New model explaining inverted source mechanisms of microseismic events induced by hydraulic fracturing

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Summary

We present a case study of detailed source mechanism inversion in microseismic dataset from hydraulic fracturing of a shale gas play. This study uses surface monitoring array to invert shear and non-shear parts of the source mechanisms from 75 individual events to characterize relationship between hydraulic fracture and induced seismicity. We observe source mechanisms dominated by shear failure with dip-slip and strike-slip sense of motion. We propose a new model explaining source mechanisms induced by hydraulic fracturing based on bedding plane slippage.

Introduction

Hydraulic fracturing is a process in which a liquid and solids are pumped into a formation under pressure high enough to cause cracks to open in the formation. This process creates hydraulic fractures that propagate perpendicularly to minimum principal stress direction. This technique is routinely used to increase permeability in oil and gas reservoirs or create flow paths in geothermal fields. The injection of the fluid and creation of the fractures that can store large volumes of incompressible proppant particles suggest that seismicity induced by hydraulic fracturing may have volumetric component.

To measure volumetric or shear component of a microseismic events one needs to invert not only a source position, but also source mechanism. Early interpretations of microearthquake activity induced by hydraulic fracture treatments (Pearson, 1981) concluded that the microseismic events result from shear failure induced by fluid percolation along preexisting fractures. These conclusions were mostly deduced from observations limited to a few offsets and azimuths in one or two monitoring boreholes. A major limitation of the borehole based source mechanism inversions was identified by Nolen-Hoeksema and Ruff (2001), who pointed out that data from a single (vertical) array of receivers in a 1D velocity model does not constrain inversion of the volumetric component of a source mechanism. Vavryčuk (2007) showed theoretically that a single-azimuth data set (as in single monitoring well) cannot resolve the dipole perpendicular to the plane of

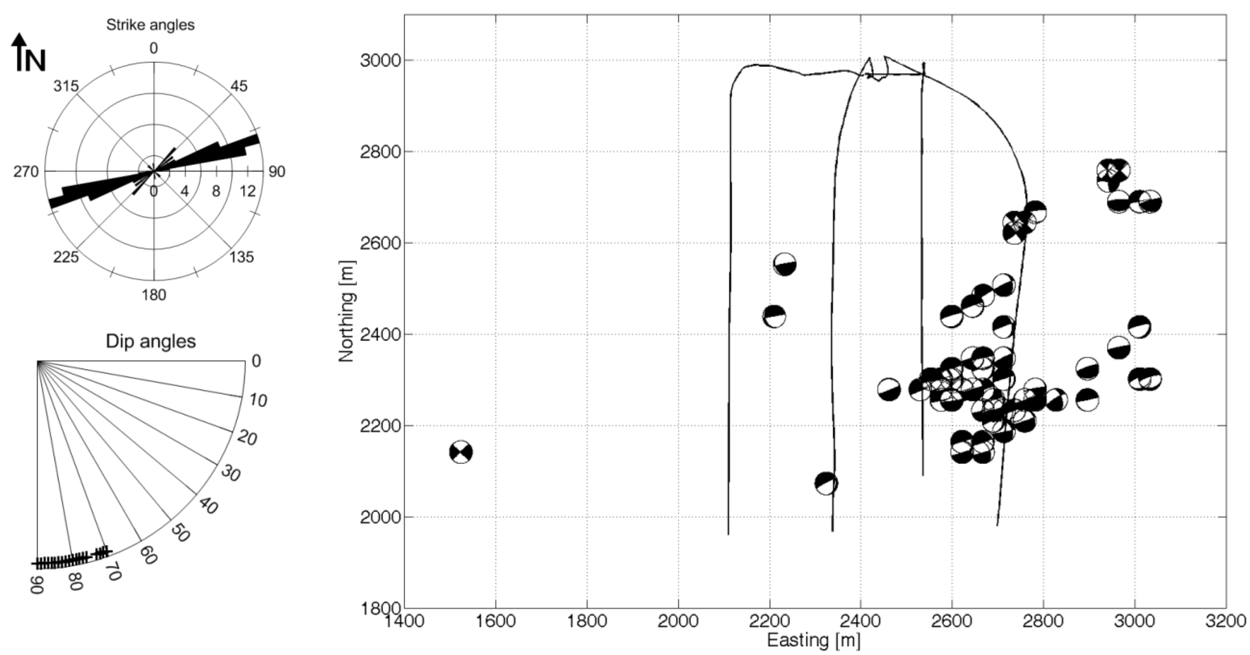

Figure 1: Rose diagrams and map view of 75 source mechanisms presented as beach balls. The rose diagram in upper left corner show orientation of strike angles. Crosses on diagram in lower left corner represent dip angles.

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stations and the hypocenter. Thus, the single-azimuth data cannot resolve tensile opening associated with volumetric changes of microseismic events. The current studies of source mechanisms of microseismic events induced by hydraulic fracturing monitored from boreholes seem to observe both shear and non-shear mechanisms: some studies conclude that all induced events are pure-shear, e.g. Phillips *et al.* (1998); Rutledge and Phillips (2003), or other studies conclude that induced events are associated with both shear and volumetric changes, e.g. Nolen-Hoeksema and Ruff (2001); Jechumtálová and Eisner (2008); Šílený *et al.* (2009), sometimes even using the same datasets. The major issue with the mechanisms of the shear events obtained from some of the source mechanisms studies is the orientation of the shear planes: the planes are (within the inversion uncertainty) within the direction of the maximum horizontal and vertical stresses, thus there should not be a shear failure on these planes due to background tectonic stress.

The first study of the source mechanisms of events induced by hydraulic fracturing from multiple offsets and azimuths of Julian *et al.* (2007) resulted in observations of some events representing tensile opening events during the hydraulic fracture stimulation and tensile closing after the hydraulic fracture stimulation and some portion of the shear events before, during and after the stimulation. Recently, Eisner *et al.* (2010) took advantage of large surface arrays monitoring hydraulic fracture stimulation in a sedimentary basin and inverted source mechanisms of several microseismic events characterizing the observed induced seismicity. They have found that the observed microseismic events can be explained as a pure shear failure with dip-slip and reverse mechanisms. Furthermore, the dip-slip mechanisms have one steeply dipping (nearly vertical) plane shows shear failure along a vertical (or horizontal) plane in both normal as well as reverse sense. The reverse mechanisms along the less steeply dipping planes do not show similar reversals. As the normal and reverse motion along the same fault plane is not possible to explain by tectonic loading, the events associated with dip-slip mechanisms must be caused by hydraulic fracture loading, while the reverse faulting along the less steeply dipping planes can be caused by merely reactivation of a pre-existing fault. This implies that the source mechanisms characterization allows differentiation of microseismic events induced by hydraulic fracturing from events induced on pre-existing natural faults.

Field and data description

We analyze microseismic dataset which has been continuously recorded during hydraulic fracture stimulation of shale gas reservoir in North America. Four horizontal wells were treated at approximately 2100 meters depth. Each of these wells has been stimulated in three stages.

Microseismic monitoring was performed with a large star-like array, covering approximately 25 km^2, with a total of 911 vertical geophones deployed at the surface. Receivers were spread out in radial lines around the wellpad in the middle. Such configuration guarantees wide coverage of azimuths and offsets with receiver offset to depth ratio exceeding 1 as it is recommended for every surface monitoring array. Using a large number of receivers allow us to perform very robust inversion for source mechanisms (Staněk *et al.*, 2012).

Migration-type of algorithm (PSET) detected and located more than 600 events during and after the pumping, all considered to be induced by the stimulation. We have chosen 75 strongest events which are clearly visible in raw data. 52 of the selected events are related to the most active well, 39 to the first stage on this well. Several strong events occurred after the injection operations during flowback regime.

We manually picked maximum amplitude of the first P-wave arrival on each trace for all selected events. When we were not able to reliably recognize first arrival, e.g. on traces of geophones lying in the vicinity of nodal lines or on noisy traces, we did not pick amplitude and did not use these traces (receivers) in further computations.

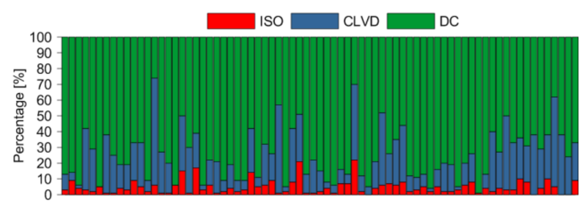

Figure 2: Products of decomposition for inverted 75 full moment source mechanisms.

Moment tensor inversion

To invert source mechanisms we employ a wave front tracing for modeling of propagation effects through 3D velocity model. There are computed rays in an isotropic model with smoothed 1D P-wave velocity profile which was derived from active 3D seismic model in monitored locality. With parameters of rays such as travel time, trajectory and slowness vectors affected by velocity model we are able to construct Green function used in moment tensor inversion. We obtain a full moment tensor (MT) by least-squares inversion of direct P-waves amplitudes. This MT is further decomposed to isotropic (ISO) and deviatoric components (CLVD and DC) after Vavryčuk (2001). Shear part of the source mechanism is also described by dip, strike and rake angles of two fault planes and scalar moment. Finally we compute L2-misfit expressing how accurately synthetic amplitudes computed for obtained MT explains observed data, i.e. picked amplitudes in their size and polarity.

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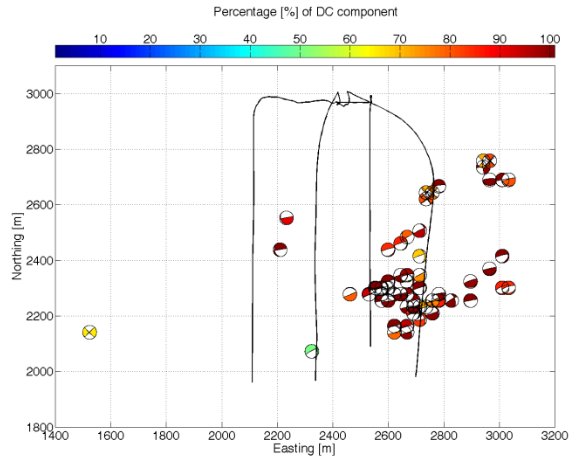

Figure 3: Map view of 75 source mechanisms colored according their real percentage of DC component.

Figure 1 shows a map view of inverted shear parts of MT source mechanisms presented as beach balls. Microearthquakes have moment magnitudes from -0,5 to 0,3.

Sixty-two mechanisms can be characterized as dip-slips. Interestingly the dip-slip sense of motion seems to be changing polarities. We observe two opposite motions: one group of dip-slip mechanisms has a northern half of beach ball with first motion down and the other group with first motion up. These mechanisms seem to alter between reverse and normal faulting. Remaining twelve mechanisms can be characterized as strike-slips. Eleven of strike-slips occurred after the fracturing.

Orientation of strikes of the more steeply dipping fault planes is summarized in a form of rose diagram in upper left corner of Figure 1. It shows dominant orientation of strikes in direction WSW-ENE or 70° azimuth consistent with regional maximum horizontal stress direction. Diagram in lower left corner shows that dip angles of the steeper fault planes are mostly from 80° to 90°. Given that majority of the shear parts are consistent with dip-slip mechanisms; it means that either fault or auxiliary plane is nearly vertical or nearly horizontal.

Full moment mechanisms of all events are composed from DC, CLVD and ISO components; percentages of these components for all mechanisms are shown as tricolor columns in Figure 2. Most events are having largest DC component, so we detect more shear than non-shear events. Eight events, i.e. only 11%, have non-shear components (i.e. combination of ISO and CLVD) greater than DC component. ISO and CVLD components are sensitive to noise and errors in the inversion; hence we investigate carefully reliability of this inversion.

Testing reliability

Staněk *et al.* (2012) showed on synthetic data, that moment tensor inversion is, in this receiver geometry, sensitive mainly to type of source mechanism and noise in data, and less sensitive to mislocation and mismodeling. Due to the noise we mainly get spurious non-shear components (ISO and CLVD).

In a real data inversion we want to separate real source parameters from artifacts appearing due to the presence of noise. So we would like to know a percentage of spurious non-shear components but we cannot quantify it because we do not know the real source mechanism. In order to obtain an estimate about the reliability of obtained parameters we carried out two tests.

First test is a comparison of full moment solution with a pure-shear moment tensor. Pure-shear mechanism is the best fitting 100% DC mechanism to observed data. It is obtained by grid search with a step of 5° in strike, dip and rake. We compare L2-misfits and orientation of principal directions of these two mechanisms. In fact, full MT mechanism always fits observed data better as it has additional two degrees of freedom to fit the data, however, the test investigates if this fit is significantly better.

When a pure-shear mechanism provides a similar misfit to data as a full moment mechanism we can say that non-shear components are not important, and likely they are false. For commonly observed misfits in our datasets, usually we consider the difference in L2-misfit lower than 2% and differences in orientation lower than <5° in principal directions to be negligible. Higher differences indicate real non-DC parts.

Second test is an estimation of expected spurious non-shear percentages for pure-shear mechanism due to noise. Firstly, we measure the level of noise in a real data as a RMS of noise to RMS of signal ratio. The RMS of noise is computed from time interval before the picked P-wave arrivals. Then root mean square (RMS) is computed from amplitudes in this interval from all receivers. Secondly, we create 50 sets of synthetic amplitudes for each of 75 pure-shear mechanisms. Every set is then contaminated with noise amplitudes taken from real data at a random time. Noise amplitudes are proportional to the amplitudes of signal to keep the measured noise level in real data. This way we create 50 realizations amplitude picks with similar level of noise.

Finally, full MT source mechanisms inverted from created synthetic amplitudes are characterized by an average, minimal and maximal values of source parameters (DC, ISO and CLVD components, L2-misfit and deviation in orientation) which we can expect for pure-shear mechanisms inverted from real data.

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Afterwards we study if parameters of full mechanisms inverted from real data fit into intervals of expected values for pure-shear mechanisms. When the obtained decomposition components of mechanism are near the average values or at least in the ranges between maximal and minimal values we conclude such events are consistent with pure-shear source mechanisms. Reversely, when the values are out of ranges, events are partly non-shear.

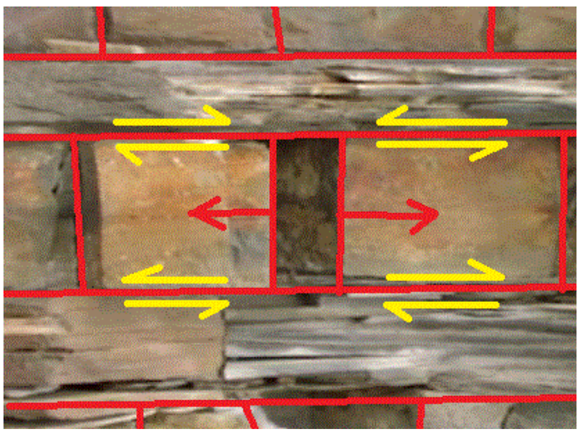

Figure 4: This is a conceptual model of shear failure (yellow arrows) along weak planes (red lines) in shales driven by hydraulic opening of vertical cracks (red arrows).

Results

After summarizing all the results we can split 75 source mechanisms into several groups according to percentages of decomposition products and type of source mechanisms.

The first group contains only pure-shear events. For these events we have got full source mechanisms very similar to pure-shear mechanisms, i.e. differences between them are very low. And all parameters of full mechanisms are also in the ranges of expected values for pure-shear. There are eight dip-slip mechanisms in this group.

Second group consists of source mechanisms very nearly pure-shear. The reason why they are not in the first group is that all their parameters do not fit into ranges of expected parameters for pure-shear mechanisms. There are 19 dip-slip mechanisms and one strike-slip mechanism.

Third group is for non-shear events. Non-DC part of their full MT mechanisms was corrected with the maximal expected non-DC part for pure-shear mechanism. Minimal real percentages of non-shear components are shown in a Figure 5. Minimum is 1% and maximum is 53% of non-DC component. In this group there are 12 strike-slip mechanisms and 35 dip-slip mechanisms. This largest group however has only small portion of probably real non-DC components.

Model

Figure 4 shows conceptual model that allows us to explain observed mechanisms and their relationship to hydraulic fracturing. We propose that the dip-slip mechanisms with nearly pure-shear failure are caused by the slip along bedding planes, the weakest geomechanical planes in shale formations. Note that this mechanism is driven by the hydraulic fracture energy and not the background tectonic stress. The background tectonic stress only determines the orientation of the hydraulic fracture that determines sense of slip on the bedding plane. This mechanism can explain opposite polarities of the induced microseismic events shown in Figure 1 or 3.

The proposed model does not explain the strike-slip mechanisms. They are probably resulting from interactions with pre-existing fault planes as their locations are tight to a small depth interval far from injection intervals and other (dip-slip) events.

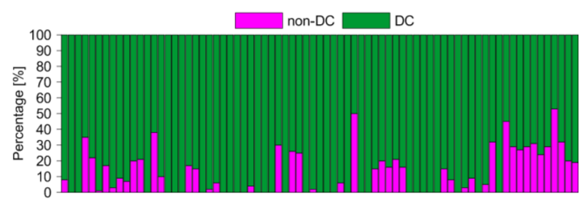

Figure 5: Minimal real percentages of non-shear components (magenta) for inverted 75 full moment source mechanisms.

Conclusions

We have inverted source mechanisms for a large number of microseismic events induced by hydraulic fracturing in shale reservoir. We observed source mechanisms dominated by shear failure with large number of dip-slip events and small number of strike-slip events. 98% of the analyzed events have DC greater than 50%. 80% of the analyzed events have DC greater than 75%. We propose the dip-slip events are caused by bedding plane slippage loaded by an aseismic tensile opening of the hydraulic fracture.

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