[PS]3-D Seismic Workflows Developed to Evaluate Out-of-Zone and Stealth Zone Microseismic Behaviors: Marcellus Shale, Central Appalachians, USA*

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Abstract

Out-of-zone and cross-stage microseismic activity along with stealth- or aseismic-zone phenomena are often observed during hydraulic fracture treatment. In this study, we examine interrelationships between 3-D seismic response and anomalous microseismic distribution observed during hydraulic fracture treatments from a cluster of Marcellus Shale wells. We preprocess seismic data for enhanced 3-D visualization and seismic discontinuity extraction in the vicinity of the treatment area using time-variant trace amplitude slicing and differential attenuation (t*attenuation) computations. Amplitude slicing uses absolute values of trace amplitude followed by bandpass filtering in a series of two to three steps to increase apparent frequency content. The output retains direct relationship to variations in signal phase and frequency content through time. The process improves visualization and interpretation of subtle amplitude and phase variations related to local structural and stratigraphic features. High frequency attenuation is commonly observed in wave propagation through fracture zones and faults. We use t*attenuation to identify areas of high frequency loss across windowed regions throughout the 3-D seismic volume. The 3-D attenuation volume is then used as an input to a seismic discontinuity detection process (in this case, Ant Tracking). Enhanced 3-D displays reveal stealth-zones in areas of more coherent signal in the overlying Hamilton to Sonyea section. Out-of-zone events are observed in the overlying Sonyea to sub-Elk strata and are among the earliest events to occur. Out-of zone events occur in areas disrupted by small faults/fracture zones and areas of interpreted local shale flowage. They are separated from contemporary microseismicity within the Marcellus by a thick stealth-zone. In a process similar to cross-stage fracturing, out-of-zone microseismic regions are repeatedly activated during hydraulic fracturing of nearby wells. Novel post-stack processing workflows developed in this study form the basis for 3-D seismic interpretation of out-of-zone and stealth-zone microseismic behavior. Out-of-zone events appear to occur in locally deformed strata while stealth-zones separating the reservoir and out-of zone events appear in less disrupted strata. The interrelationships are approximate and might be improved through use of a revised velocity function for microseismic event location.

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Out-of-zone and cross-stage microseismic activity along with stealth- or aseismic- zone phenomena are often observed during hydraulic fracture treatment. In this study we examine interrelationships between 3D seismic response and anomalous microseismic distribution observed during hydraulic fracture treatments from a cluster of Marcellus Shale wells. We pre-process seismic data for enhanced 3D visualization and seismic discontinuity extraction in the vicinity of the treatment area using time-variant trace amplitude slicing and differential attenuation (t*attenuation) computations. Amplitude slicing uses absolute values of trace amplitude followed by bandpass filtering in a series of two to three steps to increase apparent frequency content. The output retains direct relationship to variations in signal phase and frequency content through time. The process improves visualization and interpretation of subtle amplitude and phase variations related to local structural and stratigraphic features. High frequency attenuation is commonly observed in wave propagation through fracture zones and faults. We use t*attenuation to identify areas of high frequency loss across windowed regions throughout the 3D seismic volume. The 3D attenuation volume is then used as an input to a seismic discontinuity detection process (in this case, Ant Tracking).

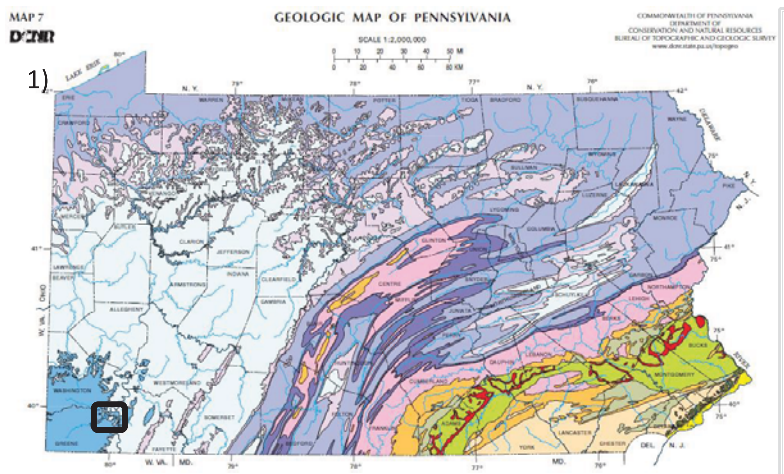
Enhanced 3D displays reveal stealth-zones in areas of more coherent signal in the overlying Hamilton to Sonyea section. Out-of-zone events are observed in the overlying Sonyea to sub-Elk strata and are among the earliest events to occur. Out-of zone events occur in areas disrupted by small faults/fracture zones and areas of interpreted local shale flowage. They are separated from contemporary microseismicity within the Marcellus by a thick stealth-zone. In a process similar to cross-stage fracturing, out-of-zone microseismic regions are repeatedly activated during hydraulic fracturing of nearby wells.

Novel post-stack processing workflows developed in this study form the basis for 3D seismic interpretation of out-of-zone and stealth-zone microseismic behavior. Out-of-zone events appear to occur in locally deformed strata while stealth-zones separating the reservoir and out-of zone events appear in less disrupted strata. The interrelationships are approximate and might be improved through use of a revised velocity function for microseismic event location.

Microseismic Distribution and Seismic Response

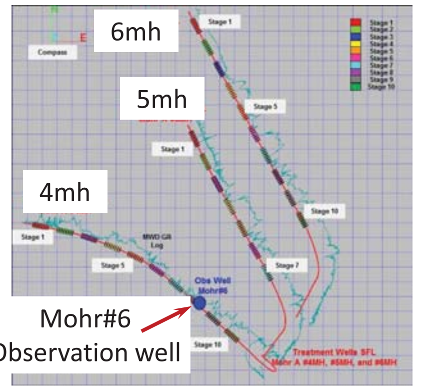
In this study we look at the distributions of microseismic events associated with hydraulic fracturing of Marcellus shale wells in Greene Co., southwestern PA (1-3). Microseismic events of particular interest in this study were produced in wells on the high side of a northwest dipping reverse fault that strikes about N27ºE (3 & 4). Out-of-zone events are shown on a regular amplitude display (5). Zones and events are also shown on a time-variant amplitude slice display (6). Seismic discontinuities intersecting the Onondaga Ls. surface (7) reveal extensive seismic scale disruption of the Onondaga and bounding intervals. Extracted discontinuities have dominant trends of ~N46ºE and N39ºW and are rotated about 20º relative to the major fault cutting through this area with strike of about N27ºE.

1)



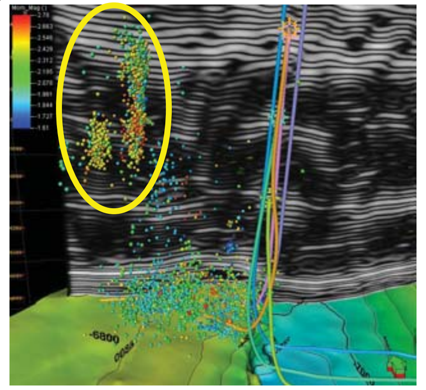
The study area is located in Greene County, southwestern PA (Taken from www.dcnr.state.pa.us)

2)



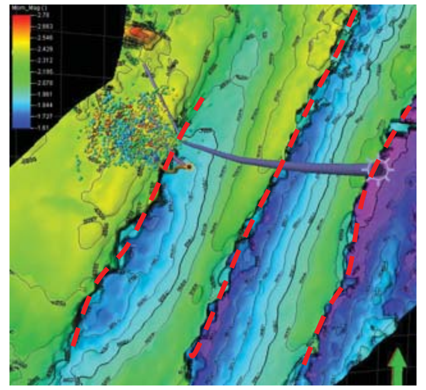
Locations of the treatment wells (4MH, 5MH and 6MH) and observation well (Mohr #6).

3)



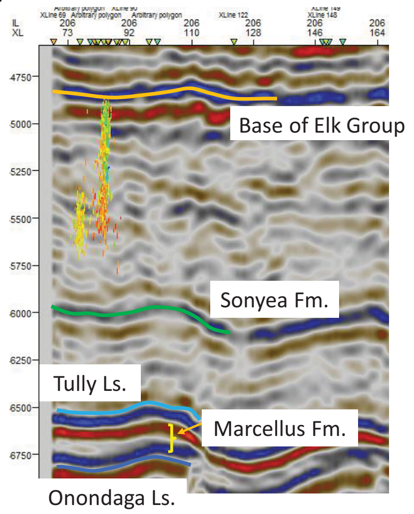
Out-of-zone microseismic events produced during the frac'ing of the 4MH, 5MH and 6MH wells occurred repeatedly in the same areas.

4)

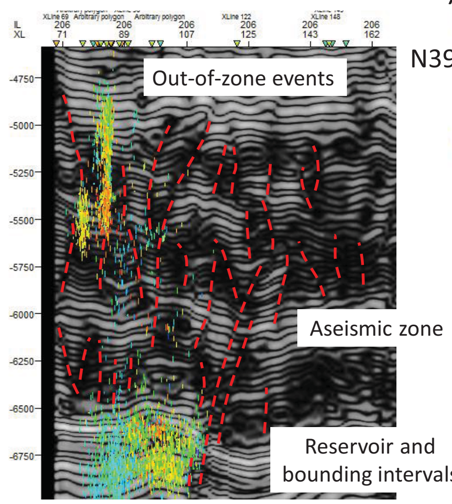


Structure on the top of the Onondaga Ls. Out-of-zone microseismic events occur in strata above and northwest of a culmination along a doubly plunging thrust fault. A series of thrust faults trend approximately ~N27E through the area (dashed red lines).

5)

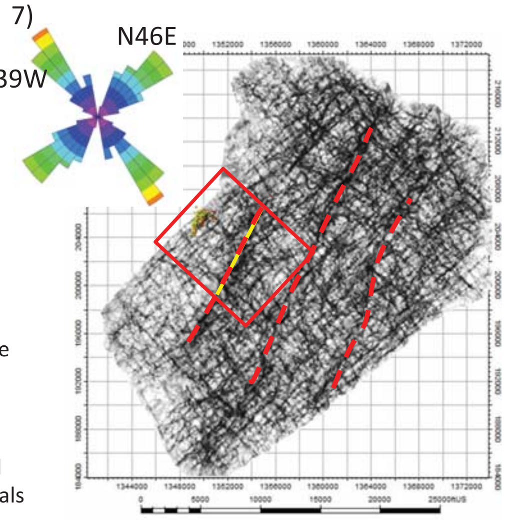


6)



5) Regular amplitude display showing stratigraphic interpretation and out-of zone events.
6) Time variant amplitude slice view with interpreted fault/fracture zones. Out-of-zone microseismic events and aseismic zones are labeled.

7)

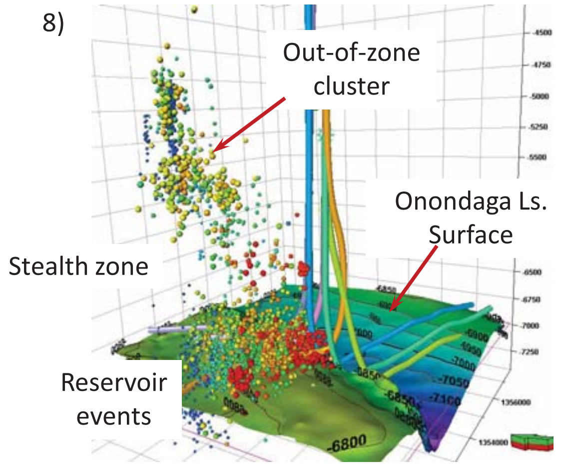


Discontinuities extracted from the t*attenuation volume. Orientations of discontinuities in the vicinity of the treatment wells are shown (upper left). Out-of-zone microseismic events are also shown along with thrust faults (red dashed lines).

Proximal Cross-well event comparisons

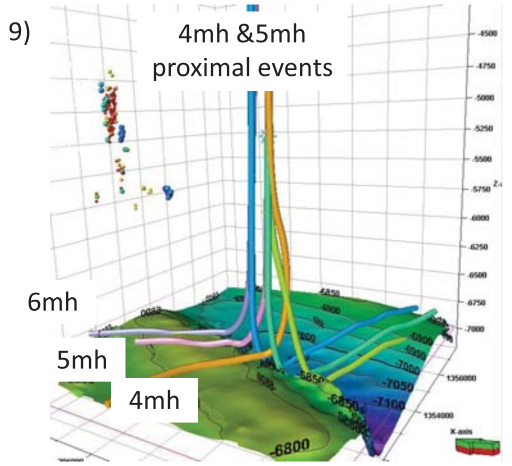
Cross-stage events are usually defined based on similarities of location and rupture mechanism (Eisner et al., 2006). This study does not include an analysis of waveforms and the judgment of events as cross-stage (or cross-well in this case) refers to proximal or contiguous events generated by separate fracture stimulations. Proximal or contiguous events were identified within regions of specified maximum separations. For initial testing, events produced by different frac stages with separations of less than 75ft, 50ft and 25ft were extracted. Events produced by the 4mh and 5mh hydraulic fracture treatments (8) although concentrated in reservoir intervals, is accompanied by a shallower out-of-zone cluster of events separated from the reservoir by a relatively quiet aseismic zone (8 & 9) referred to as a stealth zone (Pedersen and Eaton, 2013). Identification of proximal events was focused in the shallow, out-of-zone, region. Out-of-zone events produced during hydraulic fracturing of the 4mh and 5mh wells located within 50 ft of each other (9) are concentrated in the core of the cluster. Proximal events produced during hydraulic fracturing of the 4mh and 6mh wells with small separation (≤25 ft) are also distributed vertically along the axis of the cluster. Out of zone seismicity produced during the single-stage fracture treatment located at the toe of the 6mh well (10 & 11) defines the region of repeated rupture during subsequent treatment stages along wells 4 and 5mh. The events in this cluster are located at distances from about 1km to 1.5 km from the treatment location at the toe of the 6mh well.

8)



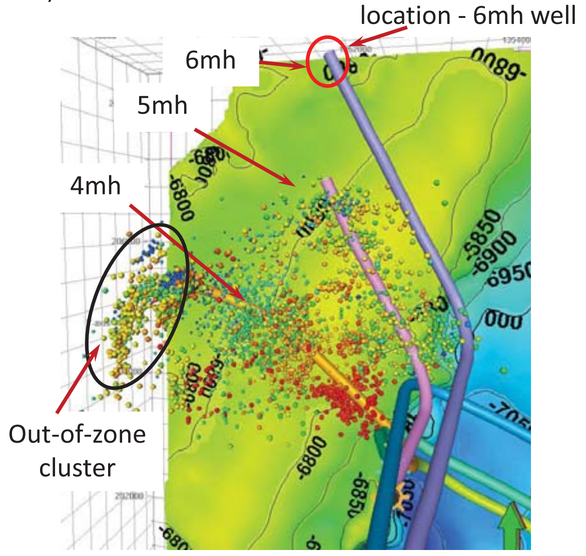
Microseismic events produced during frac'ing of the 4mh and 5mh wells.

9)



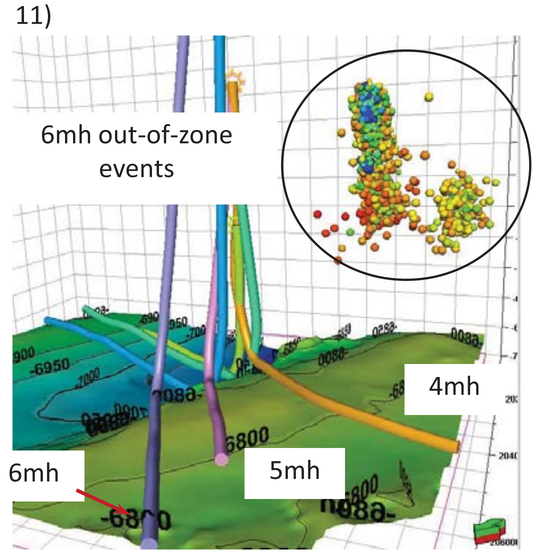
Out-of-zone cluster of 4mh-5mh proximal events with separations ≤50ft.

10)



The collection of events, both in- and out-of-zone, produced during treatment of wells 4-6.

11)



Events produced during hydraulic treatment of a single stage located at the toe of the 6mh well.

Energy release

Out-of-zone microseismic activity occurred in the second stage of a zipper frac sequence, which alternated stages between wells (4, 5 and 6mh). The first stage was conducted in the 4mh well and did not produce significant out-of-zone rupture. The second stage of the zipper frac was conducted in the 6mh well. Microseismicity produced during this stage appeared to be entirely out-of-zone at distances of 3,000ft to 5,000 ft (~1 to 1.5km) from the end of the 6mh lateral. Total energy expended in the 6mh out-of-zone region was estimated to be 22,818 joules using the approach of Kanamori and Anderson (1975) (see also Eaton and Boroumand, 2013). The total energy released by events in the 4mh frac (all 10 stages) was 66,447.8 joules, with 10,108.2 joules (15%) produced by out-of-zone events. Energy released in the 5mh frac (all stages) was 28,626.8 joules with 3,574 joules (~13%) produced in the out-of-zone region. Out-of-zone energy release produced in the single 6mh frac was about 1.67 times the total out-of-zone energy released from all 17 treatment stages in the 4mh and 5mh laterals. There were 565 proximal events in the 6mh stage 1 completion that were located within 75 feet of 240 events produced by all stages of the 4mh lateral. The 6mh proximal events released about 14,500 joules of energy. Energy released by the 4mh proximal events approached 6,000 Joules. Proximal events produced by these two initial treatments released 56% (20,435 joules) of the total energy (36,500 joules) released in the out-of-zone region. The area was repeatedly ruptured over a 4.6 day period of time with the majority of events less than 75 feet from sites of earlier rupture.

Conclusions

Analysis of microseismic events in out-of-zone clusters reveals the presence of considerable proximal or contiguous cross-well events. We speculate that these events are localized in critically stressed areas. Although seismically identifiable faults or fracture zones are not clearly associated with out-of-zone clusters, enhanced seismic views do suggest the presence of relatively ductile and chaotic deformation in out-of-zone shale strata. Shortening of the out-of-zone strata above the folded reservoir and aseismic intervals appears to have occurred along numerous, discontinuous folds and faults. These shallower strata may be critically stressed in places and prone to rupture in response to strain produced by deeper hydraulic fracture treatments without the aid of direct fluid interconnection. Significant out-of-zone ruptures produced by the initial 6mh frac stage served as the nuclei for additional out-of-zone ruptures produced during subsequent hydraulic fracture stages. Deformation in the aseismic zone conforms to that in the underlying reservoir. Following the suggestion of Pedersen and Eaton (2013) that variations in reservoir rock fabric may limit event magnitude, we speculate that rupture in the aseismic zone may occur along fractures with smaller characteristic length that produce events beneath the detection threshold of the sensor arrays deployed in the area.

Acknowledgements

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