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Surface Microseismic Mapping Reveals Details of the Marcellus Shale

B.J. Hulsey, Brian Cornette, MicroSeismic Inc., David Pratt, Rex Energy Corporation

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Abstract

The mapping of microseismic events induced by hydraulic fracturing plays an important role in well completion and design. This is especially true in a newly developing area of gas producing shales. In this case study, we will show how the microseismic monitoring of a hydraulic fracture treatment in the Marcellus Shale identified a pre-existing natural fault which intersected the wellbore. The data from nearby wells indicated several possibilities of structural evolution affecting the producing formation. These range from regional reverse or strike-slip faulting to small displacement local reverse faulting.

The hydraulic fracture stimulation was monitored using a 10 line, radial surface array composed of 1000 vertical component geophone stations. The treatment consisted of seven perforated stages stimulated with slickwater and proppant.

Microseismic activity mapped during the early stages of the treatment is consistent with the regional stress direction and indicates that stages 1-4 activated natural fractures oriented along the maximum horizontal stress direction. During stages 5 and 6, the hydraulic fracture encountered a pre-existing natural fault. A source mechanism was determined for events occurring along the fault, identifying oblique failure with strike-slip and reverse faulting along the steeply dipping fault with SSE strike. This indicates that the regional strike-slip fault, with a strike similar to the break we observed at other offset wells, is most likely responsible for the geological evolution of this formation.

Introduction

Hydraulic fracture monitoring is an effective tool that has grown in popularity for developing new plays in the United States. By using microseismic source locations and mechanisms in conjunction with other geological and geophysical knowledge of an area, engineering and completion methods can be quickly corrected and enhanced. Induced fracture height, length, and placement influence the location, orientation and spacing of subsequent wells. Microseismic monitoring allows for identification and characterization of unknown faults which intersect the wellbore and may significantly affect reservoir production and stimulation. Formations with limited exploration data, such as the Marcellus shale, are ideal candidates for microseismic monitoring.

In this case study, surface microseismic mapping identifies an intersected natural fault and is used together with local geology to fill the gap between seismic and stress data and to optimize the fracture treatment.

Treatment and Acquisition

The monitored treatment well is located in the Pittsburgh Low Plateau section of the Appalachian basin in southwestern Pennsylvania. The 2500 ft lateral section sits along the top of the Marcellus Shale formation at a depth of 8100 feet. The lateral portion of the well was oriented at approximately 340^{o} (20^{o} east of North). The hydraulic fracture treatment consisted of seven perforated stages stimulated with slickwater and proppant. The stimulation was monitored using a 10 line, radial surface array composed of approximately 1000 vertical component geophone stations. Line one of the array had the furthest offset from the well head at 11370 feet or 2.15 miles.

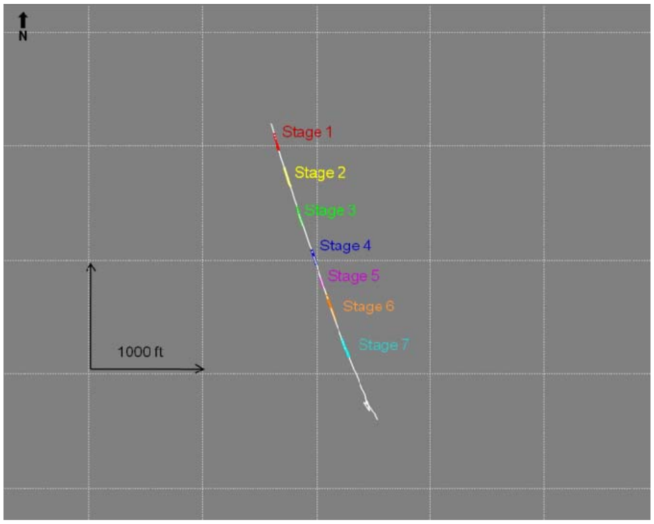

Figure 1. Map view of well showing location of treatment zones along the lateral.

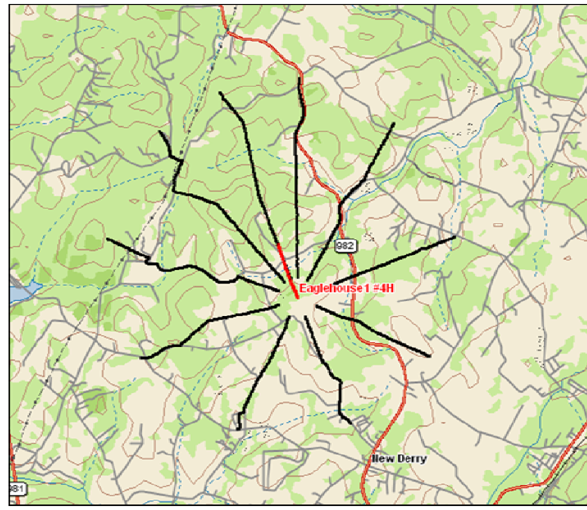

Figure 2. Surface array location shown in black with subsurface location of the well indicated by the red line. Arms 1 and 10 of the array are labeled.

Regional Geological Context

The Marcellus formation is a Mid-Devonian gas shale within the Appalachian basin, covering over 30 million acres in Pennsylvania, West Virginia, New York, and Ohio. The Marcellus formation is divided into the Oatka Creek Shale and the Union Spring Shale, and within the Shale are two small ribs of the Stafford and the Purcell/Cherry Valley Limestone. The Marcellus is the lower most member of the Hamilton Group and lies conformably below the Mahantango/Skaneateles Formation. Below the Marcellus conformably lies the Onesquethaw Group which varies laterally between 3 seperate facies, the Onondaga Limestone, the Huntersville Chert, and the Needmore Shale (Wrightstone, 2009). Subsidence of the Appalachian basin was formed in response to the tectonic loading of the Acadian Orogeny to the southeast. Sediments forming the Marcellus Shale were deposited in a shallow inland sea, and form the basal part of a thick sedimentary sequence of Devonian age. The entire sequence produced a wedged shaped deposit that thickens to the east where weight of the ancient river delta sediments caused subsidence of the basin floor. Thickness in the Marcellus Shale ranges from 250+ feet in NE Pennsylvania until it gradually pinches out at the western end of the formation in Ohio. Recorded drilling depths to the base of the Marcellus (closer to the structural front) have been greater than 8000 feet (Wrightstone, 2009). Based on thickness, depth, and thermal maturity, the southeastern portion of the basin holds the most attractive prospects; however, the structural complexity of a heavily faulted and folded region poses additional risks. In areas of the basin most remote from the structural front the Marcellus shale is thinner and shows less thermal maturity; wells such as this one located closer to the structural are thicker and more mature, but they offer reduced risk from structural complexities.

Local Geology

The data from nearby wells indicated several possibilities of structural evolution affecting the producing formation. These range from regional reverse or strike-slip faulting to small displacement local reverse faulting. A structure map and cross section of the area around the Eaglehouse 4 well is shown in Figures 3 and 4. The structure map is contoured on the top of the Onondaga (the base of the Marcellus). It shows a rollover in the area of the Eaglehouse and Panizzi horizontal wells. The steep north dip at the northern edge of the map is a rollover dip into a large reverse/thrust fault with displacementup to the northwest. The cross section goes through 3 vertical wells that Rex Energy previously drilled in the area. The middle well, the Zajdel 2, has a repeat section of 28 feet of the upper part of the lower Marcellus. As the repeat section was not visible in either of the offset wells, we have proposed four possible scenarios for the nature of the reverse faulting, which are illustrated in Figure 5. The four possible scenarios are

1. An east-dipping reverse fault at an angle high enough that it was not intersected by the Ankney well;
2. A west-dipping reverse fault at an angle high enough that it was not intersected by the Zajdel 3 well bore;
3. An obliquely striking fault with a strike similar to the microseismic event trend seen in the Eaglehouse 4 microseismic mapping resultsand thus not visible in either of the offset wells;
4. A small, localized thrust fault that soles out below the Marcellus shale.

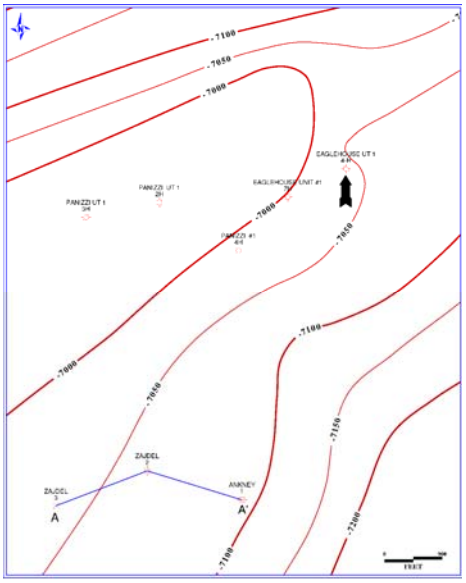

Figure 3. Structure contours on base Marcellus, black arrow shows location of the Eaglehouse 4 well. Contour interval is 50 ft. The location the well cross section in Figure 4 is indicated at the southern part ot the map.

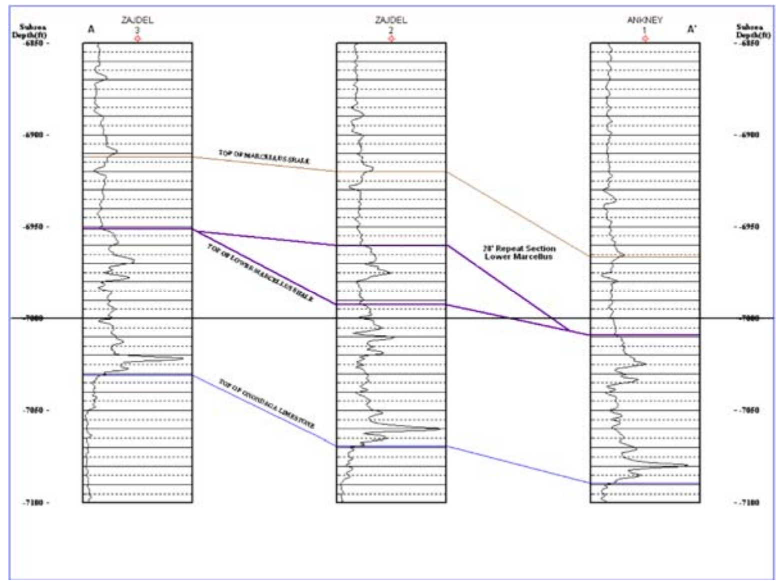

Figure 4. East-West cross section of Zajdel 3, Zajdel 2 and Ankney 1 wells, indicated at southern part of figure 3 map showing repeated section of the lower Marcellus in the center well. Purple horizon is top of the lower Marcellus, blue is top Onondaga.

The structural contours of the base Marcellus in Figure 3 suggest a fault with strike approximately north-south. The general trend of the Appalachian fold and thrust belt in this area is about 20 degrees from north, so a NNE striking subsurface thrust fault is also consistent with the structural trends visible in the surface geology (Figure 6). During drilling of the Eaglehouse 4 well, the LWD geosterring gamma ray log indicated intersection of the well bore with a fault. Approximately 20 feet of reverse throw was interpreted from this log, identifying a fault with similar displacement to the fault intersected by the Zajdel 2 well to the south. Microseismic mapping served to define the strike of this fault, as a very strong trend of microseismicity with a N-NW azimuth formed during the treatment (Figures 7 and 8).

Of the four possible faulting configurations, we interpret the last two to be most probable, as the first two scenarios imply vertical tectonics – a pure dip-slip displacement on a steep fault that is not consistent with the structural character of the Appalachian fold and thrust belt. Scenario 3 remains a viable possibility because the vertical component of slip for oblique displacement along a strike slip fault could account for the reverse slip on a steep fault. The vast majority of faulting above Silurian salt in the Appalachian plateau is reverse or thrust faulting, so scenario 4 is fully consistent with the structural character in the region, although the orientation of the microseismicity trend is oblique from the general trend of the fold and thrust belt front. Scenario 4 also explains the repeat section observed in the middle well but not in the wells to the east and west if the scenario 4 fault is interpreted to be a thrust that goes into a decollement beneath the lower Marcellus, possibly the Needmore Shale.

Microseismic Mapping

The Marcellus Shale establishes three main joint sets: J1 (~ENE-SWS, pre- or early Alleghanian), J2 (~NW-SE, early to late Alleghanian and is typically oriented normal to J1), and J3 (~ENE-SWS, neotectonic) (Engelder, 2004). The J1 and J3 joint occur in an orientation that is generally parallel the current maximum horizontal stress direction (Heidbach et al, 2009, Engelder et al, 2009). One of the biggest challenges in describing the tectonics in the Marcellus is distinguishing between the joints in J1 set from the J3 set. J1 is interpreted to have deformed pre-Alleghenian folding but survived any tectonic deformation in many black shales throughout the Appalachian basin, including the Marcellus (Engelder et al., 2009). Joint spacing in the Marcellus is approximately one meter, making the gas in the shale economically recoverable. Generally, when found together in the shale, J1 is more closely spaced than J2 suggesting that fracture density will be higher in the J1/J3 orientation. Some of the most successful wells in the Marcellus Shale have been horizontally drilled at NNW-SSE normal to current S_{Hmax} (J1/J3) and parallel to J2. The distribution of joint orientationsfrom SW to NE parts of the Appalachian Basin, see a slight clockwise rotation due to the NE directed bend of theAppalachian structural front. Overall microseismic activity observed during the treatment is consistent with the regional stresses recorded in the area.

The northwest strike and steep dip of the fault suggests that the stimulation treatment reactivated a fault or large fracture feature that is in the J2 joint set orientation. Figure 6 shows the surface array location plotted on a digital elevation model.

The structural trend of the fold and thrust belt is clearly visible. Orientations of maximum horizontal stress reported in the World Stress Map within a 150 mile radius show the dominant direction in the area to be approximately 70^o azimuth. Figure 7 shows two trends of microseismicity generated by the treatment. One trend has an azimuth close to the maximum horizontal stress direction which we interpret to occur along J1/J3 joints. WE interepret the second very strongly developed trend to be controlled by the orientation of the fault identified in the LWD log acquired while the well was drilled. The strike of this trend is approximately 325^o which is roughly parallel to J2.

Figure 7 shows all the microseismic events located during this treatment, colored by treatment stage. Microseismicity along NNW trend of the reactivated fault occurred during 4 of the the treatment stages. The locations of microseismic events induced during stage 5 only are shown in Figures 8 and 9. The depth view shows that the vertical extent of the microseismicity goes well into the Onondaga Formation, which is consistent with both fault scenario 3 and fault scenario 4 (Figure 5).

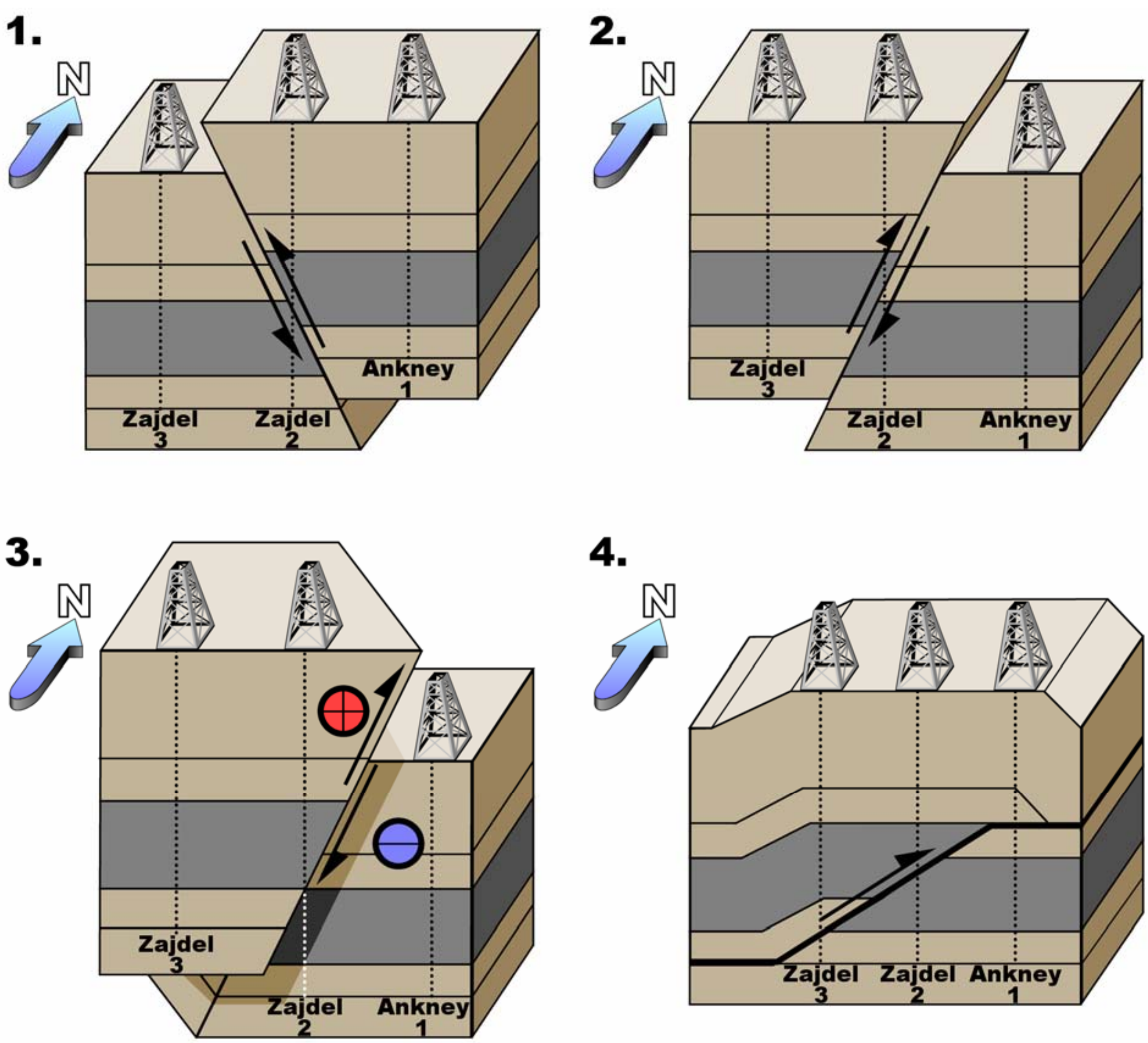

Figure 5. Four possible faulting scenarios that could explain the repeated section of the lower Marcellus in the Zajdel 2 well that is not present in either the Zajdel 3 or the Ankney 1 wells. Scenarios 1 and 2 are reverse faults that dip steeply enough that they are not encountered in the two wells flanking the Zajdel 2 well. Scenario 3 is a steeply dipping oblique strike slip fault. Scenario 4 is shows a thrust fault that soles in a detatchment horizon below the repeated section.

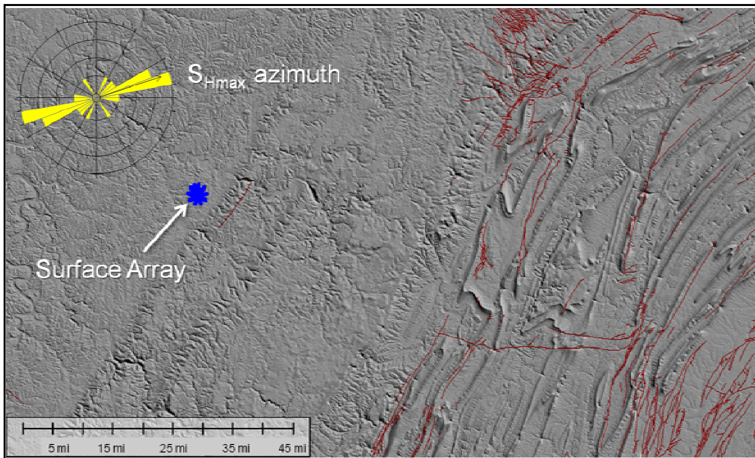

Figure 6. Surface array location plotted on digital elevation model. Surface faults are shown in brown. The azimuth of maximum horizontal stresses within a 150 mile radius of the well are shown by the rose diagram.

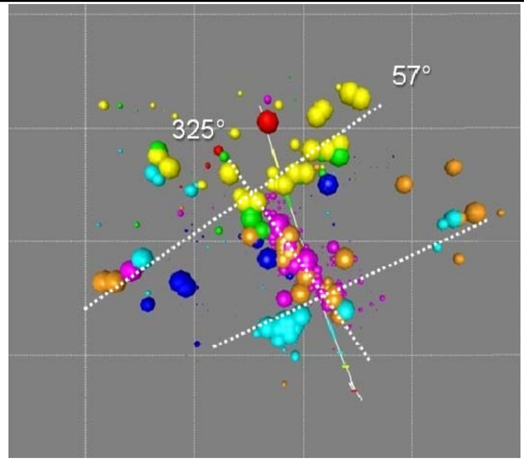

Figure 7. Microseismic monitoring result showing all stages. Events are colored by individual stage. The 325o trend includes events from at least 4 of the 7 total stages.

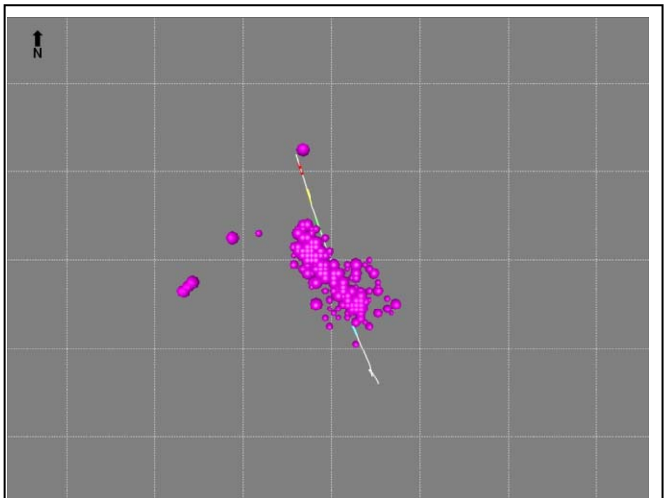

Figure 8. Map view of stage 5 microseismic activity, showing strong NNW trend of events formed in a direction close to the deviation direction of the lateral portion of the wellbore.

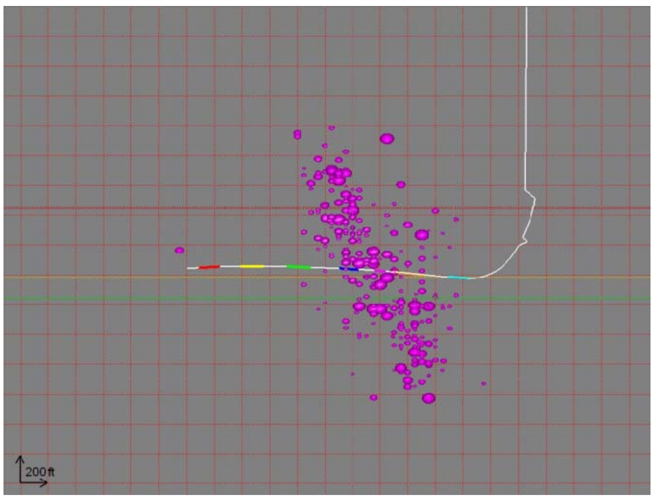

Figure 9. Depth view of stage 5 microseismic activity. The vertical extent of activity below the wellbore extends into the Onondaga Formation (green horizon).

The magnitude and number of events for stages 5 and 6 were higher than those of stages 1-4 and 7. This is a commonly observed phenomenon in microseismic monitoring when large scale pre-existing features are encountered.

Time series plots (Figures 10 and 11) are used to correlate pumping data with the occurrence, distribution and size of mapped events. A “well behaved” fracture will exhibit a steady rate of lateral growth from the wellbore fitting a constant slope in time. In this case, the dense burst of events within a short period of time illustrates that a fault was reactivated during the treatment schedule. The instantaneous onset of events both 800 feet above and 800 feet below the wellbore is highly unlikely conduct of a fracture being created by the treatment alone.

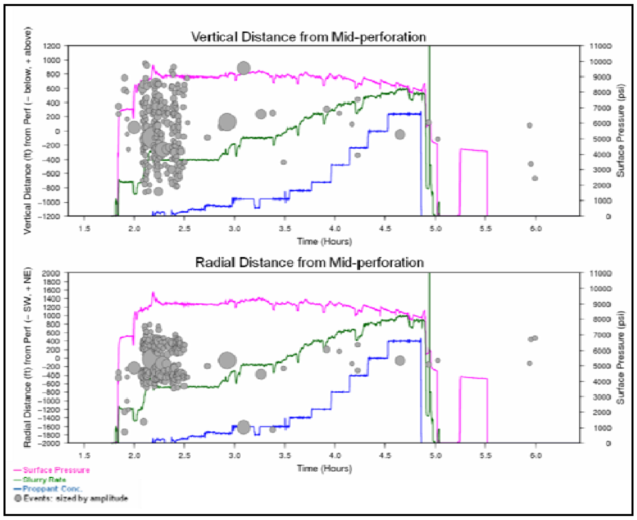

Figure 10. Stage 5 event occurrence with respect to treatment data. Top plot shows vertical growth with time. Bottom plot shows lateral growth with time.

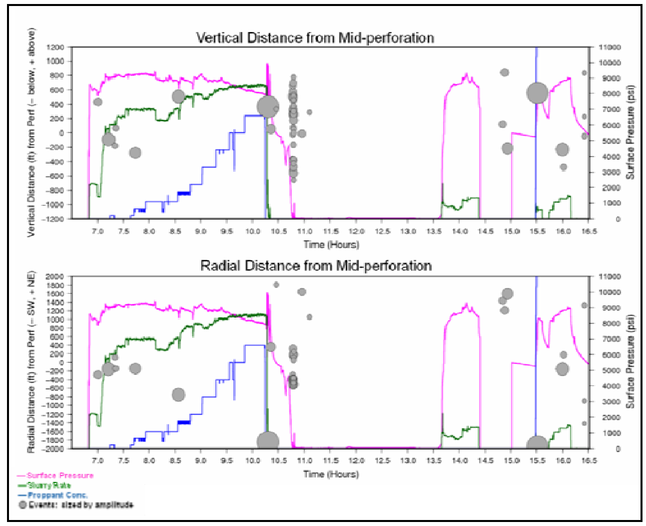

Figure 11. Stage 6 event occurrence with respect to treatment data. Top plot shows vertical growth with time. Bottom plot shows lateral growth with time.

Event Source Mechanisms

The comprehensive arial coverage of the surface array allows for broad sampling of the radiation pattern for each event. This pattern includes the sense of motion (polarity) and strength of signal (amplitude). Therefore the compressional wave data can be used to determine the focal source mechanisms of the induced microseismic events (Williams-Stroud et al., 2010). The source mechanism solution shown in Figure 12 is derived from an event during stage 5 which occurred 20 minutes into the stage. As the source mechanism solution is non-unique, the source mechanism solutions shown indicate either left lateral strike-slip displacement on a failure plane with strike NE-SW or right lateral strike-slip displacement on a failure plane with strike NW-SE. If the maximum horizontal stresses in this area of approximately 70^{o} azimuth are assumed for this location, the most likely failure plane is the NE-SW strike with left-lateral strike slip.

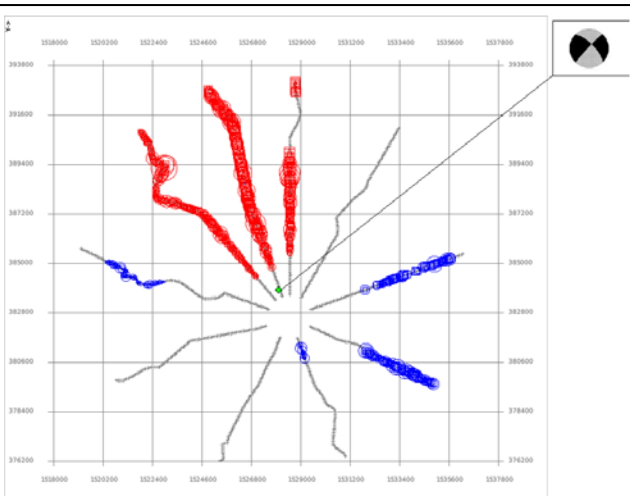

Figure 12. Radiation pattern and focal mechanism for stage 5 event 02:11:20

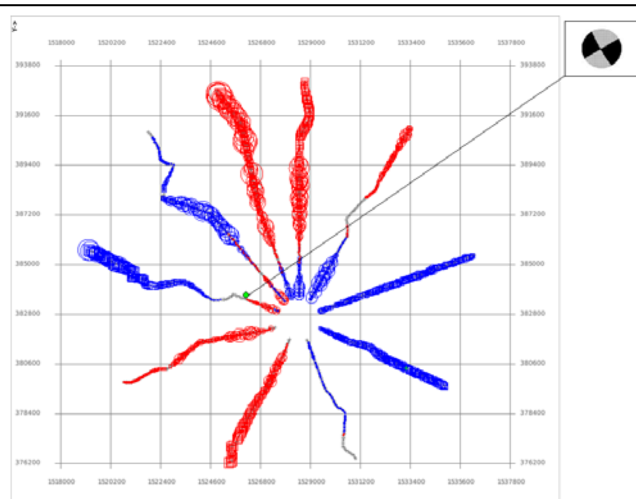

Figure 13. Radiation pattern and focal mechanism for stage 6 event 10:18:26

Although the concentration of microseismicity along the fault shows that the J2 orientation is stimulated by the treatment, the strongest source mechanisms are interpreted be associated with microseismicity on the J1/J3 joint orientation. Figure 14 shows the locations of the inverted source mechanisms, with the same mechanism in the fault zone as for an event that might be more obviously associated with J1/J3 reactivation. One possible explanation is that slip occurs along J1/J3 joints along the fault zone which formed parallel to J2 joints.

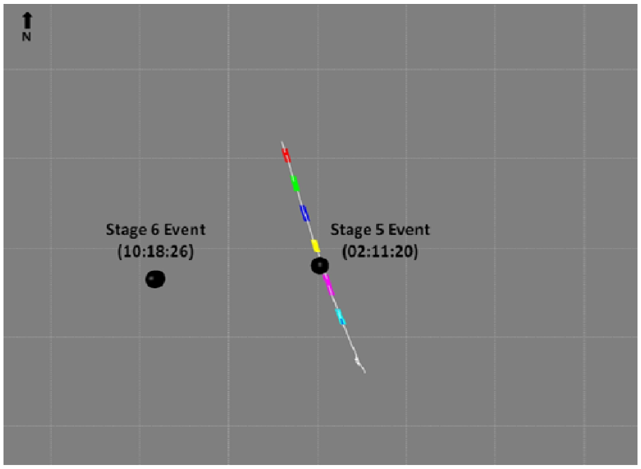

Figure 14. Event locations of sources identified in Figures 12 and 13.

Conclusions

The fault planes identified by the source mechanisms agree with the regional stress direction and indicate that stages 1-4 activated natural fractures oriented along or close to the maximum horizontal stress direction. During stages 5 and 6, the hydraulic fracture encountered a pre-existing natural fault. A similar source mechanism was determined for events occurring along the fault, identifying oblique failure with strike-slip and reverse faulting along the steeply dipping fault with SSE strike. This indicates that the regional strike-slip fault, with a strike similar to the break we observed at other offset wells, is most likely responsible for the geological evolution of this formation. The microseismic mapping allowed a confirmation of the subsurface structure and a refinement of the structural interpretation. These observations allow for a more comprehensive image of the producing Marcellus formation.

Acknowledgments

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