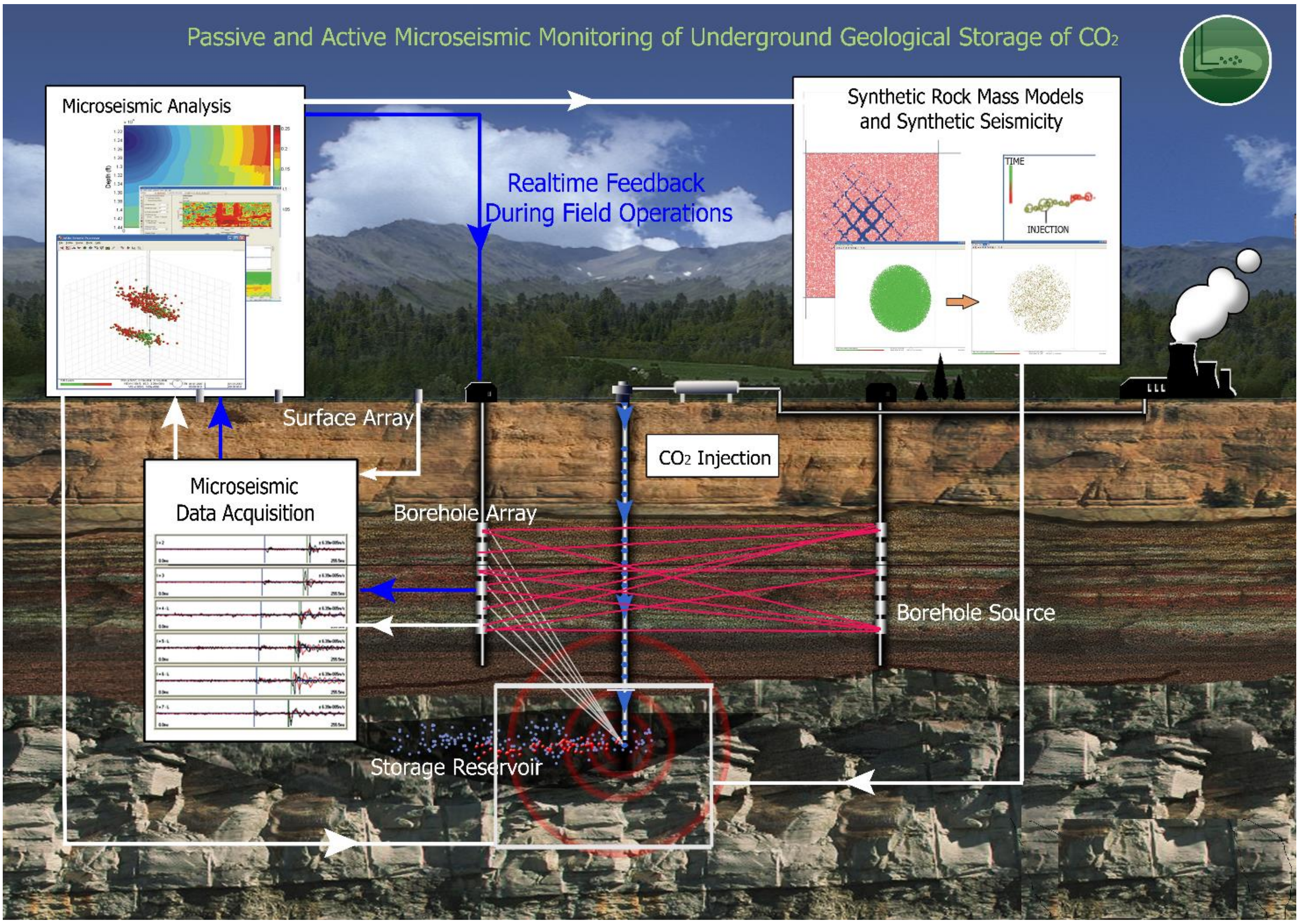
1 UNDERGROUND CO_2 STORAGE



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.

ICL 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.

ICL 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.

ICL 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.

1.1 Case Studies

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

ICL 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.

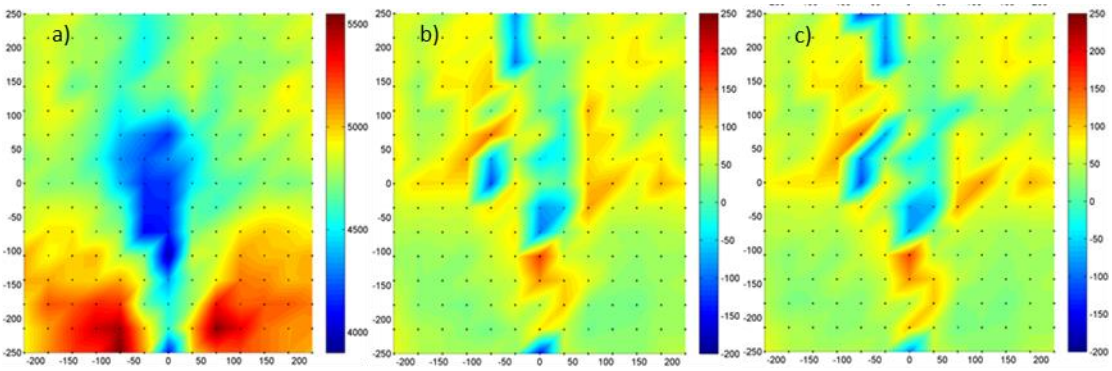


Figure 1: Measured velocities at a) the initial stage before the CO_2 injection when the source function was applied at the source (0, -280), b) at stage 1 and c) at stage 2. The units for the X- and Y-axes are in metres while the units for the colour bar are $m{\cdot}s^{-1}$.

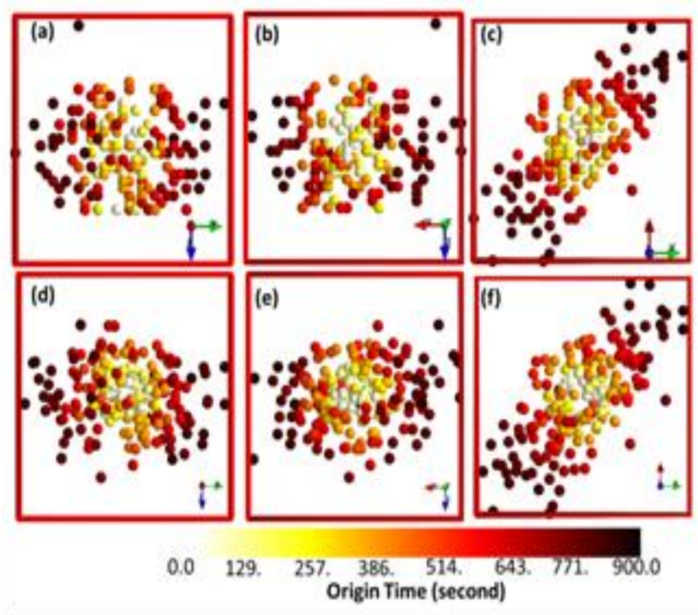


Figure 2: Locations of 176 events (a,b,c) compared with the modelled 200 events (d,e,f). Figure (a,d), (b,e), and (c,f) are viewing towards north, east, and downwards, respectively. In general, the automated location method recovers 88% of the true events.

1.2 Clients

1.3 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.

2 Monitoring of Concrete Structures

ICL 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.

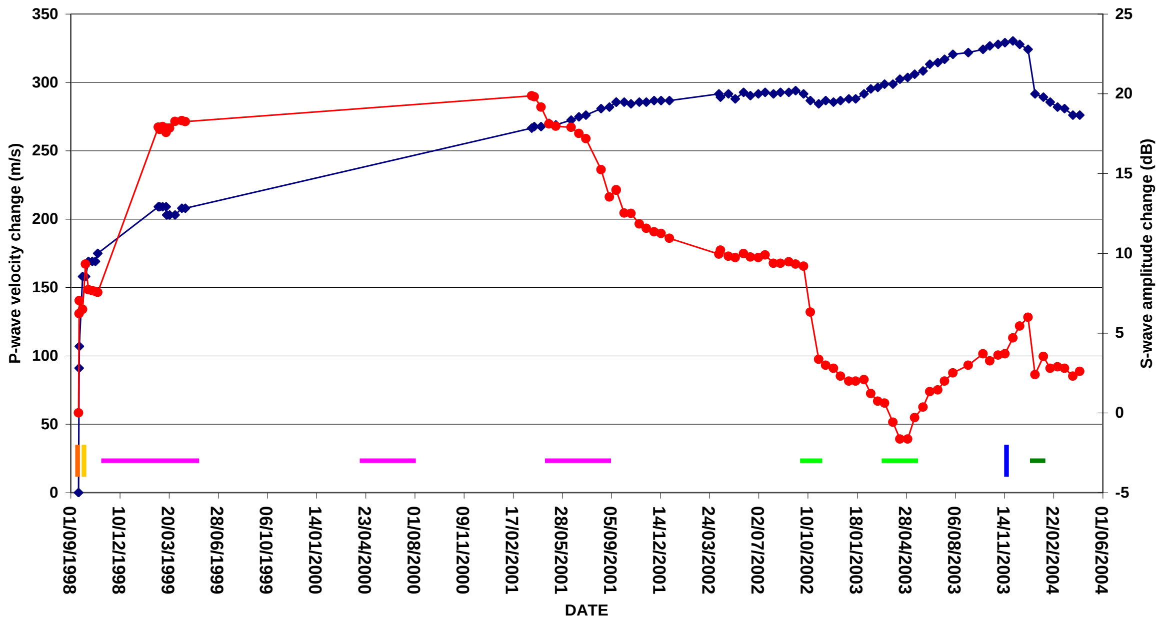


Figure 3: P-wave velocity and amplitude for a ray-path through the concrete bulkhead over a 5-year period of the TSX. (Blue = P-wave, red = S-wave)

At Fracture Nucleation	During Fracture Propagation	After Complete Fracture Growth

Figure 4: Located AE events at 3 different stages through the curing stage of the TSX (16th September - 27th October 1998).

REAL-TIME MONITORING

MONITORING DESIGN

MICROSEISMIC TRAINING

CUSTOM SOLUTIONS

QUALITY ASSURANCE

Microseismic processing & Quality Control

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.

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