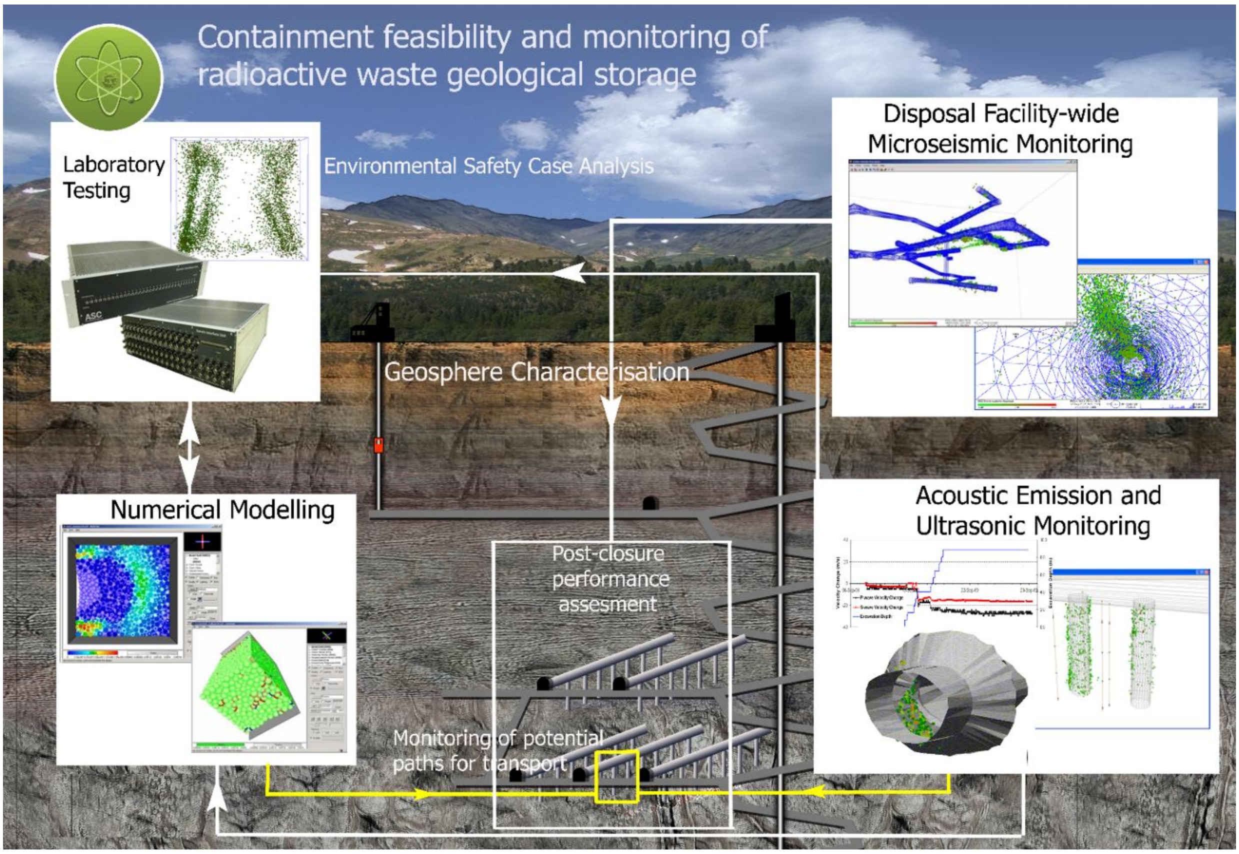
ASC
Applied Seismology
Consulting

Geological storage of radioactive waste



Applied Seismology Consulting 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

Case Studies

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 $\pm 2\ \mathrm{m{\cdot}s^{-1}}$ 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.

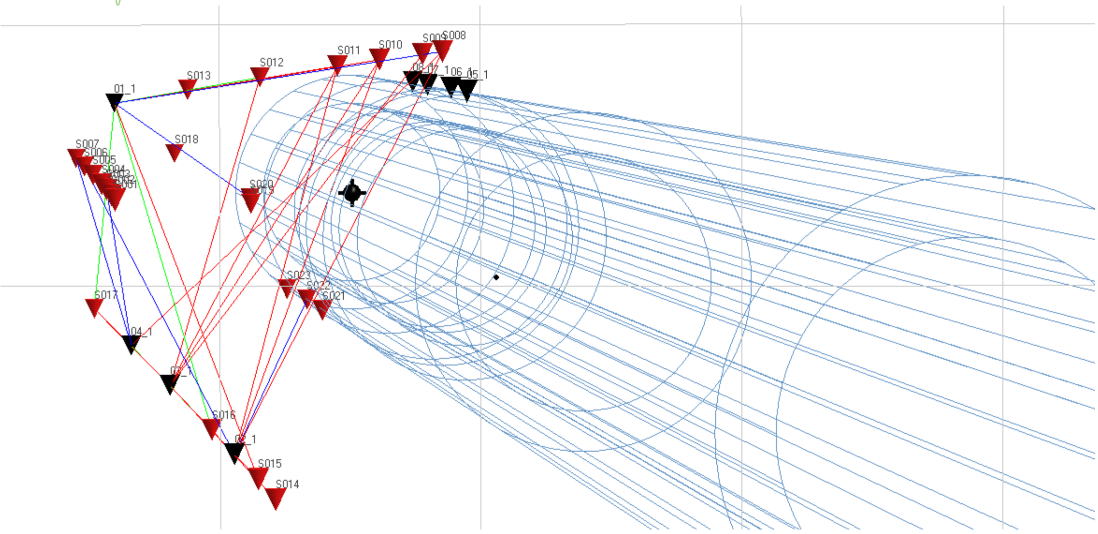


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Figure 1: Raypaths for P-wave velocity surveys shown crossing different regions in the Boom Clay host rock neighbouring the PRACLAY test gallery.

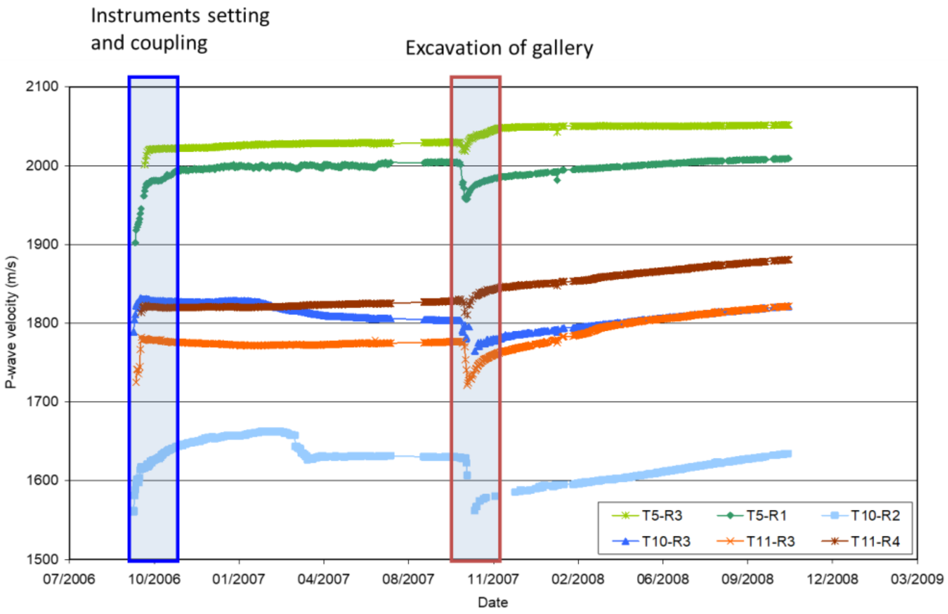

Figure 2: P-wave velocity along sample raypaths crossing different regions in the Boom Clay host rock neighbouring the PRACLAY test gallery. Showing microcrack healing or matrix compaction induced by excavation of gallery.

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.

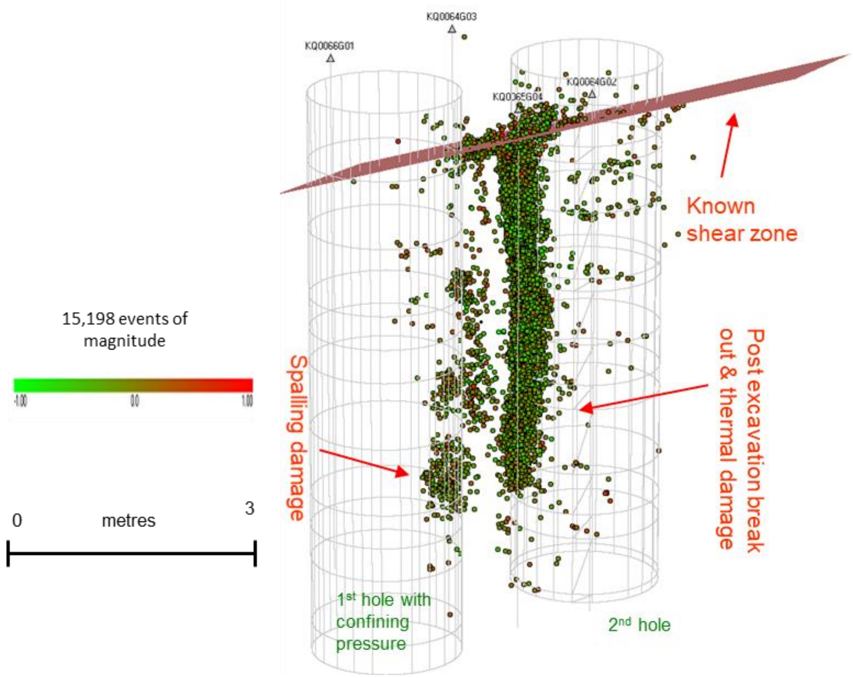

Figure 3: AE locations of all 17,360 AE events induced during the Pillar Stability Experiment.

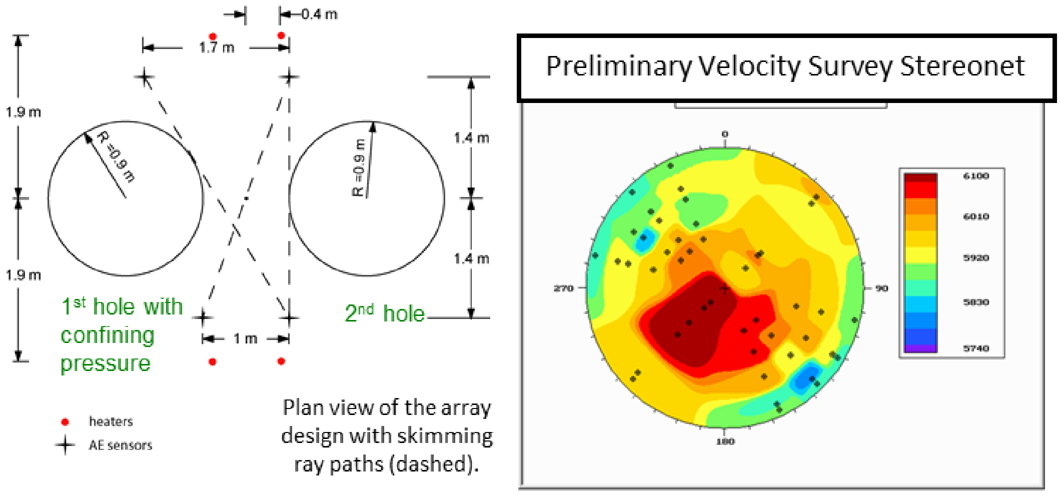

Figure 4: Sample P-wave velocity survey carried out through the Pillar between the test deposition holes

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

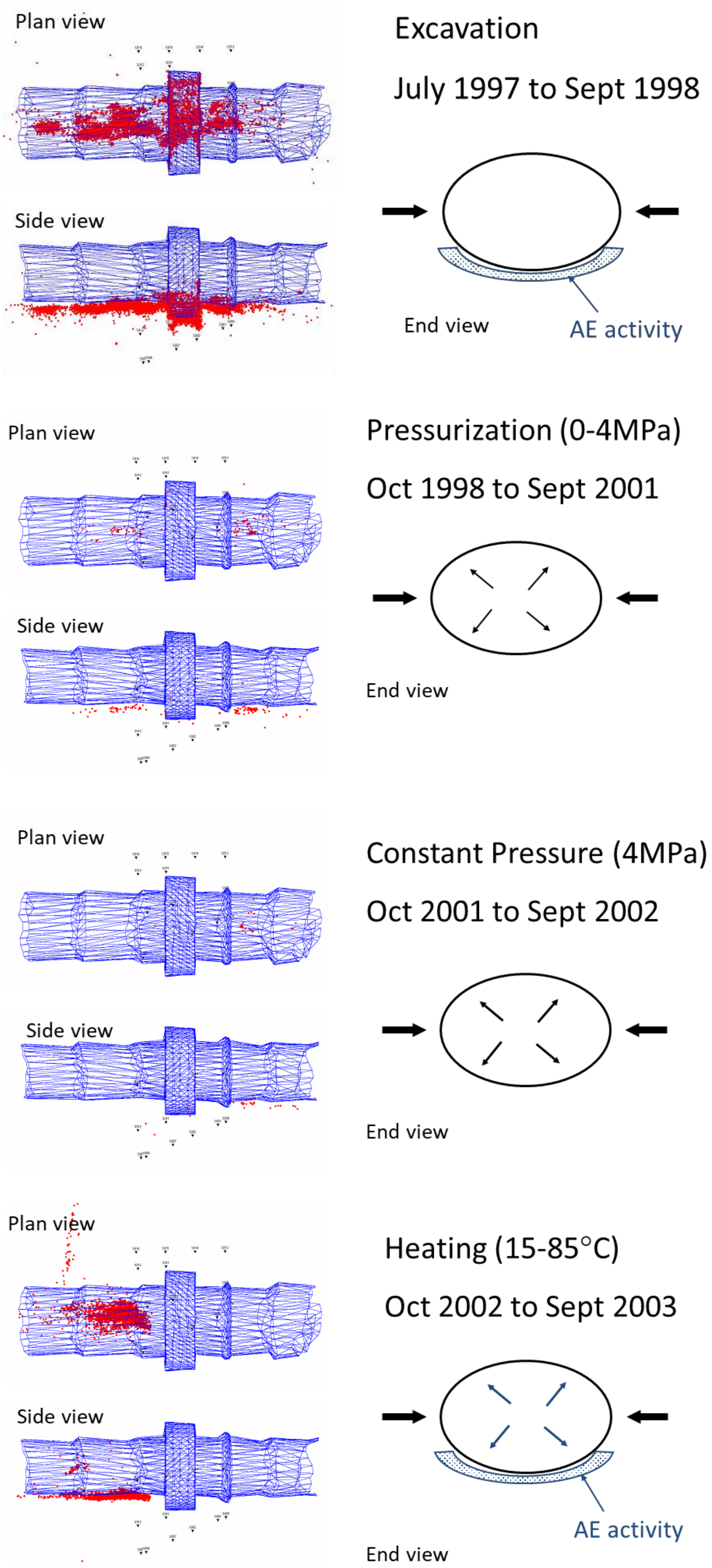

Figure 5: High-frequency AE response recorded by a local sensor array around the lower half of the Tunnel Sealing eXperiment test chamber.

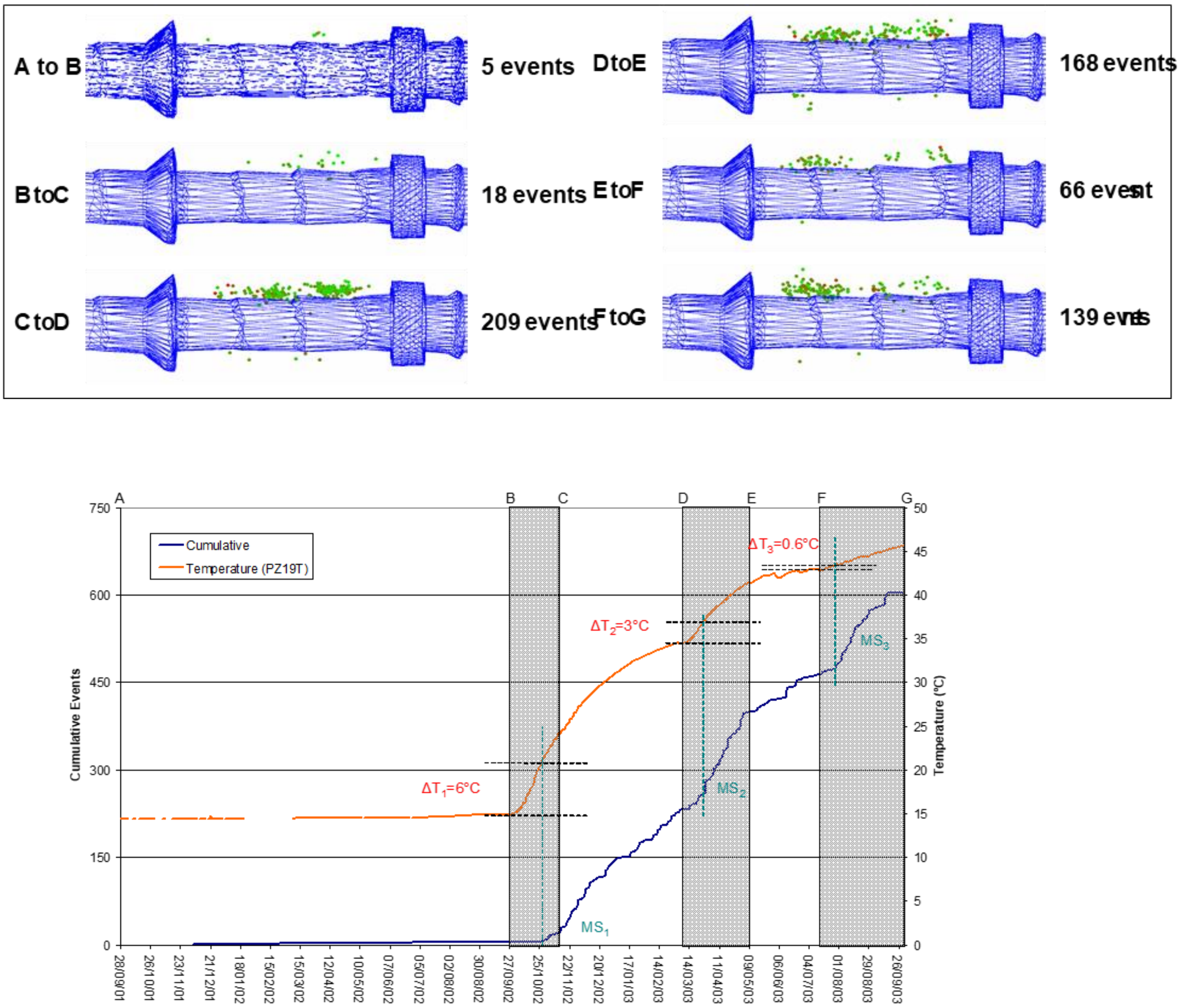

Figure 6: MS response of the Tunnel Sealing eXperiment gallery during the heating and pressurisation of the test gallery.

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.

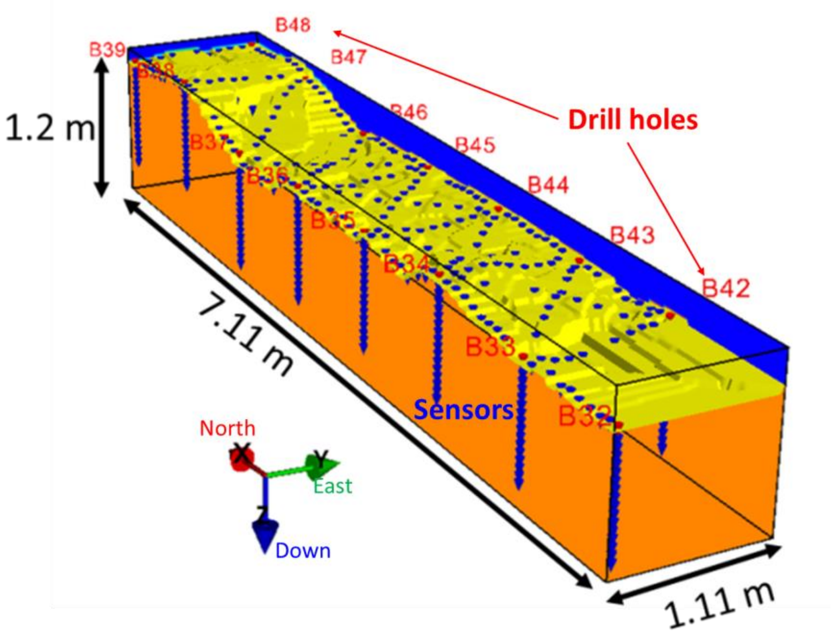

Figure 7: Configuration of the array designed for the tomographic imaging of a sample section of the EDZ

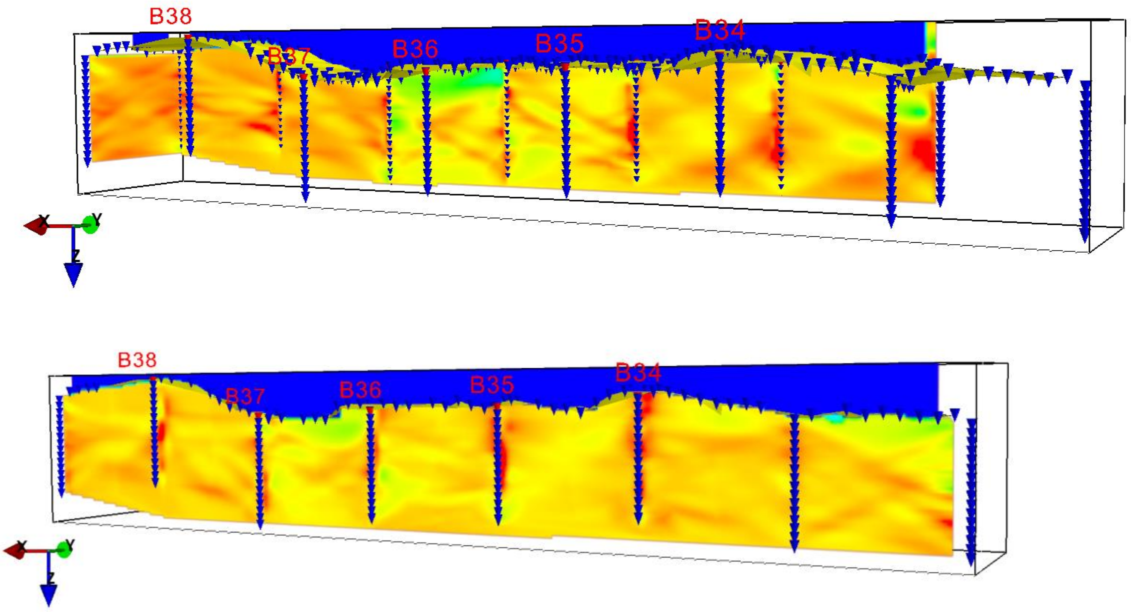

Figure 8: Summary of tomographic planes using all available surveys in 3D viewing the east side (top) and the west side (bottom) N-S planes

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.

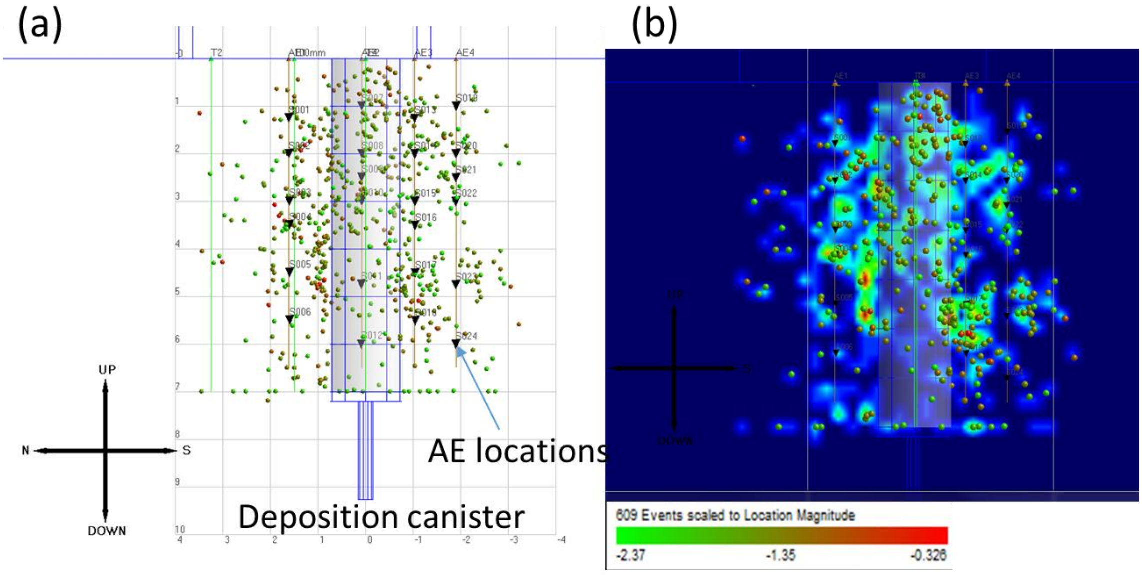

Figure 9: a) Located AE events during the monitoring period along the POSE 3 test hole. b) event density for the complete monitoring period

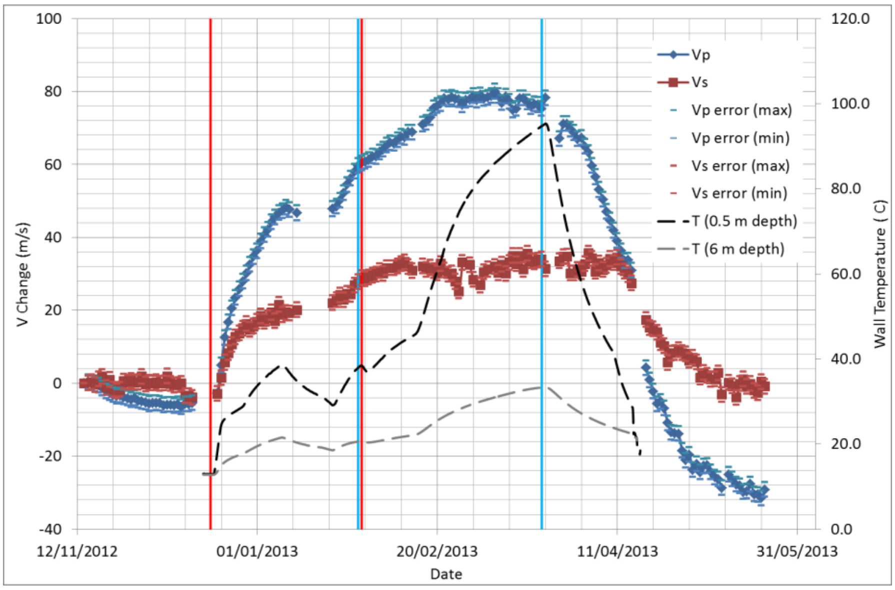

Figure 10: Changes in average transmission velocities relative to the ultrasonic survey performed on 14/11/2012. Horizontal lines above and below each data point indicate the error margin. Vertical solid lines indicate dates when heaters were switched on (red) and off (blue).

Clients

Canadian Nuclear Laboratories
Laboratoires Nucléaires Canadiens

SKB
Svensk Kärnbränslehantering AB

POSIVA

ANDRA
French national radioactive waste management agency

INERIS
maîtriser le risque
pour un développement durable

European Commission

中核集团
CNNC

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.

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Microseismic processing and Quality Control

ASC offers a fully integrated service for real-time and post-processing of seismic, microseismic and acoustic emission 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 seismic processing service can provide:

- Monitoring of excavations and critical structures
- Imaging and quantification of EDZ
- 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
- Software training and consulting.

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

- Microseismic monitoring array design
- Geomechanical modelling of planned repositories
- Characterisation of discrete fracture networks

REAL-TIME MONITORING

MONITORING DESIGN

MICROSEISMIC TRAINING

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