Comparison of simultaneous downhole and surface microseismic monitoring in the Williston Basin

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Summary

Microseismic events reported from simultaneous downhole and surface monitoring of a hydraulic fracture well stimulation were matched on an event-by-event basis and compared. Downhole monitoring was much more sensitive than surface monitoring near the observation well, detecting 4-5 times the number of events, but the downhole monitoring appeared to be lose much of it sensitivity advantage at distances greater than about 3,000 feet. The picks reported from surface monitoring varied dramatically depending on the picking criteria that were used, which emphasizes the need for a reliable pick confidence factor. In the strict assessment of the surface data the existence of the majority of the events were corroborated by the downhole data, including many sub-visible surface events. Considerable differences exist in the reported spatial location of the events picked by the two methods despite correct positioning of perforation shots for each method. The events picked by the surface method are clustered much more closely to the wellbore, which may represent a considerably lower estimate of the stimulated rock volume.

Introduction

From Dec. 9-12, 2010 a 30-stage hydraulic fracture well stimulation in the Bakken-Three Forks Petroleum System of the Williston Basin (~10,500' depth) was simultaneously monitored using a downhole array of 45 three-component geophones located in an observation well approximately 530 feet offset, and 1,246 single-component geophones located in a star shaped array at the surface over the area of interest (Fig. 1). The purpose of conducting simultaneous monitoring was to compare the effectiveness of the two methods in detecting and locating microseismic events.

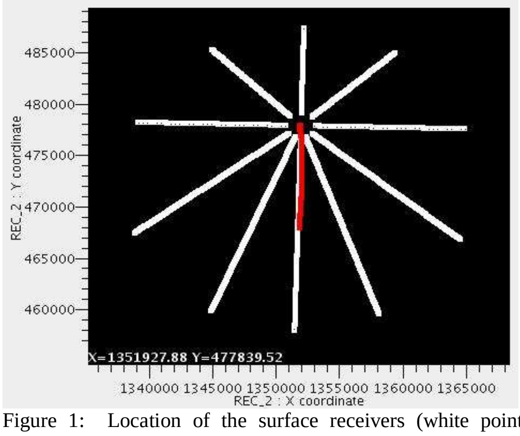

Figure 1: Location of the surface receivers (white points) relative to the borehole of the treatment well (red points).

Method

The downhole and surface data were processed independently using commercial microseismic processing services. Events in the downhole data were located using a combination of traveltime-based moveout analysis of the compressional waves, and multi-component rotation analysis (Fuller et al., 2007). Events in the surface data were located using the passive seismic emission tomography method (Duncan and Eisner, 2010).

Initial comparison of the reported hypocenters from the two methods showed poor agreement. It was determined that the threshold(s) that discriminates between valid and invalid picks was set too low for the surface data, and the

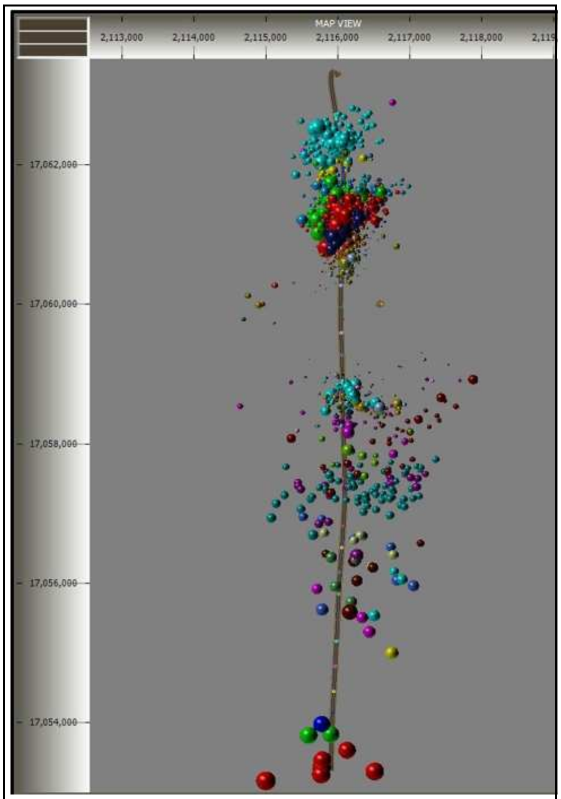

Figure 2: Map view of the hypocenters reported from the downhole data. The symbol sizes correspond to event amplitudes, and the colors correspond to stages. From Engelbrecht and Fuller, 2011.

data was reassessed with more conservative parameters. However, both the relaxed and strict set of picks from the surface data were included in the comparative analysis.

Subsequent to commercial processing the downhole data was independently rescanned for events, so that the events could be verified and the event times determined within approximately 50 milliseconds. All of the downhole events were then reviewed interactively to provide a high level of confidence in their existence and timing. All of the reported picks in the surface data were also reviewed

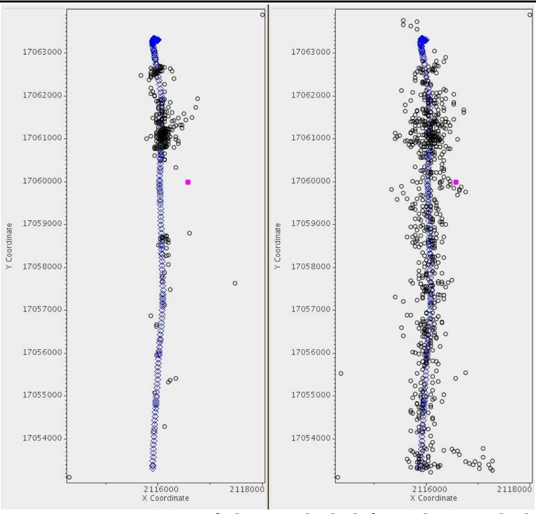

Figure 3: Map view of the matched (left) and unmatched (right) hypocenters reported from the relaxed assessment of the surface data.

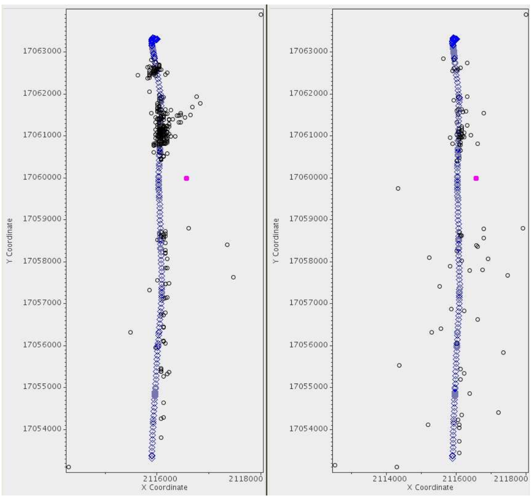

Figure 4: Map view of the matched (left) and unmatched (right) hypocenters reported from the strict assessment of the surface data.

interactively to verify that they occurred at the time that was reported from the processing services.

The events from both datasets were then compared in time, and events that fell within a tolerance of 1.0 seconds were considered to be ***matched***. A relatively large tolerance of 1.0 seconds was necessary to account for differences in instrument clock time, uncorrected differences in travel time from the hypocenters to the receivers, and rounding errors in the reported pick times. The clock time differences occurred despite care to ensure proper timing and may result from problems recording the fractional second after re-syncing with the satellite clock. Analysis of the matches with apparent clock time corrections and a tighter tolerance of 0.2 seconds reduced the match counts by only approximately 6 percent. The existence of matched events from both datasets then became the basis for all subsequent analysis.

Results

A total of 1,388 events were reported from the processing of the downhole data, which included a large gap in the events due to a lack of ball seats during the hydraulic fracture (Fig. 2). 988 events were reported from the relaxed assessment of the surface data, of which 285 were matched to downhole events, representing a 29 percent match rate (Fig. 3). 394 events were reported from the strict assessment of the surface data, of which 302 were matched to downhole events, representing a 77 percent match rate (Fig. 4). Table 1 presents a summary of all events.

The interactive review of picks in the surface data included a characterization of the visibility of the events reported from the strict assessment. In preparation for the review the surface data was whitened and bandpass filtered to emphasize the events, but no sophisticated filtering was performed. Of the 302 matched surface events from the surface data, approximately 100 of them were recognized by an experienced analyst, and approximately 200 of them were not recognized and classified as sub-visible.

The matched events can be separated into two groups, a ***proximal*** group that are less than 3,000 feet from the observation well, and a ***distal*** group that are greater than 3,000 feet from the observation well. The proximal group from the relaxed surface assessment includes 773 picks, of which 276 are matched to downhole events, representing a 36 percent match rate. The distal group from the relaxed surface assessment includes 215 picks, of which 9 are matched to downhole events, representing a 4 percent match rate. Events that were observed in the proximal downhole data but not in the proximal surface data were classified as ***missed*** events.

Discussion of Results/Conclusions

The number of sub-visible picks from the surface data that are matched is an important consideration, because large numbers of sub-visible picks are routinely reported from surface data, and the fraction of sub-visible picks that are valid is usually unknown and questionable. Of the 988 reported picks from the relaxed assessment of the surface data, approximately 890 were sub-visible and approximately 200 of those were matched, so at least 22 percent of sub-visible picks were verified. Of the 394 reported picks from the strict assessment of the surface data, approximately 300 were sub-visible and approximately 200 of those were matched, so at least 67 percent of the sub-visible picks were verified. Without this information the relaxed picks from the surface data could lead to a very different and perhaps invalid interpretation of the stimulated rock volume (compare Fig. 3 and 4).

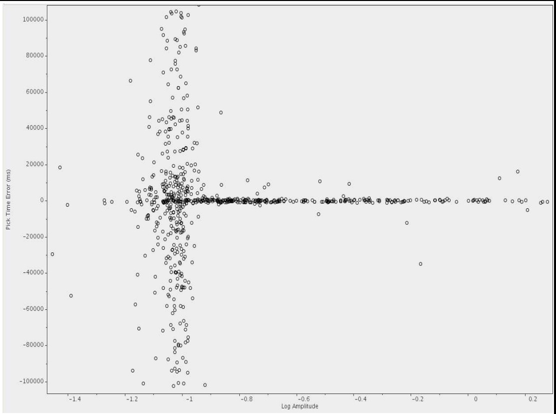

Figure 5: Logarithm of event amplitude (x axis) versus event match time (y axis) for the relaxed surface hypocenters. Surface events more than 1000 milliseconds from the y axis were classified as unverified.

There could be very useful information in the low confidence picks from surface data surveys if the fraction that are valid were known, because it would facilitate a statistical analysis of stimulated rock volume based on reported pick densities. In Figure 5 the reported event amplitudes from the relaxed picks of the surface data are plotted on a logarithmic scale versus ***match time***, where match time is defined at the difference in time from the reported event to the nearest time of a downhole event. The plot is zoomed to emphasize picks near zero match time, so not all events are visible. Surface events that are more than 1,000 milliseconds from the zero-time axis were classified as unverified, and it is significant that the clustering of the picks within 20,000 milliseconds of the zero-time axis does not suggest that these events are nearly verified. It is apparent in Figure 5 that the fraction of verified picks decreases abruptly below an amplitude of approximately 0.1 (-1 on the logarithmic scale). If this type of information were always known in surface surveys then analysts could estimate the number of valid picks based simply on pick amplitudes. Unfortunately pick amplitudes as reported do not represent true event magnitudes and will probably vary from one survey to the next, but there may be other pick attributes such as a “confidence factor” that could provide a useful quantifier of pick validity that could be used consistently from one survey to the next.

Much of the discussion thus far has been based on the assumption that where picked events are mismatched it is the surface picks that are invalid. Near the observation well this is a reasonable assumption, because the events that are reported from the surface data are visible as large events in the downhole data, and hundreds of smaller events are also clearly visible in the downhole data, which indicates that the downhole data has much greater sensitivity to detect events near the observation well. However, as Figure 6 shows, the number of reported events from the downhole data drops significantly with distance from the observation well. To be visible in the downhole data, an event 4,000 feet away from the observation well must be approximately 10 times larger than an event that is 1,000 feet away. Some of this decline in sensitivity may be due to a reluctance of the downhole data analysts to report events that do not focus well (Fuller, 2011, personal communication).

	Downhole	Surface preliminary	Surface final
All picks	1388	988	394
Matched events		285	302
Percent matched		28.8%	76.6%
Proximal picks	1340	773	352
Matched events		276	281
Percent matched		35.7%	79.8%
Unmatched events		497	71
Missed events		1112	1107
Percent missed		80.1%	79.8%
Distal picks	48	215	42
Matched events		9	21
Percent matched		4.2%	50.0%
Estimated matched		*77*	*34*
Estimated missed	*468*	*866*	*165*

Table 1: Summary of all event counts and estimated event counts.

We would not expect the sensitivity of the surface method to decline as a function of distance from the observation well. South of the observation well the arms of the star array are somewhat wider and therefore some of the source-receiver distances are greater, but that disadvantage is probably more than offset by the advantage of having greater distance from the surface activity and noise sources at the treatment well head.

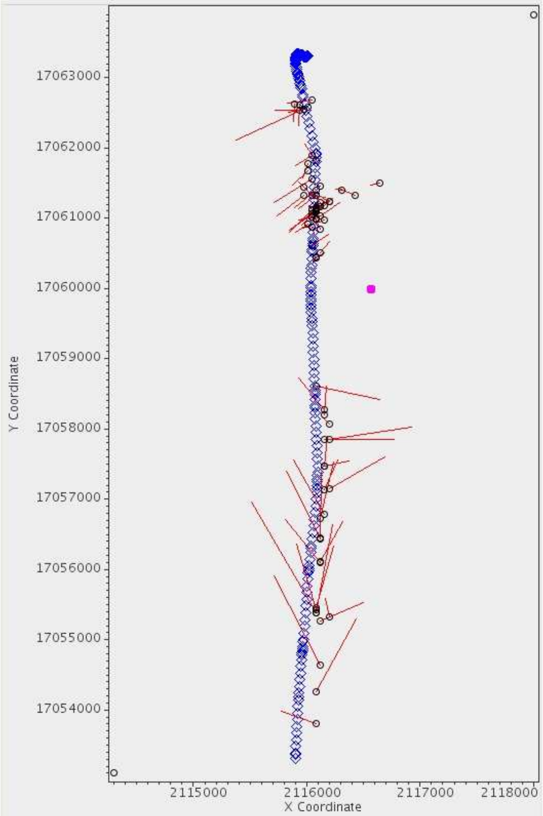

Figure 7: Location differences for matched events. The open circles represent the reported locations of the picks from the strict assessment of the surface data, the red line segments connect to the reported locations of the downhole data picks for matched events. All of the matched events were visually inspected, and in no more than 6 percent of the cases are there multiple events that are close enough in time to have caused a false match.

If we assume that the sensitivity of the surface method does not decline with distance from the observation well, then presumably the lower match rate in the distal group is due to the inability of the downhole method to detect distal events. If we assume that the sensitivity of the surface method does not change with distance from the observation well, and we also assume that the fraction of missed events from the surface data does not vary dramatically, then we can estimate the number of distal events that were missed by both methods. The summary in Table 1 includes an estimate of the number of missed events in the final row. The estimate of the number of missed events in the downhole data is based on using the mean of the number of estimated missed events in the two sets of surface picks.

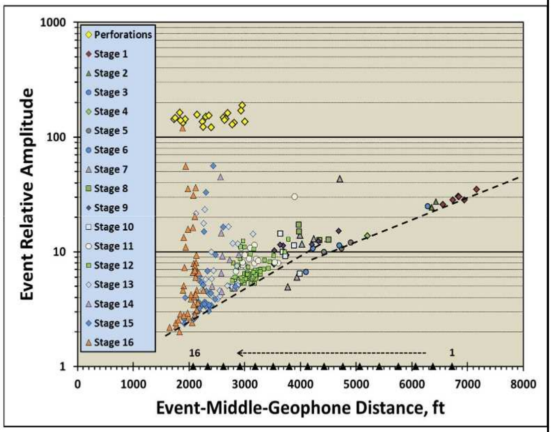

Figure 6: Logarithm of normalized event amplitude versus distance from the observation well for downhole events from stages 1-16. From Engelbrecht and Fuller, 2011.

In addition to sensitivity, another important consideration regarding the value of the monitoring methods is the accuracy of event location. Figure 7 shows the location differences for matched events from the downhole data and the visible events from the strict assessment of the surface data. The open circles represent the event locations from the surface data, and the red line segments connect to the reported locations from the downhole data. The differences are quite significant, particularly in the southern half of the area of interest, where the difference between the locations is typically more than 500 feet. This occurs despite proper location of the perforation shots for each method. More importantly, the two sets of picks show a very different grouping. The picks from the surface data are clustered much closer to the wellbore than the picks from the downhole data. It is also noted in Figure 4 that the surface matched events cluster much closer to the wellbore than the unmatched events. These differences in the locations of the downhole and surface events could presumably lead to a very different estimate of the stimulated rock volume, and these differences are the focus of continued investigation.

We expect that conclusions drawn from this study could be very different for different geology, different depths, different noise conditions, and different acquisition and processing companies and techniques.

Acknowledgments

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