approach for the monitoring of the integrity of the reservoir rock subject to changes in local stresses and pore pressure induced by the injection of the compressed CO_2. The injection of pressurised gas can cause two different effects that significantly impact the capability of the reservoir to safely isolate the disposed gas:

1. induce shearing on pre-existing fractures causing displacement of the joints, so that asperities open up the fracture network creating paths for fluid migration;
2. induce extension of existing fractures or opening of new ones, creating an increased fracture network with potential enhancement of connectivity and increased permeability.

ASC partnered with Avalon Science Ltd, a leading downhole monitoring provider, in two publicly funded research projects with the objective of developing microseismic monitoring tools for low signal-to-noise environments and producing a combined processing and numerical modelling tool for monitoring the integrity of storage reservoirs and interpreting changes in permeability and integrity induced during gas injection. The tools combined passive and active microseismic monitoring with numerical geomechanical models. capability for interpreting fracture diagnostics from microseismic source mechanics in a feedback loop between observed and simulated data.

ASC provides the following services to the energy industry focused on monitoring the effectiveness of underground gas storage operations:

- Site characterisation of existing active fractures within potential storage reservoirs

- Design and optimisation of seismic monitoring arrays.
- Real-time processing of microseismic data to provide feed-back of information to engineers on potential damage to reservoir bounds and cap rock that may affect its confining properties or can map injection paths in a treatment field. Assessment of reservoir integrity and containment effectiveness during injection
- Post-analysis of reservoir containment effectiveness.
- Delineation of potential breakthrough and communication with active fault structures.
- Fracture mapping to provide information on feasibility of target volumes for new development wells.
- Correlation with predictive numerical models for feedback on future site development
- In-depth understanding of fracture mechanisms through the integration of acquired data and "Synthetic Rock Mass" models built with Itasca's Particle Fluid Code (PFC) and site-scale degradation models.
- Acquisition system-independent seismic processing software for automatic, real-time processing of induced seismicity.
- Fully-featured microseismic training courses focussed on the principles behind the technology, processing algorithms and hands-on experience of using processing software.

6.1 Case Studies

6.1.1 **Development of Microseismic Tools for Post-Injection Monitoring of Containment Efficiency of Underground Carbon Storage**

ASC partnered with Avalon Sciences Ltd. in a design study leading to the integration of hardware and software tools for effective MS monitoring in the new market of safe geological containment of CO2. Specifically, addressed the need to monitor using tools that can be deployed for long periods of time and without the need of a deep monitoring borehole in the neighbourhood of the injection well. Under these conditions, new signal processing techniques are required in order to enhance the signal and mitigate background noise.

The result was a monitoring product combining high-gain, low-noise surface acquisition tools and processing software to monitor deep reservoirs using shallow monitoring arrays.

The project examined the signature of a CO_2 plume surveyed by active seismic shots and the use of surface and noise sources for monitoring changes in the position of the CO_2 post-injection.

The interpretation of the changes observed from active surveys were completed through the construction of forward numerical models that realistically reproduced the effect of changes in pore pressure, fracture development and CO_2 content on the transmission of acoustic waves.

During this project, a method for locating microseismic events without phase picking was developed and tested.

Cross-correlation based travel-time picking for passive seismic imaging was also developed and tested.

Honouring the coupling between the event location and the velocity model, passive imaging can provide a more realistic image of the rock velocity structure, its time-lapse variation and more accurately locate events.

In this test, due to the lack of vertical constraint, the recovered depth of each source may be at a relatively large distance from its true position. Therefore, in order to have the passive imaging technique work for surface monitoring survey, extra constraints such as the borehole monitoring geophones were included.

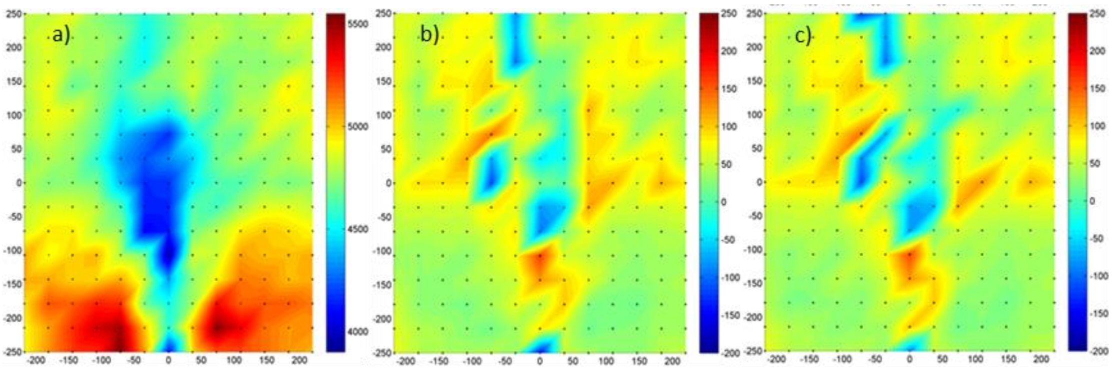


Figure 33: Measured velocities at a) the initial stage before the CO_2 injection when the source function was applied at the source (0, -280), b) at stage 1 and c) at stage 2. The units for the X- and Y-axes are in metres while the units for the colour bar are $m \cdot s^{-1}$.

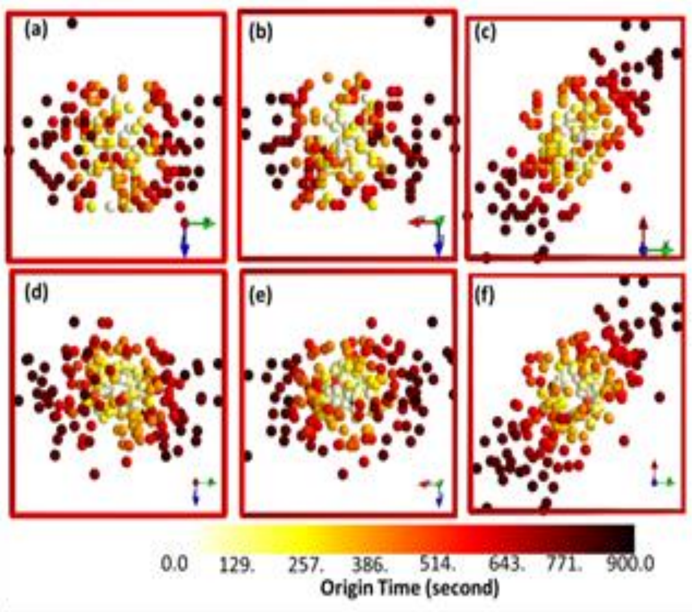


Figure 34: Locations of 176 events (a,b,c) compared with the modelled 200 events (d,e,f). Figure (a,d), (b,e), and (c,f) are viewing towards north, east, and downwards, respectively. In general, the automated location method recovers 88% of the true events.

6.2 Clients

ASL Avalon Sciences Ltd

Innovate UK

6.3 Publications

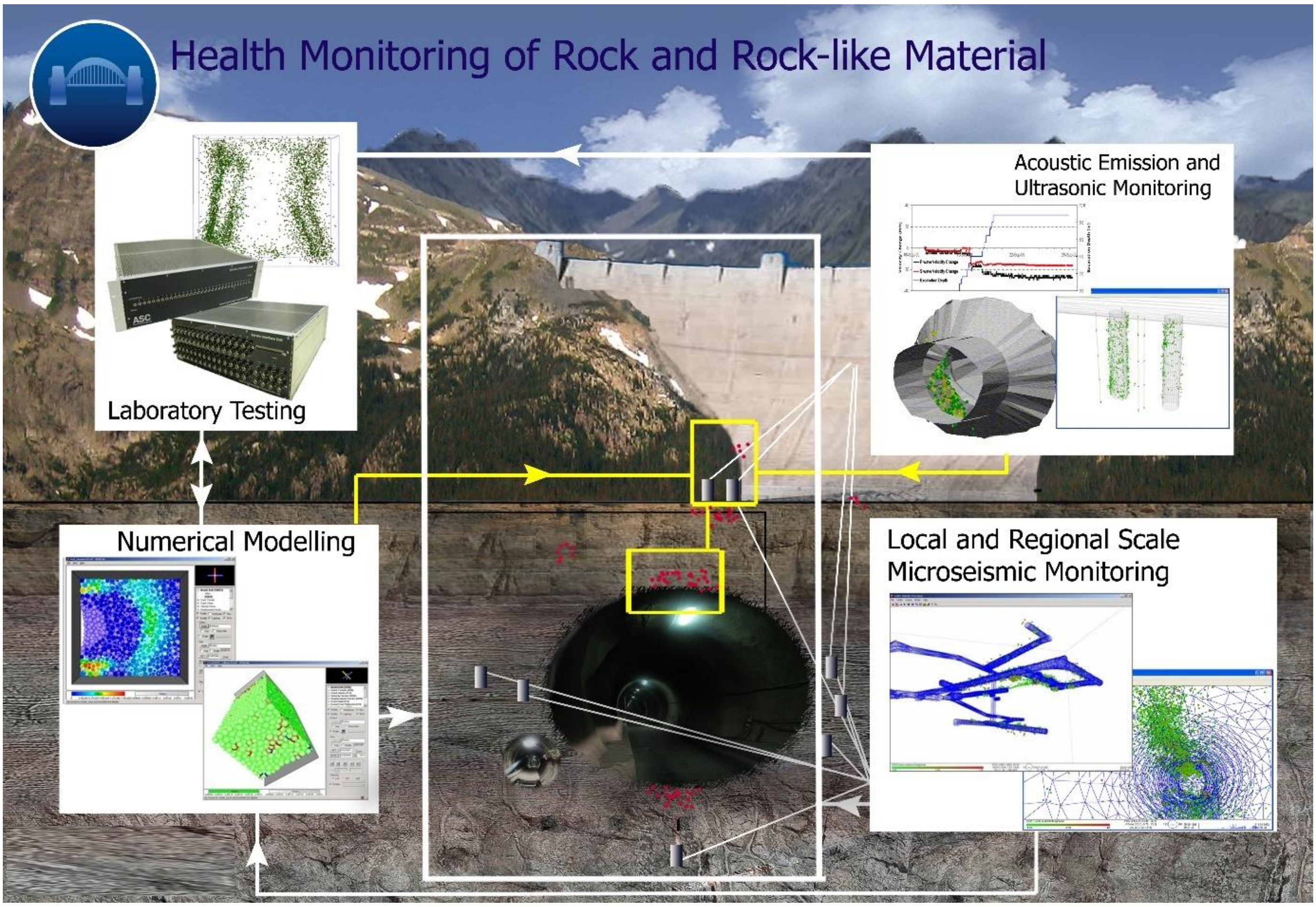
Zhao, X.P., Reyes-Montes, J.M., and Young, R.P. (2013) 'Time-lapse velocities for locations of microseismic events - A numerical example'. *Proceedings 75th EAGE Conference and Exhibition* London, UK, 10-13 June 2013.

Zhao, X.P., Reyes-Montes, J.M., Katsaga, T. and Young, R.P. (2011) 'Numerical Modelling of Microseismicity Induced by CO2 Injection'. *Proceedings of the 73rd EAGE Conference*. 23-26 May, 2011, Vienna.

Young, R.P., Zhao, X.P., Reyes-Montes, J.M. and Wills, W. (2011) 'Optimising Monitoring Sensitivity and Prediction Modelling for Microseismic Technologies in Underground Carbon Storage'. In *Proceedings, ISRM Congress (Beijing, China)*.

Pettitt, W.S., Reyes-Montes, J.M., Hemmings, B., Hughes, E. and Young, R.P. (2009) 'Using Continuous Microseismic Records for Hydrofracture Diagnostics and Mechanics'. In *Proceedings, SEG International Exposition and 79th Annual Meeting, Houston, October 2009*, pp. 1542 -1546.

7 CIVIL ENGINEERING



Microseismic and ultrasonic monitoring, both passive and active, allows engineers to non-destructively monitor the integrity of engineered structures and locate areas of weakness. Local and regional seismic monitoring is an essential tool in the assessment of risk around engineering structures and in site characterisation prior to the construction of major infrastructure. The combination of passive and active seismic and ultrasonic monitoring provides a unique tool for:

- 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.

ASC provides full solutions for the monitoring of engineered structures at all scales:

- coupled innovative high-frequency electronics architecture with real-time data processing software to provide cost-effective solutions with the highest possible data-flow rates and acoustic acquisition specifications tailored to the technological challenges of each project

- hardware-independent integrated software tool for acoustic and seismic data acquisition, processing, management and visualisation providing a full three-dimensional microseismic analysis for both passive and active surveys.

- fully-featured AE microseismic training courses focussed on the principles behind the technology, processing algorithms and hands-on experience of using ASC's hardware and software.

7.1 Case Studies

7.1.1 **Tunnelling**

Tunnels used throughout the engineering industry are monitored and investigated to ensure structural integrity, provide forewarning of any failures and feedback aid in the design of future structures. The aim is to map fracture networks and gain information on rock damage; particular attention is given towards the excavation disturbed zone (EDZ) as this is the area that is most damaged by the excavation process and stress redistribution.

ASC use several non-destructive methods to provide better understanding of the structural changes and changes in material properties occurring around the tunnels. Continuous microseismic (MS) monitoring is a technique that monitors MS events over an array of sensors covering a medium scale volume (typically hundreds to thousands of metres). Continuous acoustic emission (AE) monitoring is a passive technique that records the acoustic emissions of the structure over an array of sensors covering a smaller volume. Processing this data results in a map of fracturing throughout the structure based on the source locations of the MS events and AEs recorded and also source mechanism information.

Ultrasonic velocity surveys are employed at regular intervals to monitor changes in the material properties of the structure, in particular changes in P and S wave velocities.

The Mine-by experiment at AECL's (now CNL) Underground Research Laboratory was designed to investigate the rock failure process around a mechanically excavated tunnel. The absence of AE or MS events within the rock mass approximately a metre away from the excavation surface indicated damage was localised near the excavation surface.

SKB's Prototype Repository Experiment was designed to simulate a disposal tunnel in a real deep repository for disposal of high-level radioactive waste. The aim was to test and demonstrate the integrated function of the repository components under realistic conditions at full scale, comparing results with models and assumptions.

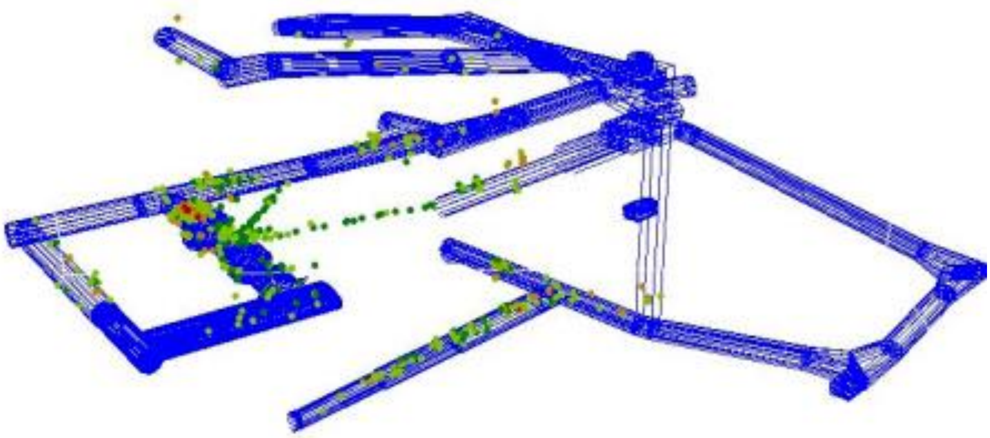


Figure 35: AECL's Underground Research Lab showing all tunnels and some of the microseismicity induced during and after its excavation.

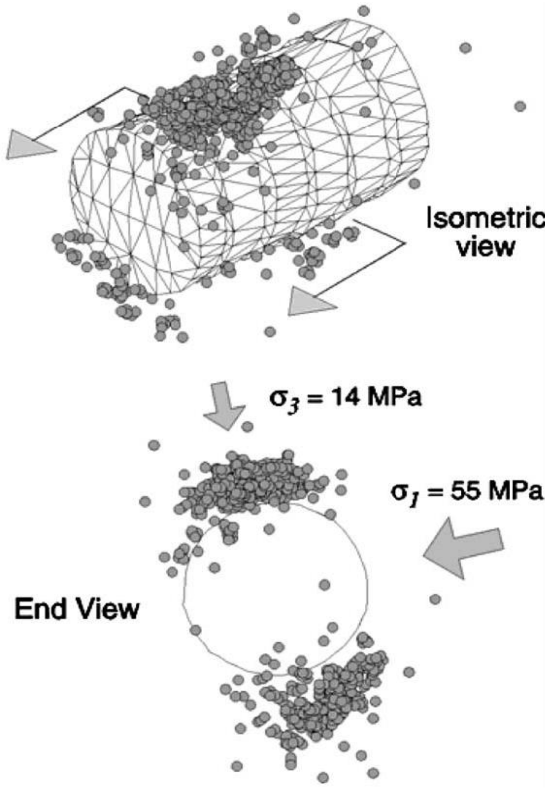


Figure 36: Microseismic event source locations recorded around the Mine-by Experiment tunnel at AECL's Underground Research Laboratory.

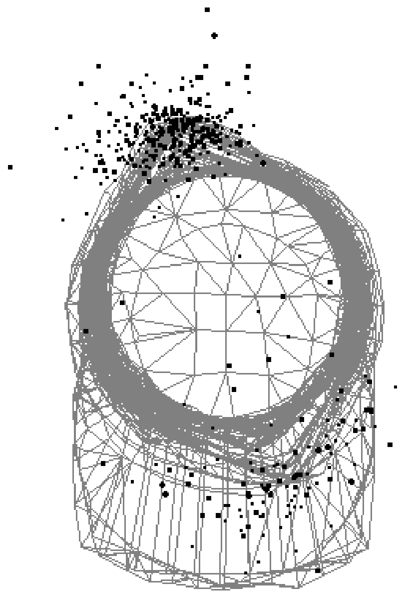


Figure 37: Development of a notch and roof and floor spalling shown by MS locations at the Mine-by tunnel at AECL's Underground Research Laboratory.

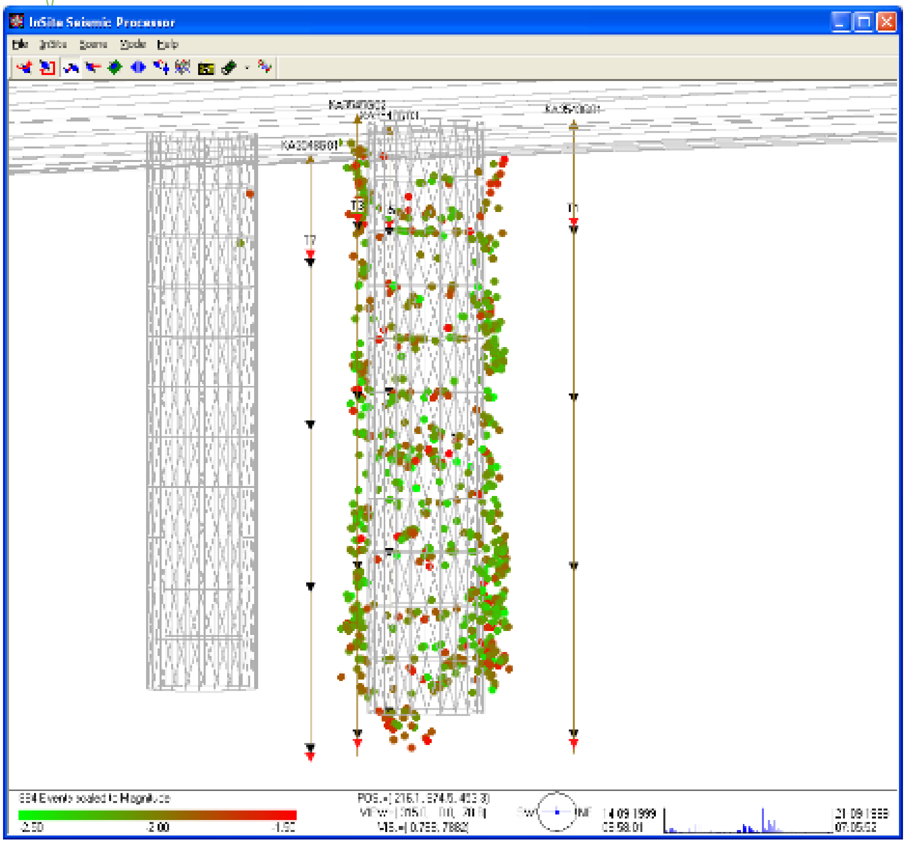


Figure 38: Sample located AE events scaled by magnitude in SKB's Prototype Repository.

7.1.2 Monitoring of Concrete Structures

ASC uses several non-destructive methods to provide the best understanding of the structural changes and changes in material properties occurring in concrete structures.

- Continuous acoustic emission (AE) monitoring is a passive technique that records the acoustic emissions of the structure over an array of sensors. This can provide a map of fracturing through the structure based on the source locations of the AE's recorded.
- Ultrasonic velocity surveys are employed at regular intervals to monitor changes in the material properties of the structure more specifically the changes in P and S wave velocities.

The methods used to monitor concrete structures can be illustrated by the monitoring of the concrete bulkhead in the Tunnel Sealing Experiments (TSX) for AECL during the curing period. The TSX was designed to test seal technology and to measure seal performance.

To do this the seals were monitored as they were subjected to combinations of heat and pressure. The concrete monitoring array consisted of 24 ultrasonic transducers 16 of which were used to continuously monitor AE events whilst the other 8 were used for active velocity surveys.

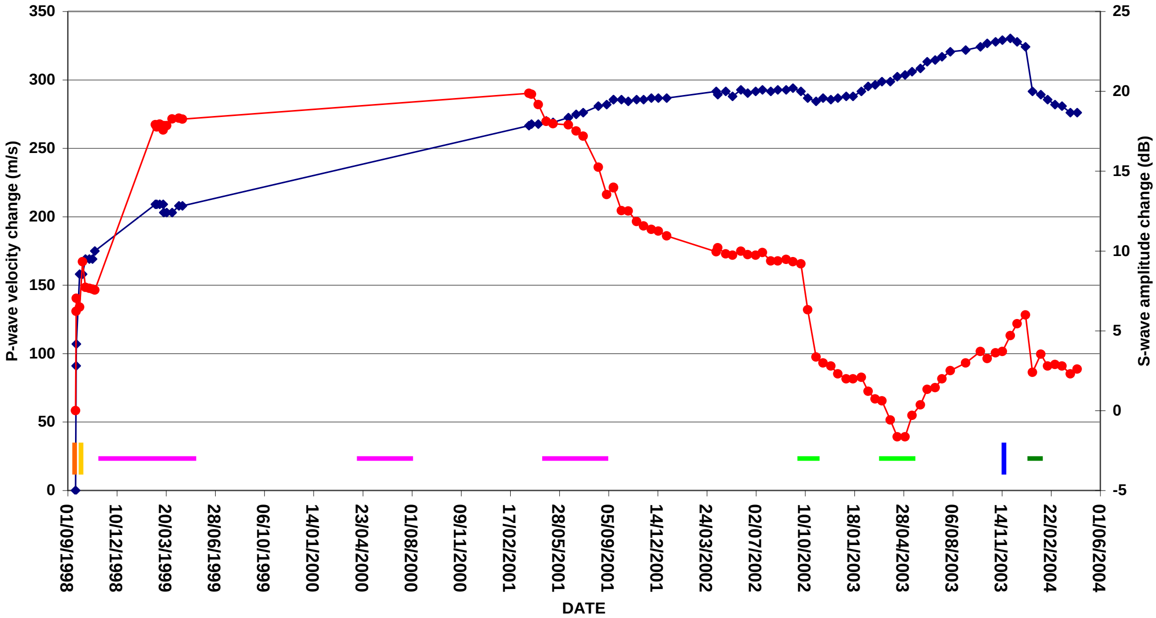


Figure 39: P-wave velocity and amplitude for a ray-path through the concrete bulkhead over a 5-year period of the TSX. (Blue = P-wave, red = S-wave)

At Fracture Nucleation	During Fracture Propagation	After Complete Fracture Growth

Figure 40: Located AE events at 3 different stages through the curing stage of the TSX (16th September - 27th October 1998).

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Consulting

Microseismic processing and Quality Control

REAL-TIME MONITORING

MONITORING DESIGN

MICROSEISMIC TRAINING

CUSTOM SOLUTIONS

QUALITY ASSURANCE

ICL offers a fully integrated service for real-time and post-processing of microseismic data. We have reviewed, quality checked and analysed third-party seismic and microseismic datasets from a wide range of applications. Our seismic and microseismic processing quality control service focuses on the review of location uncertainty and source parameter calculation, specifically sensitivity to velocity uncertainty, tool orientations, location algorithm and phase identification.

Our fully integrated microseismic processing service can provide:

- Monitoring of fracturing operations.
- Site and regional seismic characterisation.
- Monitoring of regional natural and induced seismicity.
- Quality control of acquisition settings and microseismic dataset.
- Full Post-processing and enhanced analysis.
- Post-treatment monitoring.
- Software Training and Consulting.

Our consulting services on project design cover many applications such as:

- Microseismic monitoring array design.
- Geomechanical modelling of completion strategy prior to hydraulic injection.
- Pre-analysis of structural deformation of the reservoir (compaction, subsidence).
- Borehole stability and well design.

For more information on any of our products or services

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