

Beyond the dots in the box: microseismicity-constrained fracture models for reservoir simulation

LEO EISNER, SHERILYN WILLIAMS-STROUD, ANDREW HILL, PETER DUNCAN, and MIKE THORNTON, *MicroSeismic*

Monitoring induced microseismic events usually results in locations for these events and a geometrical interpretation of these “dots in the box.” In this study, we show how additional information obtained from observed microseismic events, namely the source mechanisms, were used to generate a discrete fracture network. Using the wide aperture of a surface star-like array (FracStar) allows inversion for both shear- and nonshear-source mechanisms. Both volumetric and shear-only source mechanism inversion was done on microseismic events from the treatment of a shale gas reservoir in the continental United States. During the same hydraulic fracture stimulation treatment, both dip-slip and reverse faulting sources were active in this reservoir. The source mechanisms revealed fracture orientations more accurately than could be inferred from microseismic event locations alone. The activity of different mechanisms is interpreted as indicating reactivation of existing fractures in the rock, as well as suggesting generation of new fractures.

Failure analysis using source mechanisms on individual events allows an integrated understanding of the complex fracture interactions taking place in the reservoir, and also provides a more complete understanding of the stress conditions in the reservoir during the treatment. Fracture orientations, locations, and failure mechanisms are translated into discrete fracture network (DFN) models that can be used to verify the extent and character of the fractures created or reactivated during the fracture treatment, and may ultimately be used to generate fracture flow properties for reservoir simulation.

Introduction

Monitoring seismic events induced by completions and production processes has been increasingly used to develop and optimize oil and gas production. Such monitoring uses microseismic events caused by stress changes in the rock. These stress changes can be caused by various reservoir activities such as hydraulic fracturing, water injection, or fluid extraction. The majority of recent applications exploit location analysis of the induced microseismic events. However, the recorded seismic waveforms carry additional information on the mechanism of failure for each of these events. The mechanisms of these events can be used to estimate stress changes instead of inferring these changes from the spatial distribution of the located microseismic events. In this study, we show how the source mechanisms of the observed microseismic events were used to differentiate between microseismic events induced on pre-existing faults and those originating from induced hydraulic fracturing. The differentiation and characterization of microseismic events is a key in creating discrete fracture network (DFN) models that can be used to condition models that simulate reservoir production.

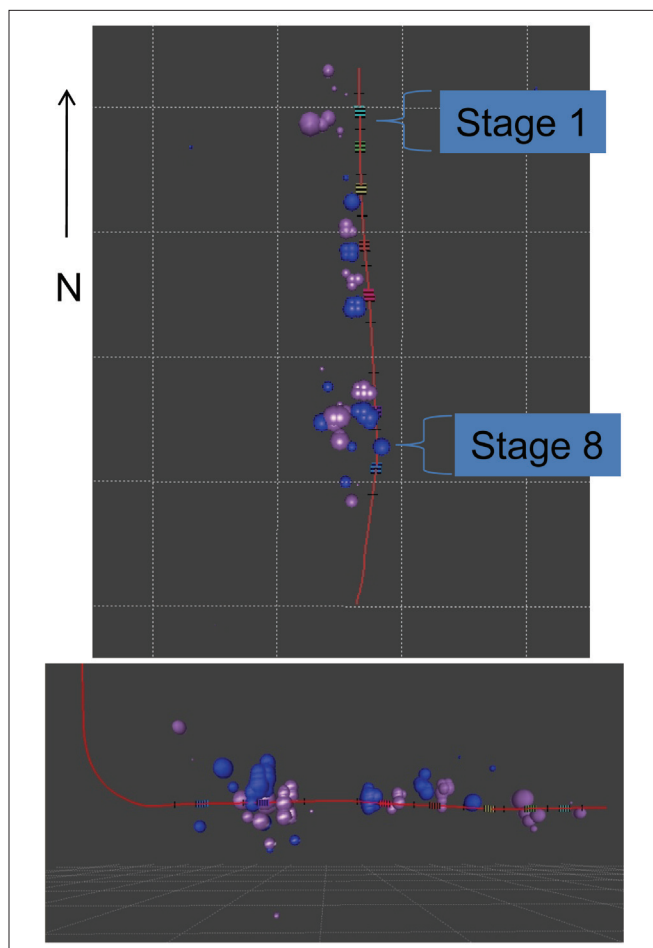


Figure 1. Map view (top) and vertical cross section (bottom) through mapped locations of the microseismic events in this case study. Two types of microseismic events are color-coded: Blue spheres correspond to locations of the reverse faulting events and purple spheres correspond to locations of dip-slip events. Sphere size is proportional to the released seismic moment; the largest sphere (stage 8) represents 9.3×10^9 nm. Treatment well trajectory is represented by the red line. The induced events are predominantly west of the treatment well while reverse mechanisms show significant vertical growth.

Perhaps the main reason why location analysis is the primary use of microseismic data is the difference in the stability of the inversion for the source mechanisms and the inversion for the location of microseismic events. Locations are derived mainly from observed arrival times while source mechanisms are inverted from relative amplitudes of either P- or S-waves (or both). Arrival times are less sensitive to small perturbations caused by medium heterogeneity. For example, arrival-time anomalies tend to “heal” along the propagation path, but amplitudes of seismic waves are more subject to local heterogeneities, making their inversion less stable. Given that

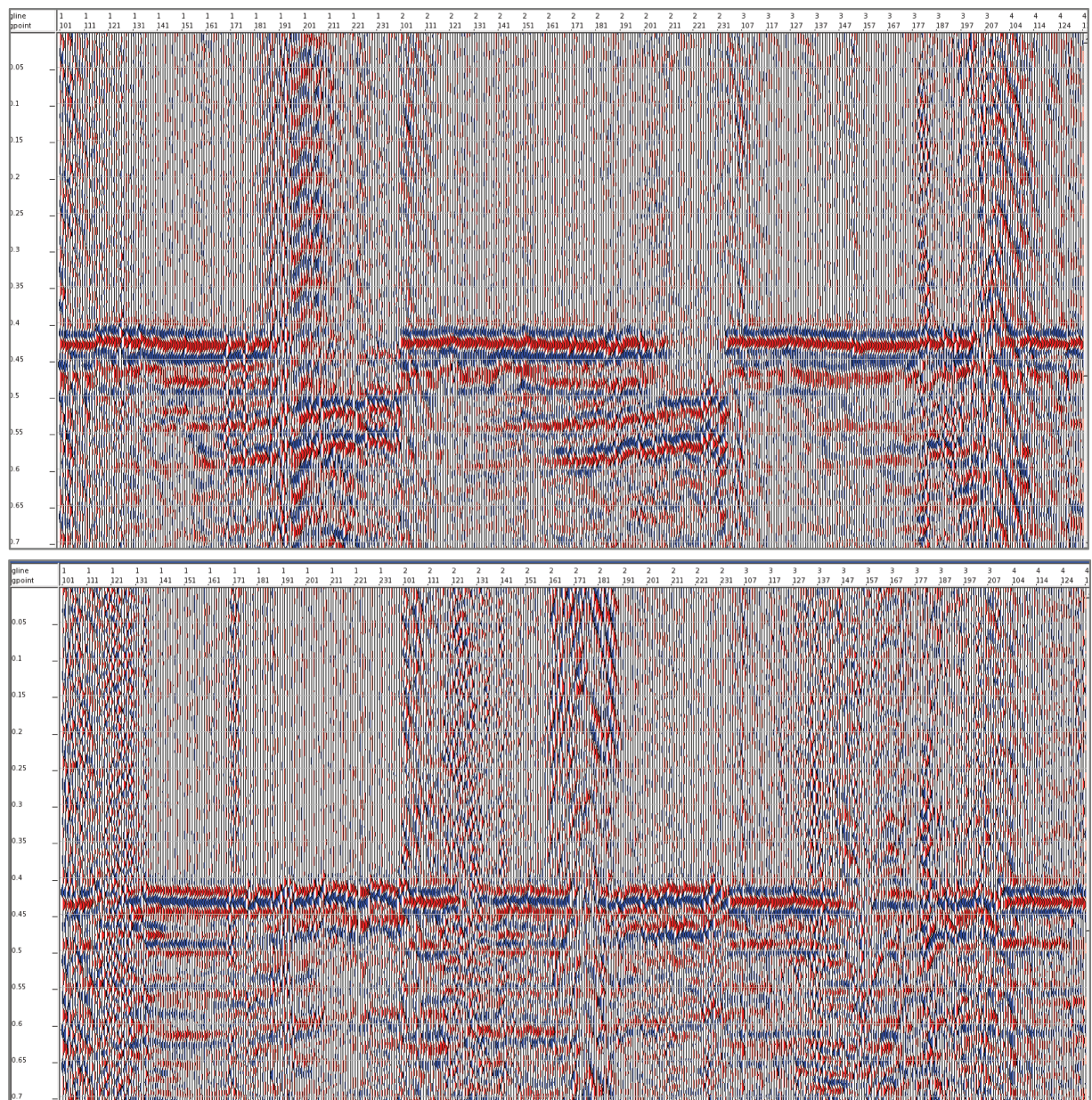


Figure 2. Two moveout-corrected sections of the vertical component first arrivals of the largest microseismic events detected in this case study. The upper plot shows an event without polarity change across the spread. The lower panel shows an event with a polarity change across the spread. The polarity changes are caused by source mechanism differences between microseismic events. The event with the polarity change is caused by a dip-slip mechanism with a nearly vertical fault plane (DSNU event); the event without the polarity change is caused by reverse mechanisms on 40-50° dipping fault planes (RSNE 1 event).

most early monitoring studies were carried out with a very limited aperture (usually with geophones in one vertical borehole), the uncertainty related to mechanism inversions from these limited observation points produced unreliable results. The source mechanism inversion becomes more stable with a larger number of monitoring receivers, such as can be deployed as a network of receivers distributed on the surface or in the shallow subsurface with geophones at multiple offsets and azimuths. The greater distance of the receivers from the events for surface and shallow buried arrays (as compared to a downhole array in a nearby

well) means a lower signal-to-noise ratio for each receiver. In the case of the surface array, the approximately 1000-fold stacking of the signal from many receivers serves to enhance the signal relative to the noise. Similarly, the noise reduction achieved by burying the geophones in a shallow buried array combined with stacking of a smaller number of receivers helps to overcome the low signal-to-noise ratio. The broader aerial coverage of such a receiver network can also compensate for unknown heterogeneities in the inversion model.

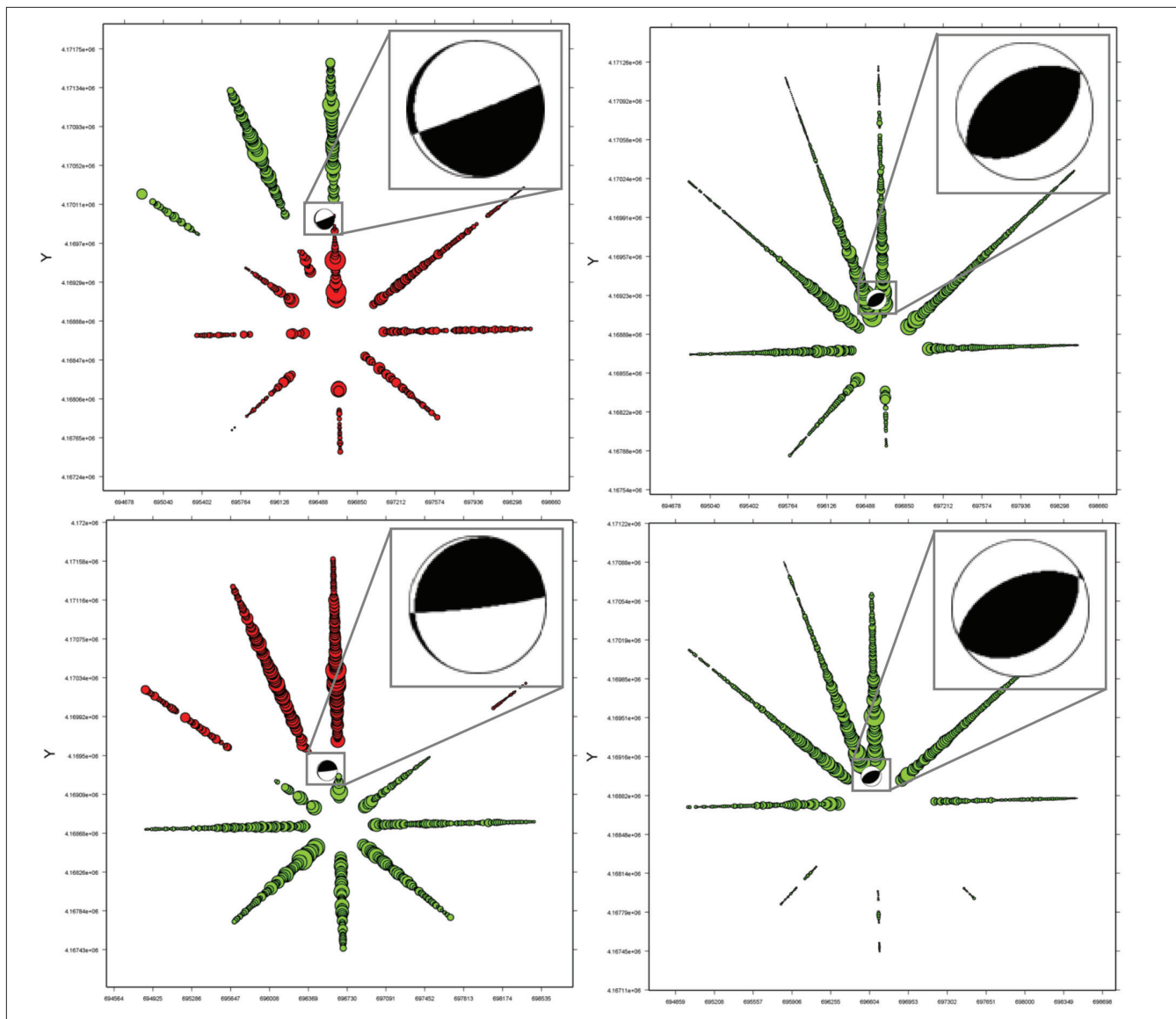


Figure 3. Map views of polarity and relative sizes of first arrivals for three types of microseismic events induced in this case study. Red circles represent motion down; green circles represent motion up. Circles are proportional to relative sizes of the observed amplitudes. The black-and-white beach balls are plotted at the microseismic event epicenters as lower-hemisphere projections of the inverted shear components of the general source mechanisms, with an enlarged beach ball in the upper right corner of each plot to show details of the failure mechanism.

Case study

Source mechanisms have allowed us to understand the complex patterns of event locations induced by hydraulic fracture stimulation on a well drilled in the continental US. This stimulation was performed on a well at an approximate depth of 6000 ft. Eight treatments of nearly two million barrels of brine with proppant stimulated approximately 4000 ft of horizontal well section. The pad volume consisted of approximately 37% of the total volume. The pumped fluid was fixed with 15% hydrochloric acid and approximately 800,000 pounds of 100 mesh sand were used as proppant. Average treating pressure was 6186 psi and average treating rate was 64.7 bpm. The maximum surface pressure reached (during treatment) was 7845 psi. The final frac gradient at the end of the job was 1.07 psi/ft. The microseismic monitoring was carried out with a star-like surface array (FracStar)

consisting of nine lines of length 4000-7000 ft. The surface monitoring array consisted of 980 single-component receiver stations laid out with approximately 1:1 offset-to-depth ratio in a star-like pattern. Figure 1 shows a map view and vertical cross section of the located microseismic events that were induced in all fracturing stages. While this data set shows good signal-to-noise quality (signal-to-noise ratios of up to 10), the resulting locations are difficult to interpret as fracture trends. There seems to be upward vertical growth of events with a reverse mechanism, as the majority of these events occur above the treatment well. Most induced microseismic events are west of the treatment well, suggesting strongly asymmetric hydraulic fractures.

Figure 2 shows the moveout-corrected sections of two large microseismic events recorded on several arms of the FracStar array. The recorded waveforms are the vertical com-

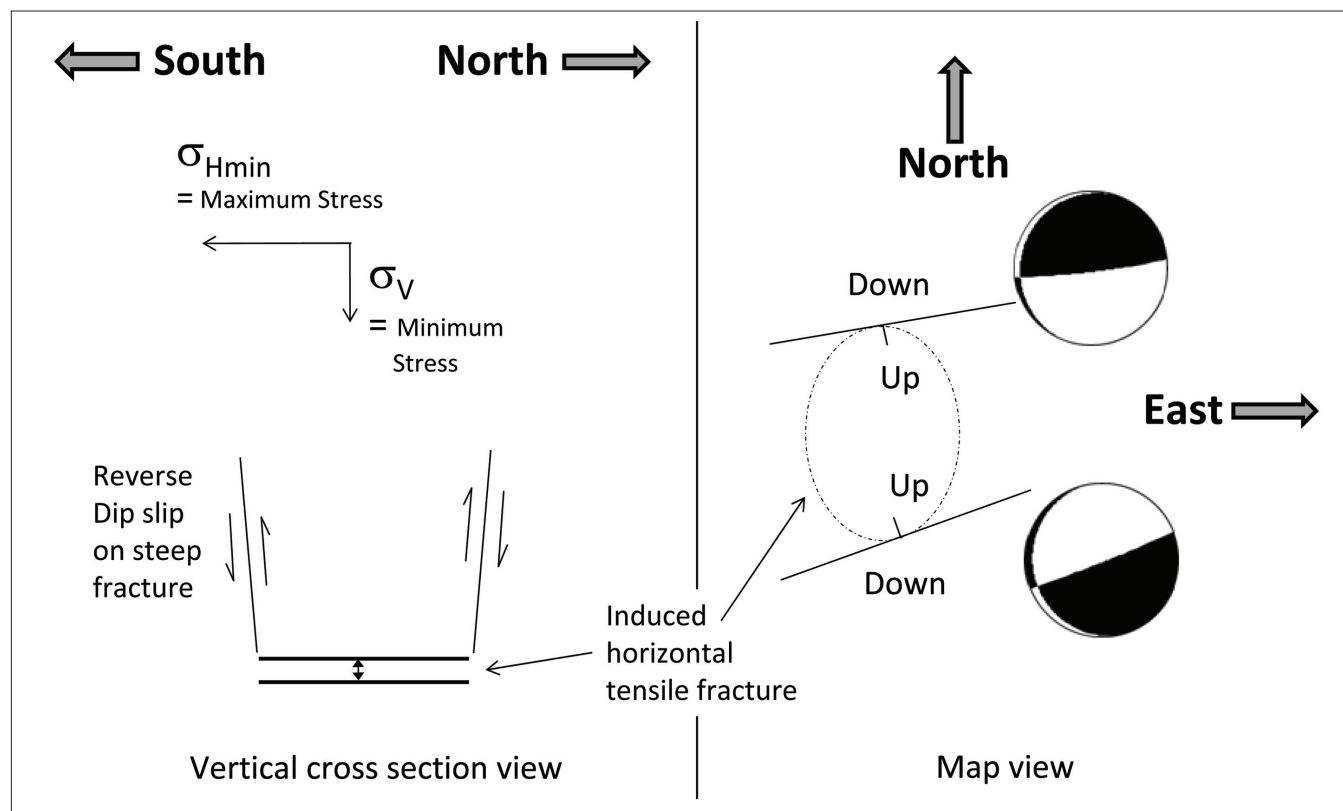


Figure 4. Schematic drawing of failure mechanisms related to horizontal fracturing during hydraulic stimulating. Minimum stress is vertical, as indicated by the unequivocal reverse faulting mechanisms, DSNU and DSND. Tensile fractures may take advantage of pre-existing horizontal fabric in the rock, and their seismic response is likely too small to be detected in this study. The source mechanisms come from the associated steeply dipping shear fracturing.

ponent particle velocity. The moveout sections were adjusted by traveltimes computed in an isotropic 1D layered model for the optimal location at a depth of approximately 6000 ft. The upper plot of Figure 2 shows the flattened arrival at approximately 0.35 s, corresponding to the direct arrival impulsive P-waves. Careful inspection of the first arrivals reveals consistent changes in the polarity of the first arrivals in the second event (lower plot) of Figure 2. The first event (the upper plot of Figure 2) does not show polarity changes. By picking the amplitudes and polarities of the first arrivals, maps were generated that show the relative amplitudes and polarity of the P-wave signal for four representative events (Figure 3). Green symbols on the maps represent upward first motion; red symbols represent downward first motion, and the relative amplitudes of the direct P-waves are represented by the circle size. Receivers without a reliable P-wave pick are not shown in these plots. Note that both size and polarity of the direct arrivals are smoothly varying with distance, indicating both consistency of the picks as well as good consistent coupling of the geophones.

The mechanism in the top left plot in Figure 3 represents dip slip along a vertical fault plane striking 70° NE, with the northern half moving up (dip slip north up or DSNU). The bottom left plot represents dip slip along a vertical fault plane striking 80° NE with the northern half moving down (dip slip north down or DSND). Both plots on the right of Figure 3 represent the same mechanism in two different locations

beneath the array — a reverse faulting with slip along 45° and 50° dipping faults plane striking 70° NE (reverse slip north-east or RSNE 1 and 2).

The absolute size of the maximum P-wave amplitude of event RSNE 1 shown in Figures 2 and 3 is approximately 600 nm/s of particle velocity peaking around 40 Hz. Also shown in Figure 3 is the location of the inverted source mechanism at its epicentral map location, represented by a “beach-ball” (graphical representation of the P-wave radiation pattern of the event in a lower hemisphere stereographic projection) plot. The source mechanism inversion of these events used all picked arrivals of P-waves fitted with modeled amplitudes in a homogeneous isotropic model with a free surface boundary condition. The four source mechanisms shown in Figure 3 represent pure shear components of the general source mechanisms, that is, the double-couple component of the inverted full moment tensor. For each event of Figure 3 the pure shear components of the general mechanisms account for more than 90% of the released moment. To verify this observation, we have also inverted the same data sets, restricting the source mechanism to pure shear faulting with an arbitrary orientation, and compared the least-squares misfit between observed data and predicted synthetic amplitudes as summarized in Tables 1 and 2. Note that the L2 misfit reduction is 65%, 71%, 76%, and 49%. This implies that the synthetic data can explain most of the observed data (except for the RSNE 2 event) and the homogeneous isotropic model sufficiently

Source mechanism	DC %	CLVD %	VOL %	Magnitude full MT	Magnitude shear	L2 full MT	L2 shear %
DSNU	94	6	-1	0.4	0.4	34.5	34.6
DSND	90	-6	-4	0.6	0.6	28.5	28.8
RSNE 1	43	43	-13	0.7	0.6	23.0	24.0
RSNE 2	92	-1	-8	0.6	0.5	50.9	51.0

Table 1. Summary of the source mechanism inversions of the three representative events shown in Figure 3. DC, CLVD and VOL represent percentages of the total moment of general source mechanisms (full-moment tensor): double-couple, compensated linear vector dipole, and volumetric, respectively. Magnitudes are computed as moment magnitudes from the moment tensor inversion. The columns “L2 full MT” and “L2 shear” are the values of least-squares misfit between the data and synthetics (normalized to data only) for full source mechanisms and shear-only mechanisms, respectively.

Source mechanism	Dips full MT	Strikes full MT	Rakes full MT	Dips shear	Strikes shear	Rakes shear
DSNU	88 10	67 168	-80 -169	88 10	65 165	-80 -170
DSND	86 7	83 205	96 33	88 5	85 195	95 20
RSNE 1	41 50	59 249	83 96	41 50	50 245	78 100
RSNE 2	44 47	89 254	101 80	45 47	95 254	105 75

Table 2. Summary of the shear planes and rake orientations of four representative events shown in Figure 3. “Full MT” indicates solution found using full moment tensor inversion. “Shear” indicates shear-only inversion solution inverted from the same data set. Dip is defined as an angle between horizontal plane and shear plane. Strike is given as the clockwise angle from north. Rake is the direction of slip on the failure plane, defined as the angle from horizontal (strike) in the plane (see Aki and Richards for more detailed description). Two rows of each mechanism represent two fault planes that equally explain the observed data. Note the remarkable stability of the inverted dips and strikes.

explains both polarization as well as amplitude distribution of the data. While a 1D or more complex velocity model may improve the fit to the data, given the maximum signal-to-noise ratio (10), we do not see a need to fit data better for source mechanism inversion. Note that each source mechanism inversion has a nonunique solution that results in two possible planes for the pure shear mechanism since slip motion along the two possible planes explains the observed data equally well. Surface monitoring (i.e., a large number of the receivers in multiple offsets and azimuths) allowed us to study in detail the shear and nonshear ratio in the source mechanisms. Table 1 shows that both DSNU and DSND are very well explained by pure shear mechanism. Shear-only inversion provides nearly the same fit to the observed data. Full-moment tensor (MT) mechanism inversion always fits observed data better as it has an additional two degrees of freedom to fit the observed data. The small difference between the misfit of the pure shear and the general mechanism shows that the pure shear mechanisms satisfactorily explain the observed data and nonshear components most likely result from inaccurate modeling and noise. The ability to test the shear-only component is important in the case of the reverse mechanism because of its large nonshear component (43% volumetric component) but the simpler shear mechanism also explains the data equally well for this event. In other surveys, nonshear mechanisms were found to provide a significantly better fit to the observed data.

Table 2 summarizes the orientation of the shear planes and rakes of the inverted mechanisms. Note that both full MT and

shear-only inversion provide remarkably stable dips (less than 2° difference for all inverted mechanisms), strikes, and rakes (less than 10° difference for the steeply dipping planes). If we assume that the DSNU and DSND occur on nearly vertical but not exactly vertical planes, then the DSNU mechanism is interpreted to be normal while the DSNE mechanism is reverse. Both failure mechanisms should not exist within the same stress field. However, dips of both DSNU and DSND mechanism are nearly vertical so that within the inversion uncertainty (which also includes location estimation) they could be interpreted to be vertical, or dipping a few degrees in the opposite direction. Deviations of the rakes from 90° (which represents pure dip slip) would indicate a significant nonvertical orientation of the one of the principle stresses. All source mechanisms correspond to one of the principal stresses being close to vertical (Table 2). If DSND and DSNU are not vertical and have opposing dip directions, they could represent conjugate fracturing of opposite motion on the fault planes. Rutledge et al. (2004) explained this type of relationship in their Cotton Valley data set, as the result of left and right-lateral strike-slip motion along fractures associated with the hydraulically opened tensile fractures that have failure planes closely aligned with, but not parallel to, the fracture trend.

We believe a variation of the model of Rutledge et al. can be applied to explain the seemingly contradictory DSNU and DSND source mechanisms in this data set. Our model also involves reactivation of existing natural fractures. The best candidate for the activated natural (pre-existing) fault plane is

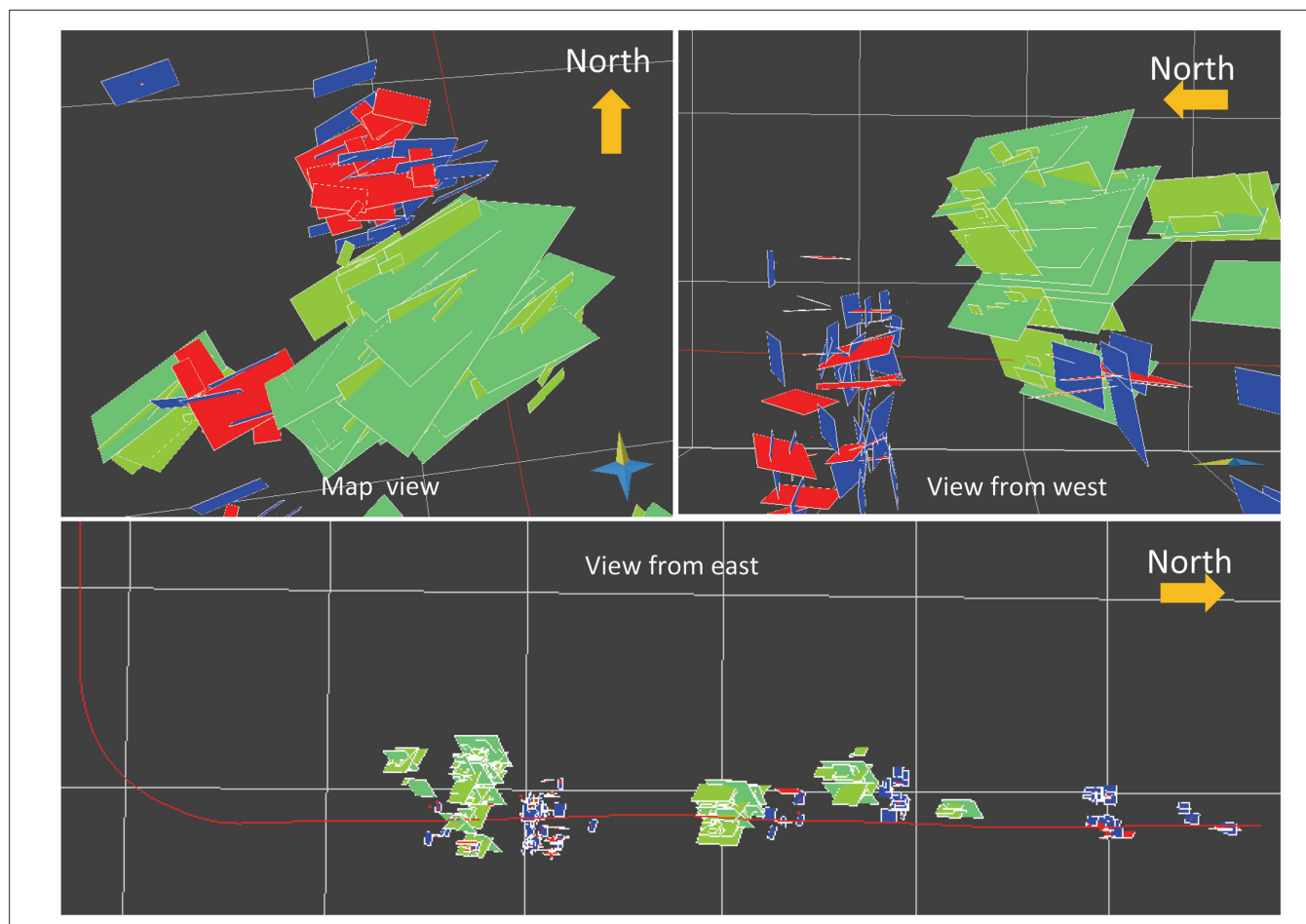


Figure 5. Discrete fracture network generated from microseismic event locations and inverted source mechanisms. (top left) Map view; green- and turquoise-colored fractures on the reverse failure mechanism planes. (right top) Vertical view looking from the west, displaying fracture planes representing the horizontal fractures (red) and associated dip-slip fracture planes (blue). (bottom) Fractures from all frac stages are displayed along the wellbore; view is from the east.

the reverse faulting source mechanisms (RSNE 1 and 2). All of these mechanisms are distinctly reverse dip-slip on moderately dipping planes (plots in the right column of Figure 3). Because normal dip slip and reverse faulting cannot occur in the same stress field, we assume that the unequivocal reverse failure mechanisms indicate the tectonic stress: vertical stress is the minimum stress. This constrains the mechanisms on the steeply dipping planes to be reverse displacement as well, thereby allowing us to interpret beyond the uncertainty in the source mechanism solution. We interpret the steeply dipping failure planes to be caused by slip associated with tensile opening of fractures parallel to bedding. This orientation of fracturing may also take advantage of pre-existing planes of weakness in the rock, as oil and gas shales often have a very strong horizontal fabric that can be enhanced by the formation of hydrocarbons (Lash and Engelder, 2005). The upward displacement of bedding layers results in the formation of a mini-pop-up above the horizontal fracture (Figure 4, left diagram), facilitated by existing natural fractures that are essentially perpendicular to bedding. The magnitude of the seismic response of tensile failure is believed to be too small to be detected in this study, but the source mechanism comes from the associated shear fracturing.

Discrete fracture modeling and source mechanisms

Source mechanism characterization in this case study allowed us to determine the stress state of the reservoir. In particular, the determination was made in the absence of borehole stress measurements in a tectonically active region with a wide variability of stress orientations. The local in-situ stress is important for understanding the hydraulic fracture behavior and evaluating its extent. An unexpected result was the possibility of horizontal tensile fracturing, which is contrary to the assumption of a vertical maximum stress that is reasonable for many sedimentary basins. This study represents a case where very different failure mechanisms occurred in the same fracture treatment. By integrating geological knowledge with the geometric requirements of the failure mechanisms, we were able to reduce the uncertainty related to the source mechanism inversions and determine the most likely orientation and failure modes of fractures in the reservoir.

In addition to the conceptual validation that is possible by visualizing a three-dimensional discrete fracture network (DFN) represented by the microseismicity, modeling the flow behavior of the stimulated reservoir can be facilitated with such models. Properties such as fracture permeability, fracture

porosity, and fracture connectivity can be calculated from the DFN and used to populate reservoir simulation grids. Figure 5 shows a fracture network constrained by the event locations and mechanisms previously discussed. The fracture size is poorly constrained by wellbore and reflection seismic data attributes, but by using the seismic moment of the events, a reasonable estimate of fracture size per event can be made (through source radii). The largest fractures in Figure 5 have dimensions consistent with a magnitude 0.7 event based on observations of small induced reservoir earthquakes, such as those analyzed by Tomic et al. (2009). For a given magnitude, the surface area and slip distance are inversely related, but they can both be further constrained by using measured rock rigidity values. The DFN model is based on possible fracture sizes, rather than subjective guesses based only on something that looks reasonable to a geoscientist.

Through this analysis, we used the mechanism to interpret differences between microseismic events induced on pre-existing natural faults (RSNE mechanisms) and natural fractures (DSNU and DSND mechanisms). This identification allows us to differentiate between various trends observed in microseismic locations which would be otherwise considered just a “cloud of dots in a box.” The source mechanism distinctions are critical for building DFN models that represent the stimulated fractures in the reservoir, and provide very specific constraints on fracture size and orientation in the DFN. The stability of the inverted dips and strikes provide more reliable estimates of the fracture orientation than location estimates only. In fact, the stability of the inverted dips compensates

for the lower resolution of the vertical position of the located events as illustrated by Eisner et al. (2009). Furthermore, the activation of the natural faults explains the trend of the shallower events and upward growth of the microseismicity. **TLE**

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Corresponding author: leisner@microseismic.com