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Passive seismic imaging of Discrete Fracture Networks

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1 INTRODUCTION

Engineering operations such as underground mining, reservoir treatment through fluid injection, infrastructure excavation or laboratory tests subject rock masses to stress changes that induce the opening and remobilization of fractures at different scales. Passive seismic monitoring records the elastic energy released in these processes through an array of seismic sensors. The location of seismic, microseismic and acoustic events provides a unique method to image, evaluate and quantify the damage induced in a rock mass subject to stress changes, e.g. delineating the EDZ around underground excavations, quantifying the stimulated reservoir volume in enhanced geothermal reservoirs and oil and gas recovery operations or defining the seismogenic zones in deep caving mining. A deeper analysis of both the seismic catalogue and the seismic waveform can provide further details on the nature, geometry and temporal evolution of the active discrete fracture network associated with any of these operations. This paper presents an overview and case studies from the application of a series of statistical tools to the spatial distribution of seismic events and waveform analysis tools implemented in InSite Seismic Processor to extract information about the orientation, persistence and spacing of the fracture network induced or mobilized during different engineering and rock fracturing projects. This information has been applied to the validation of predictive Synthetic Rock Models and can also be used as a unique input for the definition of a Discrete Fracture Network in the modelling of the behavior of jointed rock masses.

2 METHOD

2.1 *Statistical analysis of passive seismicity*

The spatial distribution of the seismic events induced from stress changes imposed on a rock mass can be used to characterize the fracture network mobilized or opened in response to the different stress changes. This is done through a statistical approach applying the three-point method (e.g. Reyes-Montes & Young 2006, Fehler et al. 1987). This method has been applied to microseismic events induced at underground excavations and deep caves identifying dominant structures and providing the orientation, persistence and spacing of the dominant fracturing (e.g. Reyes-Montes et al. 2007). The method provides a real-time tool for the detection of fracture development and the identification of mobilized structures. The characterization of the fracture network provides a unique tool for the direct comparison of the impact of stress changes between different rock volumes and also comparing the induced in-situ seismic activity and the results obtained in controlled synthetic rock mass models subjected to known strain paths in order to predict the behavior of the jointed rock mass (e.g. Pierce et al. 2007). The over-sampling of the group of events makes this method less sensitive to Gaussian location errors than methods based on inter-event distance distributions.

The statistical technique calculates the planes that fit every unique combination of three events. The poles of the calculated planes can then be plotted on a stereogram, where a high density of poles will reveal any preferential orientation. This preferential orientation can be interpreted as the orientation of the macro-fractures formed by multiple microcracks that describe a macroscopic active Discrete Fracture Network. Further analysis of the distribution of the separation and extent of the fitted planes following the observed dominant orientation can be used to obtain information about the spacing and persistence of the dominant fracturing, providing the essential information for the definition of the active DFN.

2.2 *Seismic Discrete Fracture Network*

Passive seismic record has a wealth of information beyond event location that can provide information about the fracturing process. The inversion of source mechanism from waveform amplitude and polarization provides one of the most complete sources of information for the imaging of the fracturing process, particularly fracture plane orientation, source radius and information on the in-situ stress and strain. The calculation is based on the measurement of P- and S-wave relative amplitudes, variables controlled by the radiation pattern associated with a type of rupture along a particular plane (e.g. Zhao & Young 2011). Typically, the mechanism of shear events can be described by the motion of P-wave arrivals plotted in a lower-hemisphere stereographic projection of the space surrounding the source, known in seismology as beach balls. These beach balls provide information on the orientation of the shearing plane, corresponding to the active fracture.

A more general inversion, applicable to the full range of potential fracture mechanisms is provided by the inversion of the moment tensor calculated from the full waveform amplitude recorded on three-component sensors. The radiation pattern of the P-wave can then be used to calculate the orientation of the rupture plane (e.g. Chapman & Leaney 2012)

A robust inversion of the mechanism at the source requires a good azimuthal coverage, with seismic sensors ideally surrounding the seismic source, a configuration that is not always feasible in in-situ monitoring projects with sensor placement constrained by cost and logistic of access to suitable areas. A monitoring array with a limited azimuthal coverage of the source volume restricts the estimation of waveforms P-wave polarities, and hence the inversion of its source mechanism. Grouping events for a composite solution can overcome this limitation. The grouping is typically performed based on the ratio of amplitudes for the different phases, i.e. P, SH and SV arrivals measured as a function of the angle of incidence connecting source and receiver. The comparison of this distribution with modelled radiation patterns allow to constrain the most likely source mechanism for the group of events and defining a fracture plane.

3 RESULTS AND DISCUSSION

An example showing the characterization of the fracture network mobilized or opened in response to excavation and thermal-induced stress changes is shown in Figure 1. The structure analysis was applied to the population of 15,198 Acoustic Emission events induced during the different processes around two deposition holes excavated in diorite at SKB's Äspö Hard Rock Laboratory and monitored using an array consisting of 24 transducers mounted on four borehole frames, (Haycox et al. 2005). One borehole remained open, while the other was pressurized to 0.8 MPa before being subject to a heating and cooling cycle on both deposition holes. The analysis was split between the clusters of events induced in the vicinity of each deposition hole and divided in depth at 0.5 m intervals. The results provide a characterization of the macroscopic fracturing induced in the pillar between the holes, showing fracturing dominated by a network of sub-vertical well-defined fractures oriented sub-parallel to the holes walls, with well-defined shallow dipping planes on the upper section likely corresponding to the activation of in-situ fractures, a set of fractures confirmed after the removal of floor spalling and borehole mapping. Structure appears more clearly defined around the unconfined deposition hole indicating a better developed fracture network (sub-vertical slabbing). The relatively lower degree of structure definition in the confined hole can be interpreted as an indication of a higher abundance of scattered Acoustic Emission (AE) events corresponding to isolated microcracking.

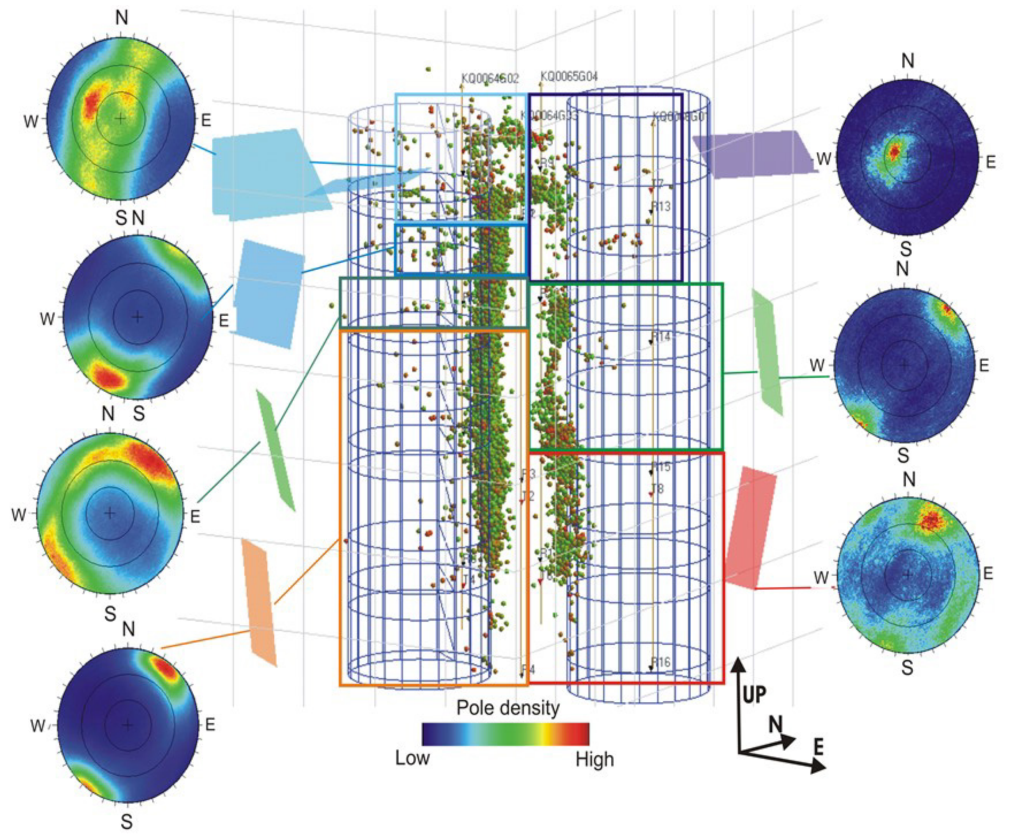

Figure 1. Stereographs showing the relative density of poles to the planes fitting the AE events induced at different levels of two deposition holes at SKB's Aspö Hard Rock Laboratory. The diagrams show the corresponding interpreted dominant planar structure that represent the Fracture Network at each level. Grid spacing is 1m.

Figure 2 shows an example of AE monitoring at rock sample scale from the true-triaxial compression of a sandstone cubic sample. The test was monitored using a transducer array, consisting of 16 piezoelectric pinducers placed in direct contact with the rock sample (King et al. 2011). The structural analysis was used to analyze the evolution of fracturing during the test and image the evolution of the induced fracturing during the test. The stereographs on Figure 2(b) show the development of the induced fracture at five stages of the compression test, clearly identifying the development of two well-defined sets of subvertical fractures parallel to σ_1 from early stages of fracturing, with secondary sets of horizontal fracturing only defined at early stages and a set of 50° dipping sets at late stages.

The geometry of the monitoring array provides full azimuthal coverage, allowing the inversion of source mechanisms and moment tensors from the amplitudes of the recorded waveform arrivals. The results for a sample subset of events are shown in Figure 2(c) with events plotted as 'beach-ball' focal spheres. The spheres represent the distribution of compressional and tension forces at each of the induced micro-cracks, together with conjugate fault plane solutions. The results show fault planes generally consistent with the observed subvertical macrocracks observed from the analysis of the structure defined by the AE location distribution.

The microseismic (MS) events induced during an example single-stage hydrofracture treatment in a tight-gas sand formation is presented in Figure 3. The treatment was monitored using a string of 12 triaxial geophone tools deployed in a vertical well in the proximity of the treatment well (Sharma *et al.* 2004). In this case, due to the poor azimuthal coverage provided by the single vertical array, a composite source mechanism approach is followed in order to determine the fracture plane for each of the located MS events. Relative amplitudes of P, SH and SV phases were used to group events that fitted a single-source radiation pattern. Fracture planes are represented as disks and show a distribution of orientations roughly opening normal to the propagation direction of the induced macrofracture.

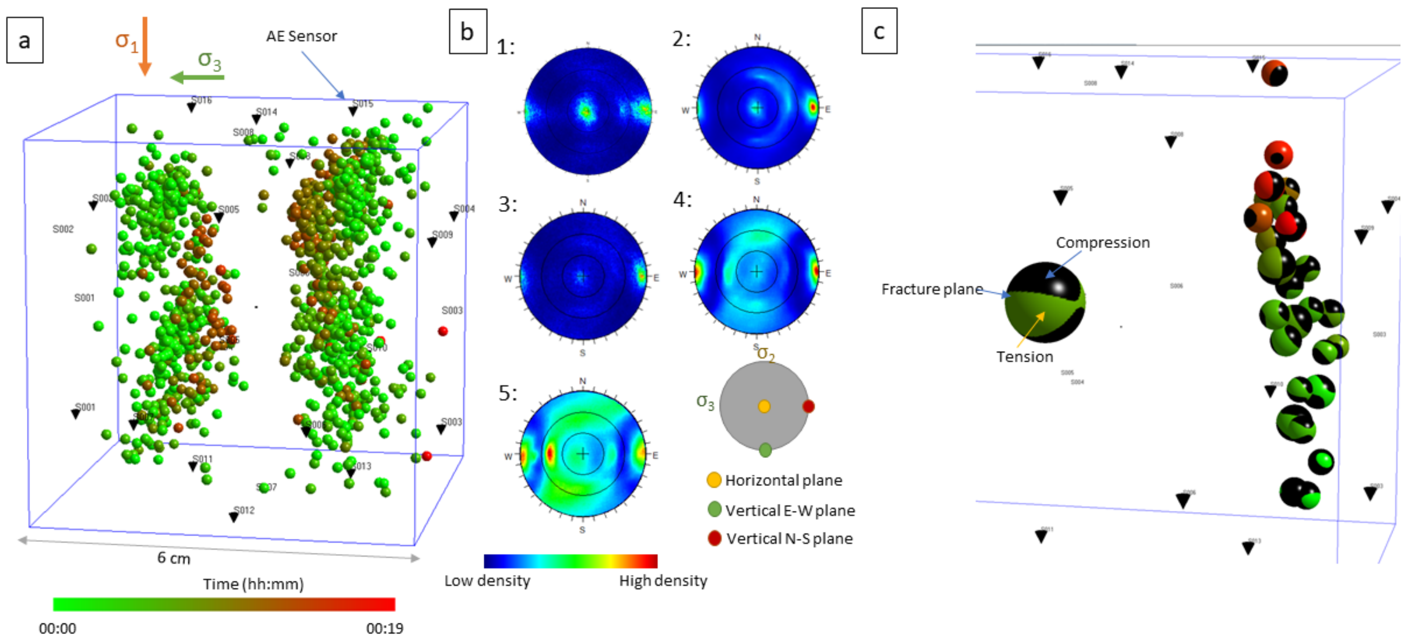

Figure 2. (a) Location of AE events color-scaled to time induced during the True Triaxial compression test of a sandstone sample. (b) Temporal evolution of the structure defined by AE activity showing the orientation of the dominant induced fracturing. (c) Source mechanisms for a sample population of events represented by their 'Beach ball'.

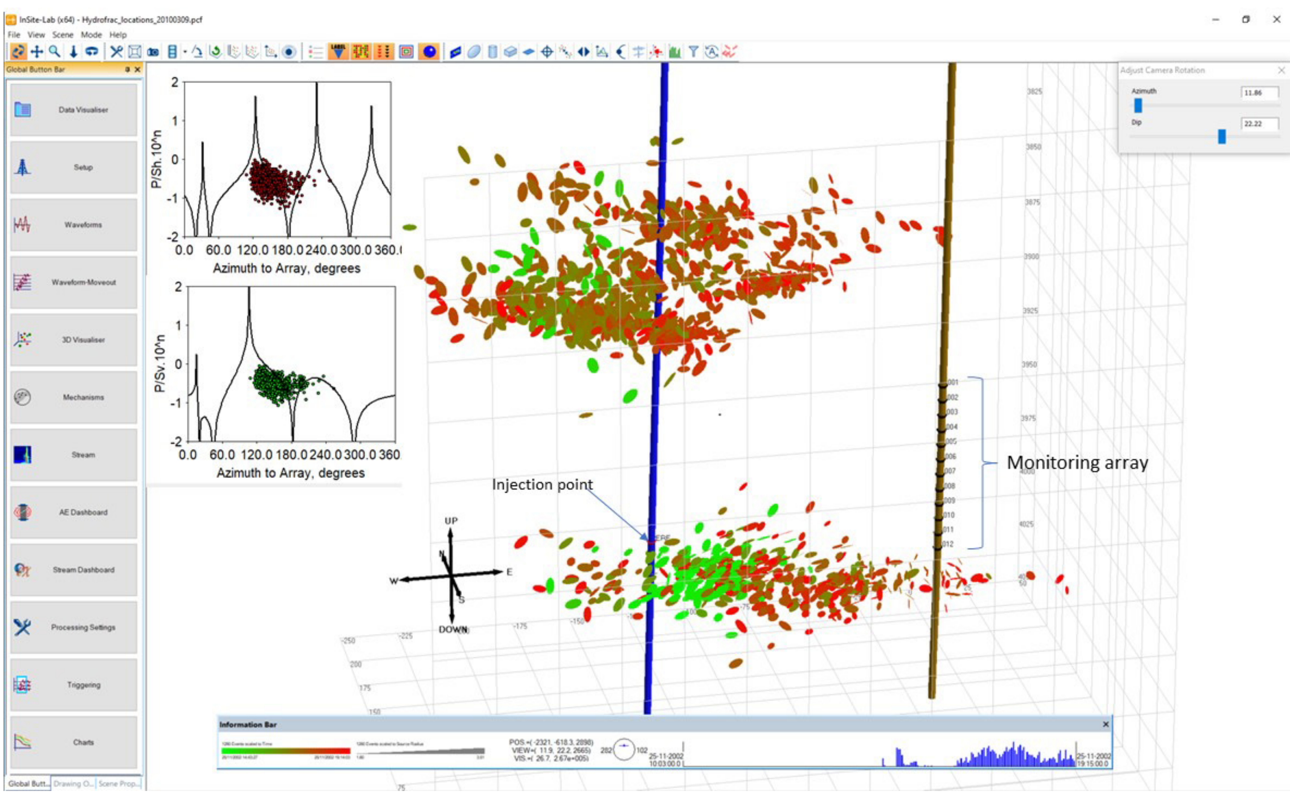

Figure 3. Location of the MS events induced during the hydraulic fracturing of a tight-gas sand reservoir. MS events are represented by the interpreted fault plane solution from a composite analysis combining events with amplitude ratios fitting a single source model. The orientation of the fault plane solution can be used to characterize the induced DFN.

4 CONCLUSIONS

Passive seismic monitoring is a unique tool for imaging fracturing processes in real-time at all scales from tectonic natural faulting to laboratory rock fracturing tests. The spatial, temporal and energy patterns in the monitored seismicity can be analyzed to characterize the induced and mobilized fracture network, providing an image of the evolution of the geometry, extent and nature of the induced fracturing.

The imaged active fracture network can be used for updating the Discrete Fracture Network in Synthetic Rock Mass models, validating their results and improving the predictions for the evolution of brittle rock masses under multiple stress conditions.

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