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# Identifying reservoir drainage patterns from microseismic data

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## Summary

Microseismic data provides insights on the efficiency of a hydrocarbon field stimulation program. Current interpretation is often limited to assessing stimulated fracture geometry and number of events. Classical flow patterns, based on symmetric and homogeneous flow, are then often assumed to predict drainage areas and production volumes. In an attempt to link geophysical data with reservoir engineering, we here present a novel approach, using *in situ* measurements on the strain imparted on the rock mass by individual rock failures. Moment tensor inversion of the microseismic events yields the failure mechanism and orientation of each event. Historically, the resultant strain field of all events has been used to mapping compartments of parallel strain. Here, we here extent this approach assuming that tensile strain on the rock mass opens preferred flow path ways. By mapping stream lines through the strain field it is thus possible to identify drainage patterns of individual ports throughout the stimulated reservoir volume.

## Introduction

Efficient production of stimulated volumes is the ultimate goal of enhanced oil recovery (EOR) and unconventional shale gas and oil projects. Microseismic monitoring is increasingly used to provide *in situ* measurements of stimulation programs. In hydraulic fracturing, microseismic event locations provide detailed information on the paths of fluids during stimulation and thus the success of the design. In real-time projects engineering parameters such as pressures can then be adopted to improve event rate and stimulated reservoir volume. The geometry of the fractured zone (length, height, width, and azimuth) then provides important constraints on the accessible hydrocarbons.

While event locations provide valuable information on the response of the rock to stimulation, they use only time domain information. Down hole recordings can make use of the frequency content as well and thus provide directly, i.e. without calibration, source parameters such as moment magnitude and source area. These source parameters are then used to define the seismic deformation, proportional to the seismic moment per unit volume, to constrain the stimulated reservoir volume (SRV) to regions of significant seismic activity. Small and/or isolated events, which are not connected to the wellbore and thus do not contribute to production, can thus be disregarded. In contrast to simply using the envelope of seismic event cloud, which provides and optimistic SRV, the deformation based $SRV_D$ incorporated more available information from the recordings and thus a more realistic estimate of stimulated volume.

Early attempts to predict flow paths through the stimulated volume neglected vertical extent of the event cloud and connected linear features in event location maps. These lines were then interpreted as fractures and fracture network (e.g. Fisher et al., 2002). Post-processing algorithms, such as collapsing and clustering (e.g. Nicholson et al., 2000) reduce effects of location error in such approaches and provide statistical constrains on the significance of a linear feature. It can be applied to identify compartments and potential fluid sinks when planning a stimulation program.

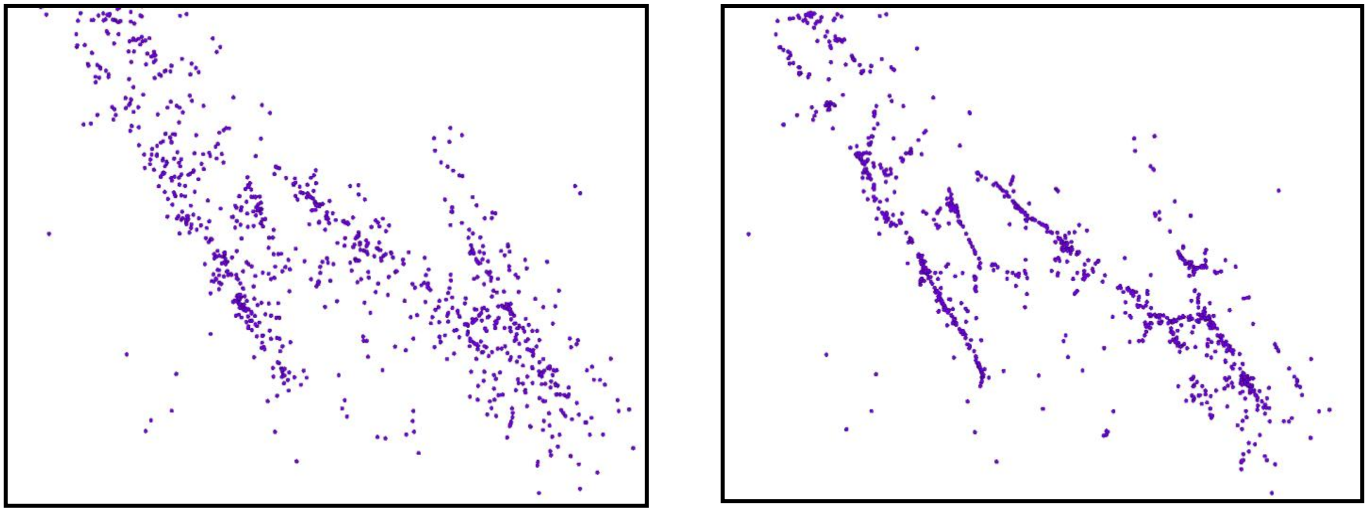

Figure 1) Event location map before and after a collapsing algorithm is applied. Faults are delineated much clearer. Note that individual events are moved within their respective error bounds to reduce the overall error.

While such an event location approach is only useful for reservoir-scale mapping of the fault system, local variations of the fracture network remain unresolved. Here the method of Seismic Moment Tensor Inversion (SMTI; e.g. Baig and Urbancic, 2010) offers direct insight into the discrete fracture network stimulated by individual cracks. By including polarity and amplitude in the phase arrival information, the fracture mechanism can be resolved. Thus, tensile and shear-cracks as well as their opening and closing components can be distinguished, each of which has different implications on the generated permeability. Furthermore, the orientation of individual fracture planes can be inferred. For example, it has been shown that vertical and horizontal fractures are predominantly stimulated in different lithologies of a reservoir during a single stimulation. This information provides valuable constraint of reservoir flow models.

In this paper, we use the seismological information of individual fracture mechanisms to obtain a geomechanical model of the strain imparted on the rock mass. Such a resultant strain field has been used (Urbancic et al., 1997) in mining applications to characterize local stress variation caused by excavation. We translate this approach to a hydraulic fracturing setting. We relate the (tensile) strain direction to the failure direction in the rock mass, thus obtaining a dominant flow direction at each grid point. We can then follow flow through the stimulated volume towards the ports and identify the drainage pattern.

## Example Dataset

We illustrate this concept of drainage pattern on an example dataset from the Horn River Basin in British Columbia, Canada. More than 33000 SMTI solutions of a multistage zipper frac stimulation program have been calculated. The strain field is then calculated following the nearest-neighbor method of Urbancic et al. (1997). At each grid point the average moment tensor of nearest neighbors within the grid cell is calculated from which the principal strain (P, B and T) axes are then determined. Following standard seismological convention, the P-axis corresponds to the most compressive orientation, the T-axis to the least compressive (i.e. most tensile) and the B-axis to the intermediate orientation.

Figure 2 shows the orientation of P and T axis orientations at main stimulation depth. The lengths of the markers correspond to the inclination of the axis. The principal strain orientations vary widely throughout the stimulated zone: In the strain maps (Figure 2), The Eastern areas show homogeneous (parallel) orientations of the principal strain axis. Note that in these areas the P- and T axes are also approximately horizontal. Other areas, for example in the North-West show more complex variations of the strain axis. These features remain stable when tested with different gridding parameters and sub-sets of the data. Note also that the azimuths of P-axis are generally different from (i.e. not parallel to) the NE-SW regional stress field. This highlights the fact that assuming the regional stress field orientation in post-stimulation reservoir simulations is an oversimplification of the local strain field. Rather, complex compartmentalization of stress and strain dominates, which is probably caused by variations of lithology, elastic moduli, and/or dominant fluid flow paths caused by the discrete fracture network.

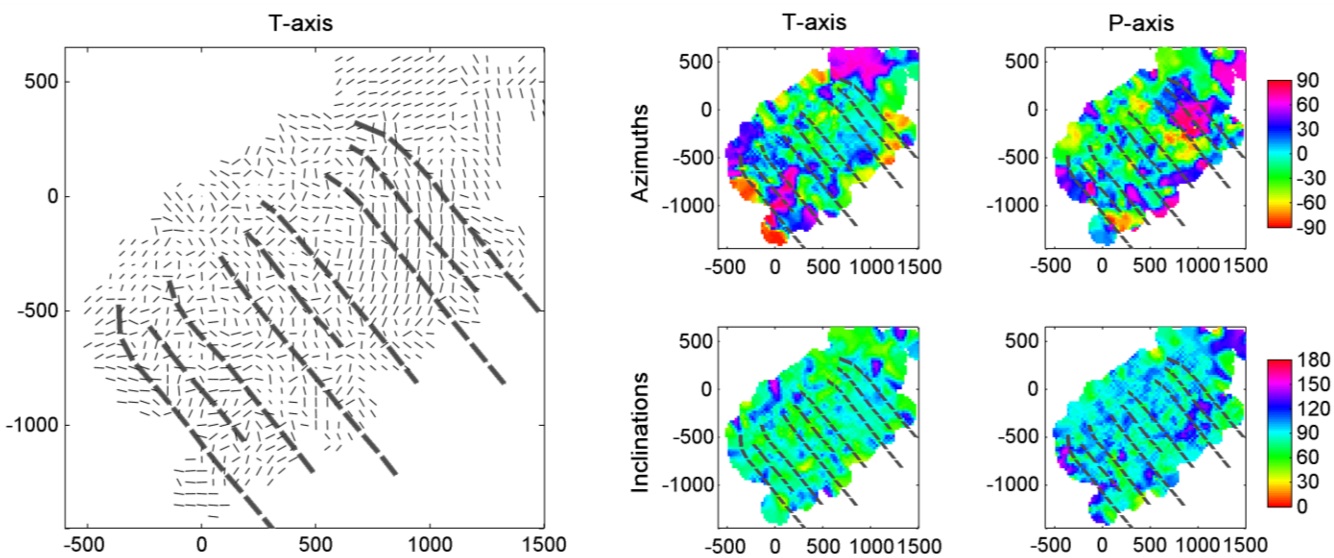


Figure 2) Orientations of strain axis at stimulation depth inferred from more than 33000 individual SMTI results of a multi-well hydro-frac stimulation. Lengths of the markers correspond to inclination of the principal strain axis, with vertical inclination represented by a dot. Both, T-axes (a) and P-axes (b) vary largely from the NE-SW regional stress field, with strong variations and compartmentalization on a local scale. The stage ports along the different wells are shown as gray bars.

We then use the strain field to identify flow paths within the stimulated volume. The T-axis represents the orientation of most tensile strain on the rock matrix. This in turn relates to the orientation of openings. In contrast, the P-axis is related to the dominant orientation of inhibited flow. The flow can then be visualized by stream lines, with seed points at each individual stimulation port. Each line thus traces the origin areas of gas or oil reaching the port. Furthermore, areas of parallel stream lines are likely to be drained easier, whereas complex stream line patterns are to be related to complex, inhibited flow.

The stream lines aid identifying the origin of the hydrocarbon flow arriving at each port, but not the strength of the expected flow. We can however complement the flow maps with other established microseismic parameters. Similar to the estimation of Stimulated Reservoir Volume, we here use as proxy for generated free surface area the Seismic Deformation, proportional to cumulative Seismic Moment per unit volume. Figure 3 shows thus the flow paths through the reservoir underlain by the seismic deformation underlying. Areas of high seismic deformation and parallel stream lines are very easy and fast to drain of hydrocarbons. Ports associated to convoluted stream lines and which have only access to low seismically deformed areas, will drain slower. Obviously this method cannot predict the actual hydrocarbons in place, but offers unique calibration points for reservoir models and production curve analysis.

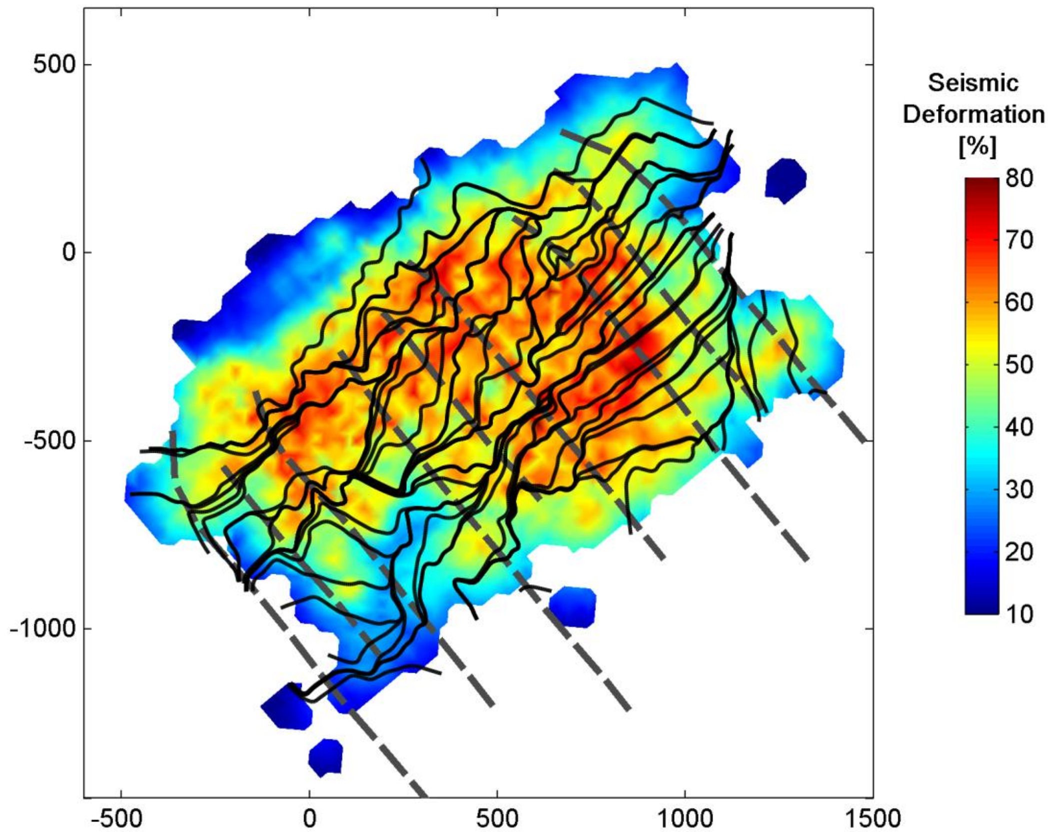


Figure 3) Streamlines along dominant crack opening orientation as inferred from the strain T-axis of SMTI solution illustrate drainage patterns in the reservoir. In combination with Normalized Seismic Deformation, which shows areas of strongly shattered rocks, the drainage potential, can be inferred. Note areas variability stream lines, which are some areas markedly parallel and in others highly convoluted.

## Conclusions

Microseismic data can offer a wealth of information about the geomechanic processes involved in hydraulic fracturing. Especially, multi-array recordings allow us to go beyond simply locating events, but resolve individual fracture planes. Furthermore, the full strain field after stimulation can be inferred form *in situ* data. This strain field is much more complex and shows strong local variations from the regional stress direction. We have here presented then a methodology to illustrate flow paths towards the ports. In combination with seismic deformation as proxy for strength of shattering of the rock, this method illustrates drainage patterns and drainage potential of the stimulated reservoir volume.

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