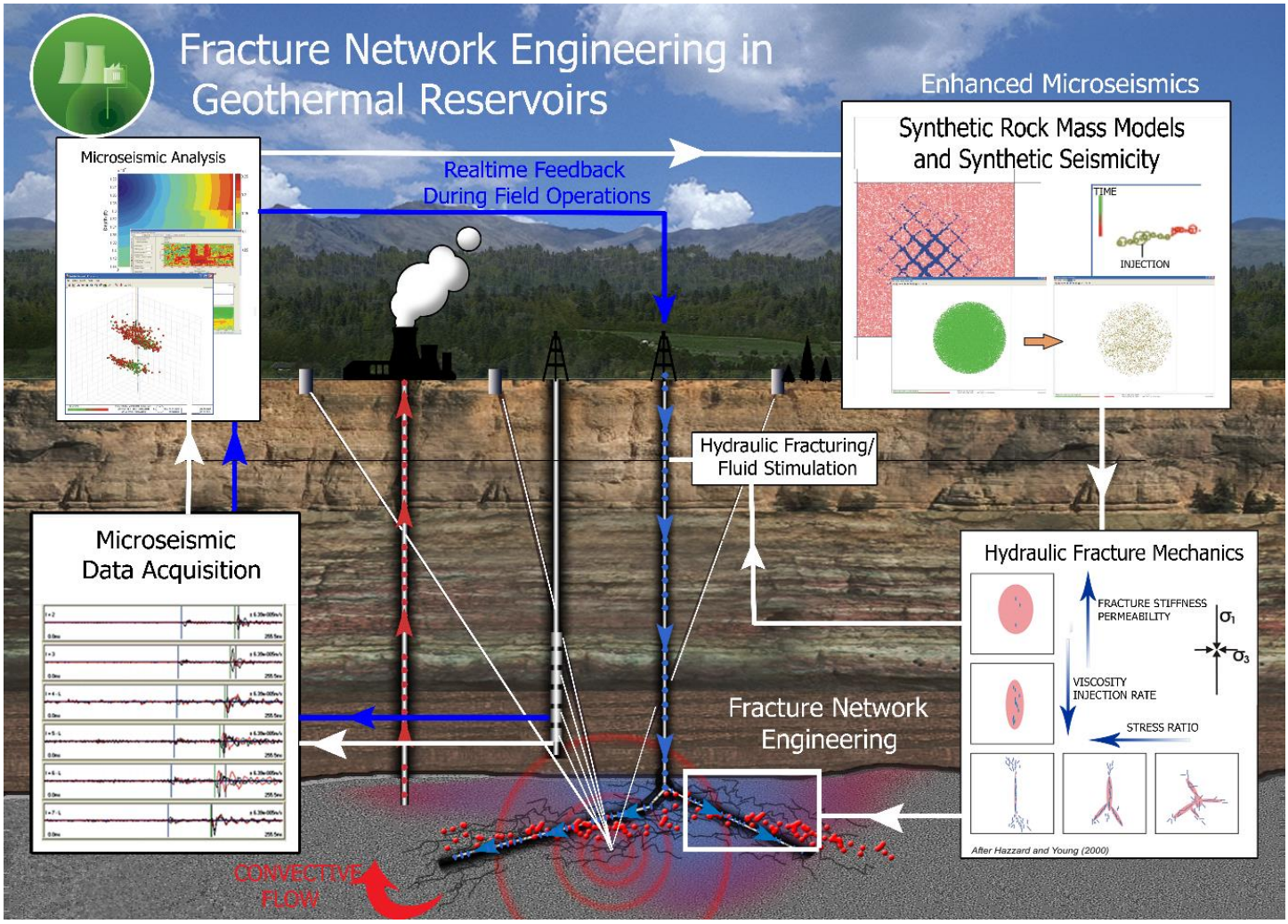
1 GEOTHERMAL



ICL 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. ICL'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

ICL 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. ICL'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. ICL 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.

1.1 Case studies

1.1.1 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 ICL 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.

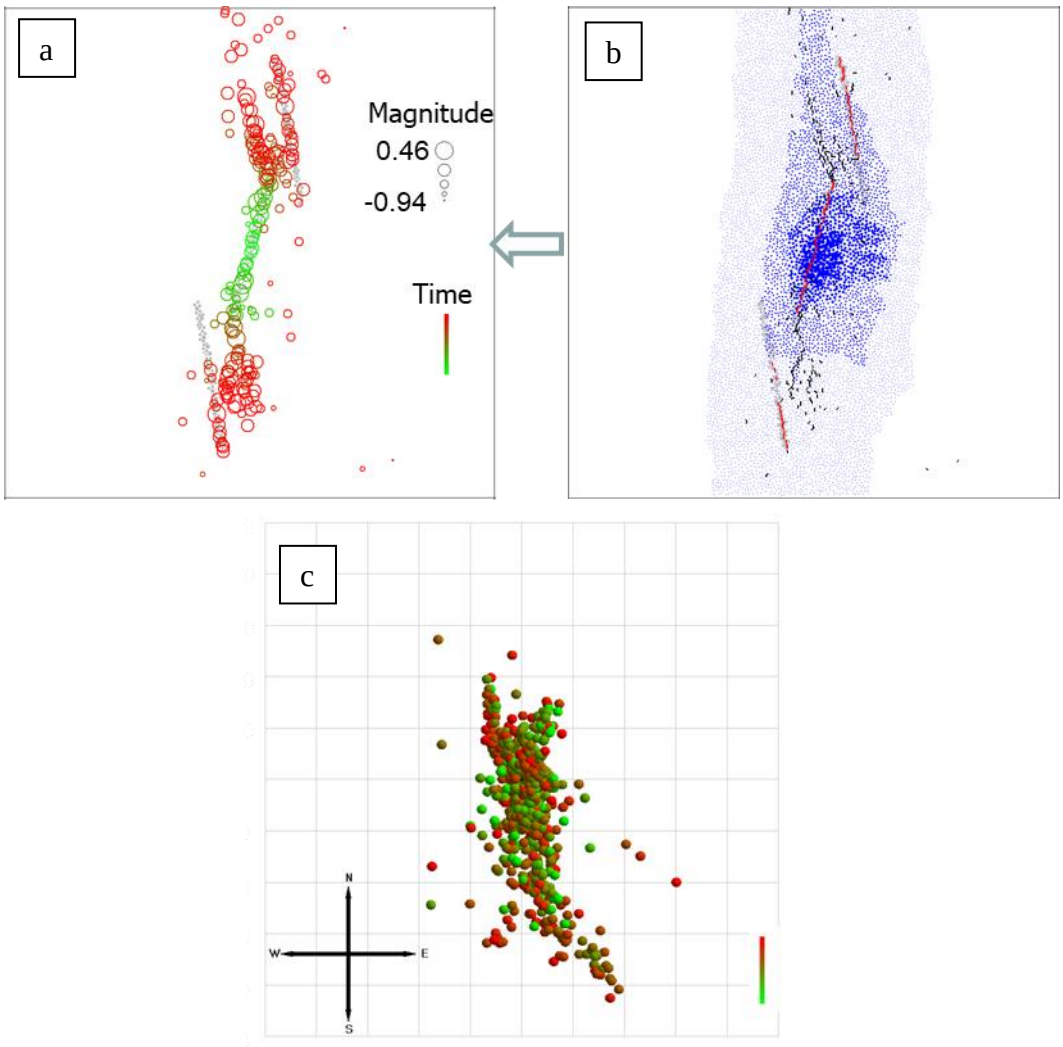


Figure 1: a) synthetic MS events induced in an SRM sample subject to fluid injection for 63.8 hours. b) Fluid flow and induced cracks in the SRM sample subject to hydraulic injection. c) MS events induced during the EGS treatment at Soult-sous-Forêts.

1.2 Clients

1.3 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.

Microseismic processing & Quality Control

REAL-TIME MONITORING

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.

MONITORING DESIGN

MICROSEISMIC TRAINING

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.

CUSTOM SOLUTIONS

QUALITY ASSURANCE

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

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