

## Microseismic Signal Loss From Reservoir to Surface

S.C. Maxwell\*, D. Raymer, M. Williams, and P. Primiero, Schlumberger

smaxwell@slb.com

### Summary

A comprehensive test is used to compare microseismic monitoring from surface, shallow well and downhole arrays. In particular, a long-aperture borehole array was deployed with sensors spanning from the reservoir depth to surface. This array allows tracking of microseismic signals and measurement of the signal degradation that occurs between the various normal monitoring configurations. The experiment is a unique opportunity to fundamentally understand the signal degradation, and hence the sensitivity differences between common microseismic array configurations.

### Introduction

Microseismic imaging has proven to be the key technology to optimize hydraulic fracture stimulation of unconventional reservoirs. As the industry has moved to multiple stimulations of horizontal wells, microseismic monitoring configurations have expanded from downhole monitoring using vertical boreholes to combinations of vertical and horizontal wells and monitoring using arrays deployed on surface and near surface in shallow holes (for simplicity, surface and near-surface monitoring will be collectively referred to here as surface monitoring). Fundamental questions persist about how microseismic results compare from these configurations, including the sensitivity and detection limits to record small-magnitude microseismicity from different array configurations.

Over the last several years, numerous attempts have been made to compare surface monitoring with a benchmark from downhole recording. In most cases, the two data sets have been recorded separately and then processed with very different workflows, leading to several challenges in the comparison. The resulting final microseismic locations can be directly compared, but timing differences between the two recording systems often make one-to-one comparison of individual microseismic events difficult or impossible. This has severely limited the opportunity to more fully investigate differences between the two methods. Here we describe a comprehensive study to compare differences between various monitoring arrays, and specifically deployment of a borehole array from the reservoir depth to surface enabling a unique opportunity to track microseismic signals between each array.

### Monitoring Array Comparison Test

A wide variety of monitoring configurations were used in this study as shown in Figure 1, including both horizontal and vertical near-reservoir borehole arrays, shallow well arrays, surface lines and 2D patches combining 1C and 3C sensors, and broadband seismometers. Exact time synchronization between all recording systems was used to ensure that the same

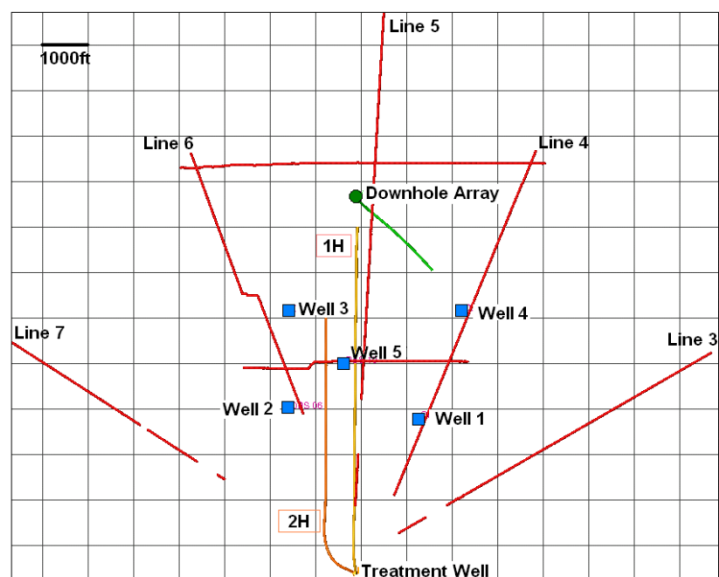


Figure 1. Map view of the multi-array monitoring geometry.

microseismic event is identified on all monitoring systems. The monitoring was performed in the relatively shallow Fayetteville shale (3600 ft true vertical depth), where common events were detected on all of the monitoring arrays (Figure 2). Details of the experiment including survey design, acquisition and comparisons of signals, noise and detection can be found in Peyret et al., 2012.

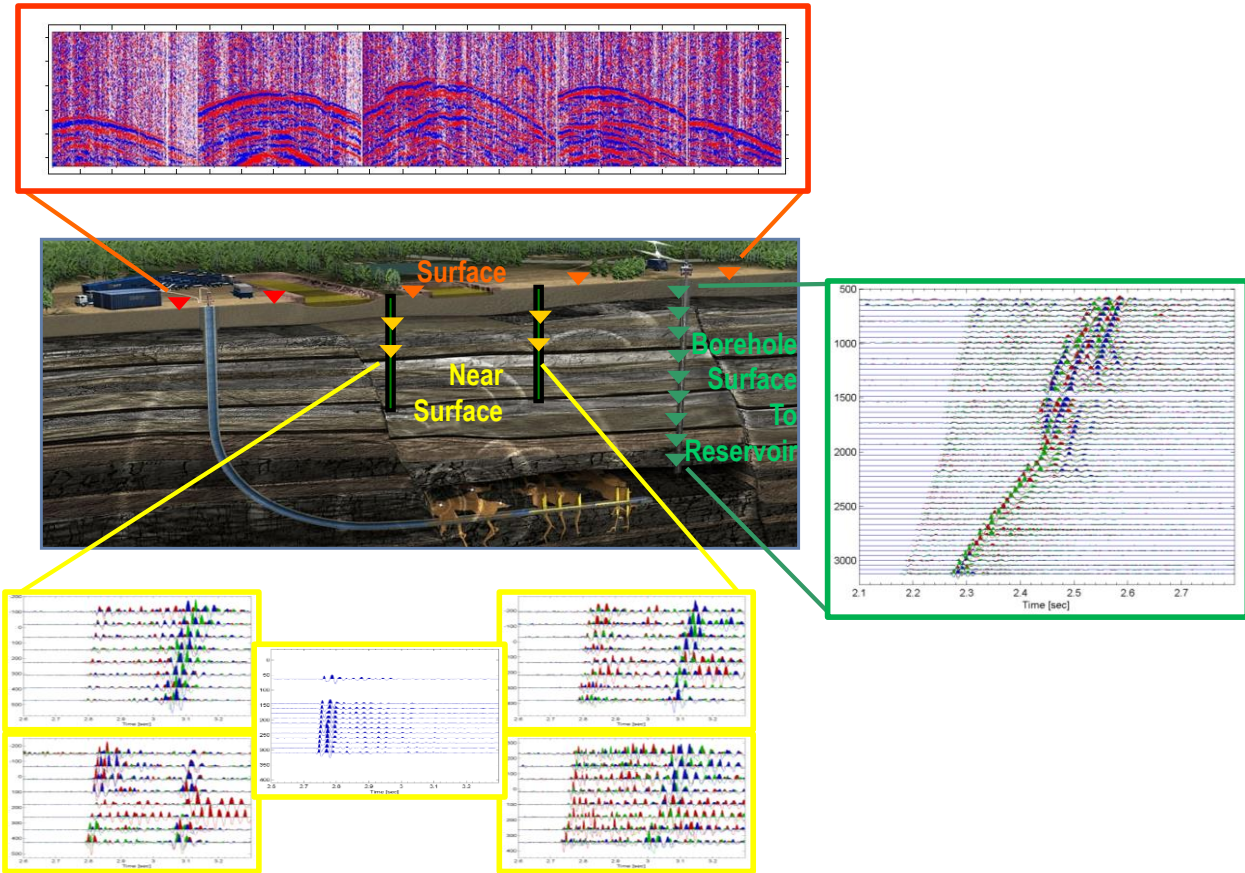


Figure 2. Simultaneous recording of a single, relatively large microseismic event on all monitoring arrays.

### Observed Signal Degradation

Observed microseismic signal intensity depends on the source strength, or moment magnitude, and travel distance to the recording site. Ground motion intensity decreases with distance due to geometric spreading and attenuation. Vertical propagation to surface also results in signal loss and waveform complexity associated with reflections and mode conversions at impedance contrast interfaces. Microseismic sources have a specific source radiation pattern dependent on the source deformation mechanism or moment tensor, which also impacts observed amplitudes. Free surface effects increase amplitude for surface deployed sensors, although this effect will not be discussed further here, it is well known and documented elsewhere. Stacking and potential signal-to-noise ratio (SNR) enhancing processing are not discussed here, but in a pre-survey design can be used with the amplitude quantification described here to define the required number of sensors to achieve a specific detectability. Although the basic geophysics of signal degradation is well defined (e.g., Warpinski, 2010 and Eisner et al., 2011), the technical debate has resulted from the relative importance of each of these factors.

The monitoring array comparison test provides a unique opportunity to both measure and model the signal degradation. Signal amplitudes can be measured on discrete signals recorded at different depths on the large aperture borehole, for example the signal shown in Figure 2. The recorded signals can also be used to investigate the frequency content recorded at different depths. For example, inspection of the S-wave signal shown in Figure 2 shows that the dominant frequency is reduced from the deepest

to shallowest sensors. Spectral ratios were used to estimate the seismic attenuation (Maxwell et al., 2012).

Measured signal amplitudes were used to calibrate a model of the expected P-wave amplitude at different depths. The model includes the amplitude decrease resulting from spherical divergence (-9 dB for these distances), attenuation (-14 dB for characteristics below) and estimated transmission losses (-9.6 dB) across impedance contrasts (see Maxwell et al., 2012 for details). Figure 3 shows the modeled amplitude along with observed amplitudes for two discrete events. The model provides a reasonable match of the observed amplitudes over the entire depth interval, although under or over estimating the amplitude at certain intervals.

### Array Sensitivity

Extrapolating to larger offsets can be used to illustrate the signal detectability that might be expected when monitoring a frac with a specific array configuration at different distances or depths. The detectability estimation assumes that the characteristics used in the Fayetteville model can be extrapolated to longer offsets, to estimate the minimum relative source strength (seismic moment) that would result in an observed signal amplitude detectable as a 'visible' event above similar background noise (Figure 4a). Here a 'visible' event is defined as an event with SNR greater than 1 and hence detectable as a discrete signal. The plot can be interpreted as the minimum source strength for a discrete event relative to a downhole array at 1000 ft offset reference point. Remember that no account has been made for a weathering layer, increased noise levels or free-surface effects: making this a best-case scenario. Further, no account has been made for signal enhancement or stacking to improve SNR.

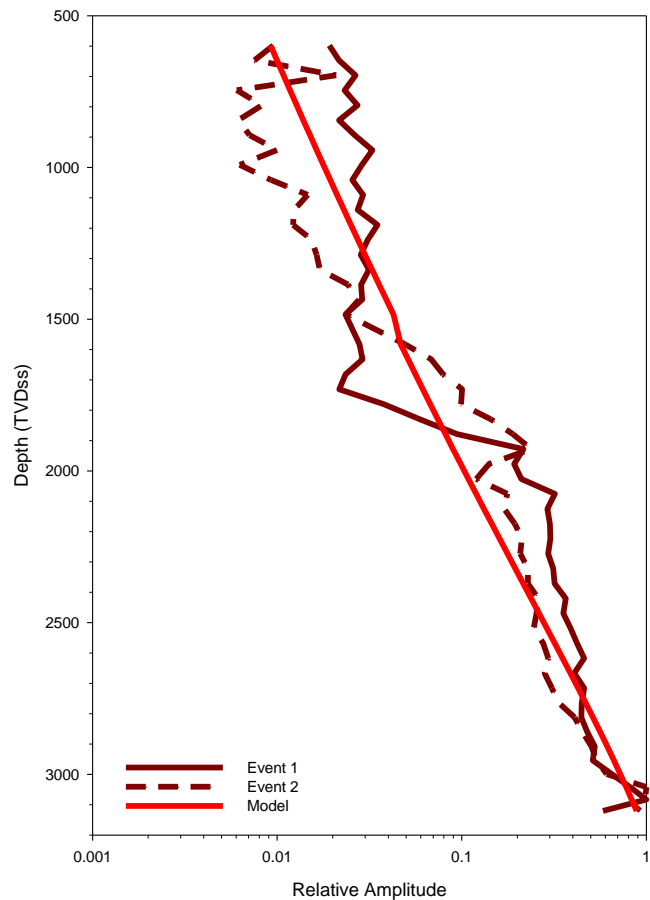


Figure 3. Modeled amplitude decrease compared with the relative p-wave amplitudes of two events.

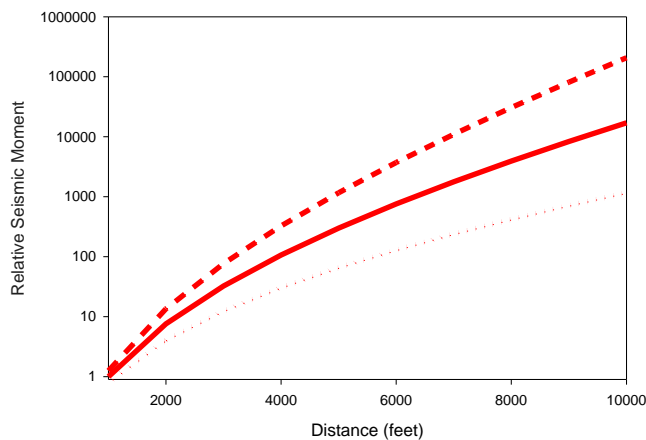


Figure 4a. Estimation of the minimum relative source strength that would be detectable as visible events. Solid is the same parameters as Figure 3, long dash is more and short dash is less attenuation.

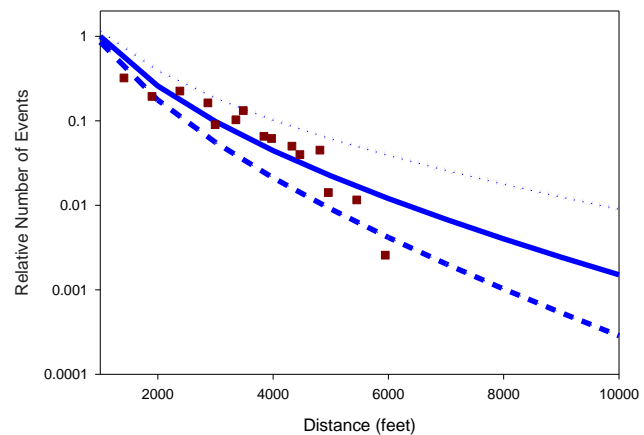


Figure 4b. Relative number of events estimated by a typical frequency-magnitude relationship (blue curves) compared with the relative number observed downhole for several stages (red squares).

Based on this estimated source-strength-detectability model, the fraction or relative number of events can also be estimated by assuming a typical frequency-magnitude power-law relationship. Here a frequency-magnitude relationship is assumed, consistent with fault activation type relationship that typically results in larger microseismic magnitudes (e.g. Maxwell et al., 2009). The fraction of events relative to the number detected at a 1000 ft offset reference point is shown in Figure 4b and is compared with the fraction of events observed downhole at various distances to validate the model. The plot represents the number of visible events and is approximately (within an order of magnitude) consistent with the relative number of events detected on the surface and near surface arrays (see Peyret et al., 2012), although in practice more events are typically processed using array methods to improve the SNR. These plots of the empirical signal decay model and corresponding relative number of events are included as an example to illustrate the potential utility as part of a pre-survey design tool.

## Conclusions

In light of the ongoing controversy about detecting signals at surface, this experiment has indeed successfully demonstrated that signals from common events can be tracked between monitoring arrays and the larger magnitude events can be detected at the surface. Furthermore, the experiment provides a unique opportunity to examine actual microseismic signal degradation and clarify the corresponding sensitivity of various monitoring options. While the signal degradation will obviously vary between locations, the other important issue that has yet to be discussed is the magnitude of the microseismic events generated for a given frac job. Microseismic experience has shown that the size of the biggest events detected during a hydraulic fracture is variable from field to field, well to well and even between stages in a single well. The upper magnitude limit can be related to the hydraulic energy associated with the injection (Maxwell, 2011). However, there is often a large range of magnitudes and number of microseismic events encountered for identical injections, particularly when the frac intersect pre-existing faults. Since downhole monitoring offers better sensitivity, an array deployed in a proximal monitoring well generally provides better detection capability for a richer, more populated microseismic dataset. However, the sensitivity of borehole monitoring decreases with distance from the array, resulting in reduced sensitivity and increased location uncertainty over the length of a long horizontal. While less sensitive, surface and near-surface monitoring have potential for more uniform sensitivity over a wider region. To understand the suitability of surface monitoring at a particular site, a planned borehole array can be supplemented with at least a sparse surface array can establish the detection limits of visible events and potentially validate an amplitude attenuation model as done here. In cases where no proximal monitoring wells exist, a pre-survey design can be used to estimate the minimum magnitude (either as discrete events or after stacking) as described here to establish feasibility by comparing with microseismic magnitude ranges of previous monitoring projects in the same area or possibly analogues in cases with no prior magnitude information.

## References

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