The Magnitude vs. Distance Plot – A Tool for Fault Reactivation Identification*

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Abstract

On a multistage fracturing job monitored from a borehole for microseismic activity, high-magnitude microseismic events are characteristic of reactivated faults. When plotted against their distance from the monitor-well and compared to events from other hydraulic stimulation stages, it becomes apparent that these microseismic events are associated with fault reactivation. Presented here is an example, Magnitude vs. Distance Plot, used to discriminate between fault reactivation (i.e., stimulation failure) and other successfully completed stages. Plot analysis and treatment record suggested reactivation of a fault during the hydraulic fracturing, but no other subsurface data supported this interpretation. As soon as a 3D reflection seismic volume was available, it was clear that microseismic events aligned with a fault plane interpreted on seismic profiles, thus corroborating the hypothesis of a preexisting fault reactivation. This work shows that in the absence of other subsurface data (or integrated with all the available information), Magnitude vs. Distance Plots provide a useful tool to analyze stimulation results and support decisions regarding completion strategies in real time.

Introduction

Sheriff (1999) defines a fault as a displacement of rocks along a shear surface. Most of this movement releases energy that propagates as elastic waves (i.e., seismic information). Magnitude is a measure of this energy. The works of Shemeta and Anderson (2010) and Baig and Urbancic (2010) review in detail the magnitude concept within the context of the microseismic technology. Maxwell and Cipolla (2011) describe the fundamentals of fault mechanics as pertinent to microseismic exploration. For the purposes of this publication, I rely on the aforementioned publications simply stated that magnitude values of the recorded microseismic events are proportional to the size of the surface and the displacement involved in faulting. Therefore, assuming that surfaces and displacements associated with preexisting faults are bigger than those of hydraulically-induced fractures, then, during hydraulic stimulation, registered higher magnitudes should characterize fault reactivation.

Borehole microseismic is a diagnostic tool used to monitor seismic activity generated during hydraulic fracturing. Magnitude is usually one of the parameters derived from borehole microseismic measurements. In practice, microseismic recording sensors only detect microseismic events occurring within a certain radius from them, usually no more than a few thousand feet. One way to quantify this phenomenon is with a Magnitude vs. Distance Plot (MDP). This plot shows the relationship between the energy associated with a particular event and its distance from the monitor well.

The MDP is a useful analysis tool in microseismic interpretation for all the information it summarizes on a simple graphic display, as demonstrated in the schematic diagram presented in Figure 1 (Zimmer, 2011). For instance, events with a combination of highest magnitude and highest distance away from the monitor well define the maximum detection distance, which can be used to plan the maximum distance for monitor well placement in future jobs. The rest of the recorded events populate the middle upper left portion of the MDP graph, forming a quasi-triangular pattern. Notice that closer to the monitor well, it is possible to detect relatively lower magnitudes and therefore more events than farther away from it. The curved base of this triangular shape also identifies the minimum detection limit due to ambient noise (ambient or background noise refers to all other signals registered by the microseismic sensors, commonly not associated with the stimulation job). Finally, an upper boundary depicted by the constant high magnitude value associated with all the stages of a particular treatment-well also delimits the set of events.

The presence of faults in the subsurface and their reactivation during hydraulic stimulation thus becomes noticeable on MDP's because magnitudes of events associated with fault reactivation are usually higher than the rest. Figure 2 shows a MDP example from a Barnett shale stimulation (Warpinski, 2009). In this particular example, the typical maximum magnitude of microseismic events associated with the stimulation treatment is -2.5, and the group of events with significantly higher magnitudes (as high as -0.5) could be detected in response from fault reactivation.

Also highlighted in Figure 2 is the biased data. This area of the graph represents the low magnitude events identified only because of their proximity to the monitor well. For some interpretation purposes, it is common to discard these events during the analysis phase in order to compare events without the bias associated with the location of the sensors. In that sense, the MDP also has results to be a very useful tool for filter parameters selection. However, we do not favor totally discarding these low-magnitude microseismic events, as in my opinion, they contain most of the information from the hydraulic-fracturing stimulation. For example, Figure 3 shows differences between a data set of events and a filtered version of it based on a particular magnitude threshold. By eliminating these data points, it is difficult to convey a robust interpretation for parameters such as stimulated fracture azimuth based solely on filtered microseismic events. Indeed, it seems that this portion of the well has not been stimulated at all while production records prove otherwise.

As an additional example illustrating the use of MDPs, Figure 4, from Warpinski et al. (2008), shows the MDP as an associated expression of fault reactivation from hydraulic fracture stimulation from multiple geographical regions.

A few other examples of Magnitude vs. Distance Plots suggesting the reactivation of faults are available in the literature (e.g., Wolhart et al., 2006; Downie et al., 2010; Maxwell and Cipolla, 2011). Nevertheless, to the best of our knowledge, no publication has presented multiple independent data in support of the fault-reactivation interpretation. This work illustrates an integrated case study in which fault reactivation is interpreted based on independent data sets, including microseismic MDP, 3D reflection seismic sections, and pressure plots in order to build confidence in the use of MDP's as a robust interpretation tool.

Fault Reactivation Identification – and Integrated Case Study

We used the Magnitude vs. Distance Plot evaluation technique described in the previous section to discern fault reactivation in a microseismic monitoring exercise performed real-time during hydraulic fracturing operations. The results are shown in **Figure 5**. In this figure, the higher magnitudes events associated with possible reactivated faults are highlighted by a dotted blue circle.

When implementing the hydraulic stimulation, no surface seismic data was available and subsurface geologic maps, built solely on sparse wells information, did not foresee the possibility of a fault in the area. This encouraging geologic model also supported the drilling and stimulation of the treatment well.

After more than a year of the stimulation of the well associated with Figure 5, newly available 3D reflection seismic data provided a better image of the subsurface near the well. Unfortunately, due to resolution limitations, the broadband frequency data from this 3D reflection seismic survey does not provide unequivocal evidence for the presence of a fault. However, coupling the 3D seismic data with the microseismic events interpreted as the response of fault reactivation, it is possible to infer the presence of a fault in the seismic image. This is clearly illustrated in Figure 6 by showing sections with and without the microseismic events. The simple image of the microseismic events overlaid on the 3D seismic vertical section suggests the presence of an antithetic fault in the subsurface and its possible reactivation due to hydraulic fracture stimulation. The microseismic event set aligned very well in the direction of the interpreted fault plane.

Further analyses implementing the use of simple seismic attributes also enhance and support this interpretation. For example, after computing Similarity on the 3D seismic volume and extracting a surface slice from this volume at the zone of interest, it is possible to interpret the presence of a fault crossing the path of the treatment well. Good correlation between microseismic-event lineation and the extrapolation of Similarity trends provides further evidence for the hypothesis of fault reactivation due to the hydraulic fracturing treatment. This is illustrated in the map view presented in Figure 7.

As an additional support for the fault reactivation interpretation, Figure 8 displays the microseismic events associated with a later hydraulic fracturing stage. A zoom-in over the area presented in Figure 7 makes clear an azimuth change observed between a regular stimulation and a fault reactivation. This characteristic, solely based on microseismc-event location, provides another tool to derive subsurface geological information not emphasized in previous publications. It is thus our claim that in the absence of additional supporting data (e.g., 3D seismic coverage) an azimuth change observed from microseismic sets coupled with anomalously high magnitudes for the same events, could create enough evidence for interpreting a fault reactivation. Moreover, when integrated with treatment pressure information, these microseismic observations could be used in the decision-making process of changing a predesigned treatment job and could significantly reduce completion costs.

Conclusions

The example presented in this publication serves to validate and support the use of microseismic-derived Magnitude vs. Distance Plots as a tool to identify fault reactivation in the absence of additional subsurface data. Moreover, as shown in this case study, when combined with other independent measurements (e.g., 2D or 3D reflection seismic sections) MDP's could unequivocally characterize the reactivation of a fault based on higher amplitudes and possible azimuth changes. This work also shows that 3D seismic is a powerful tool to mitigate drilling and completion risks as those encountered when faults are not anticipated along the well path. In the case given above, availability of 3D seismic data beforehand could have improved well placement and possibly resulted in lower completion costs and better well performance.

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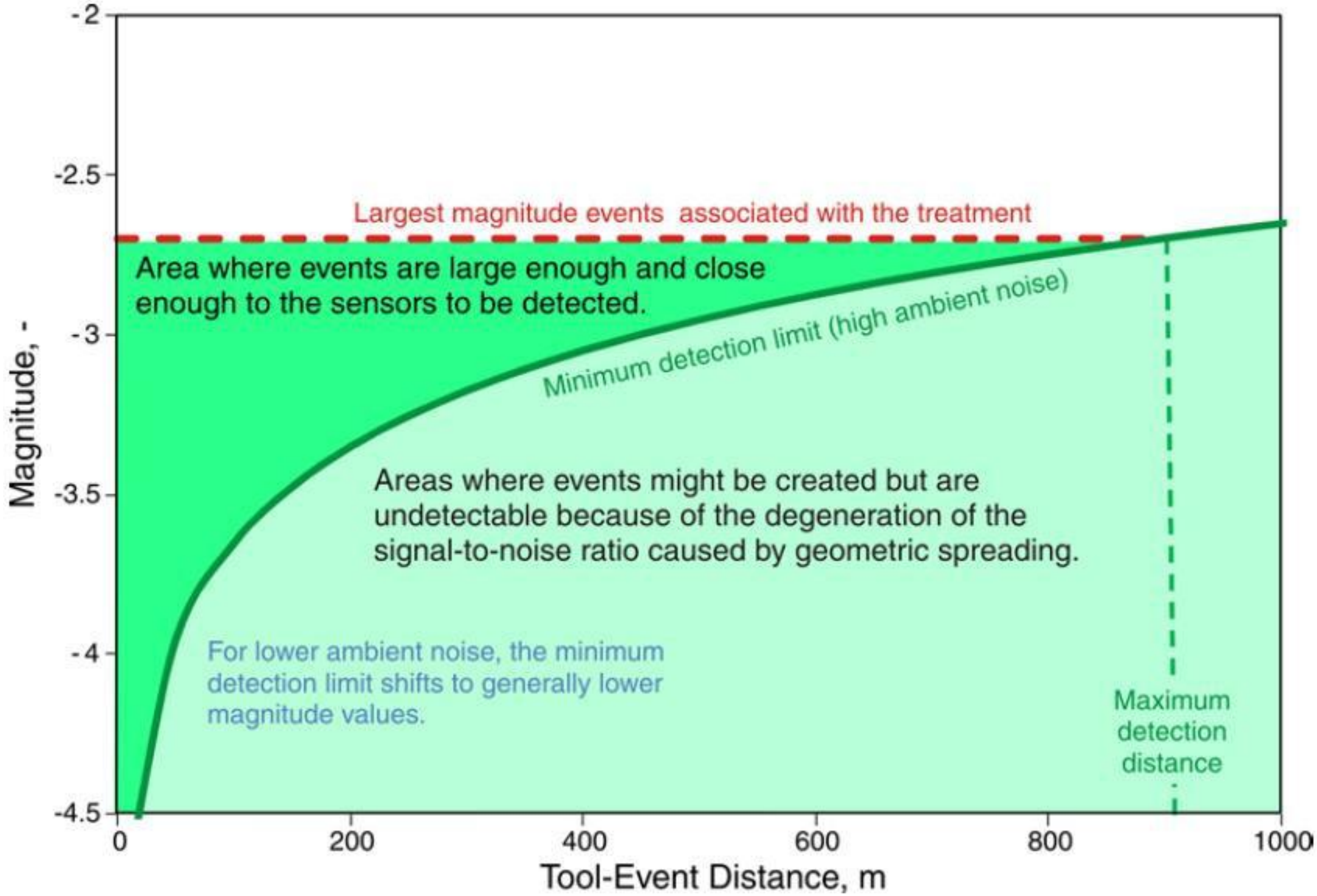

Figure 1. Schematic Magnitude vs. Distance Plot (Zimmer, 2011). During a hydraulic stimulation treatment monitored from a borehole for microseismic activity, most detected microseismic events fall within the quasi-triangular area with concave downward base, colored dark green. Copyright 2011, SPE.; reproduced with permission of SPE; further reproduction prohibited without permission.

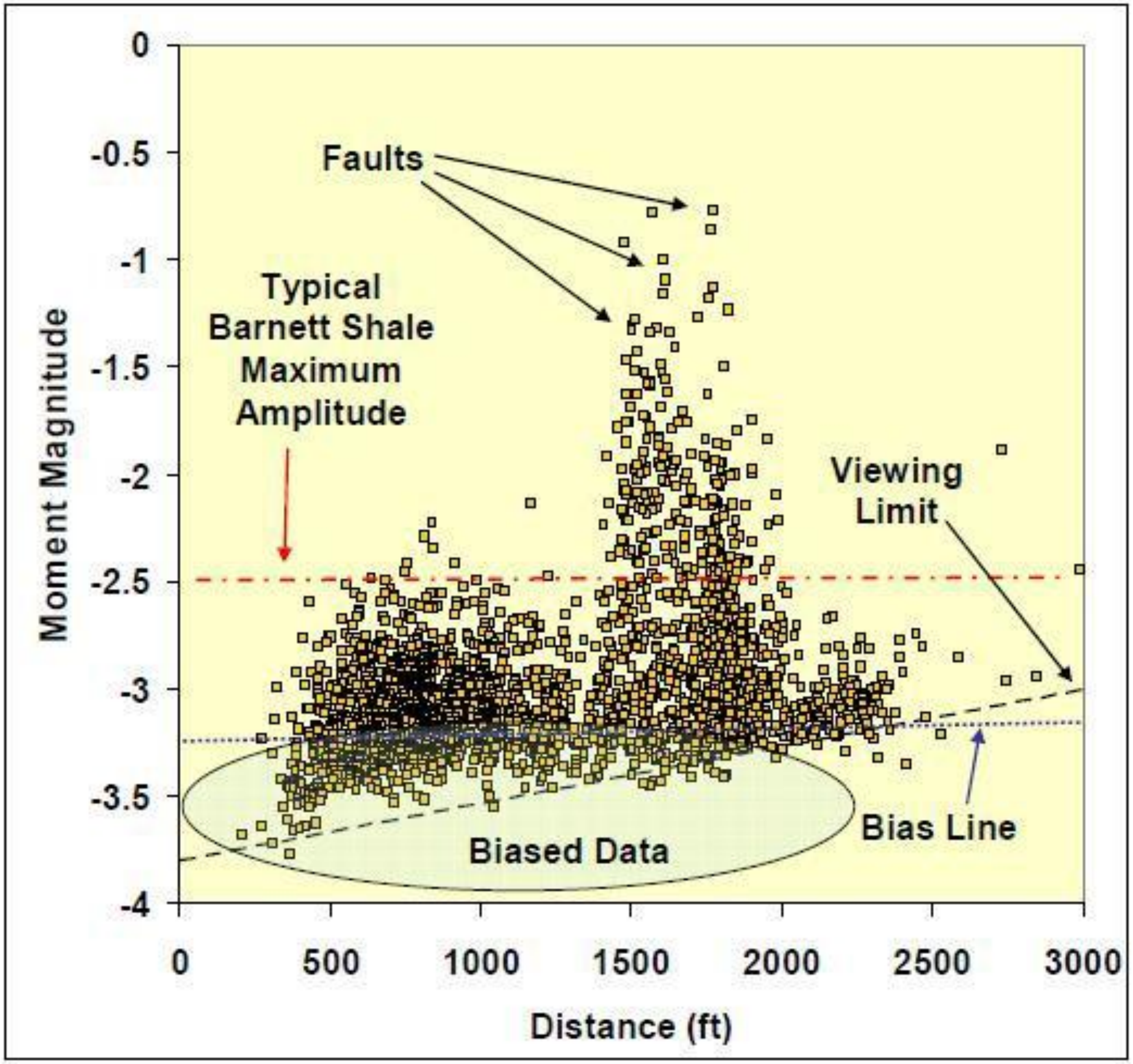

Figure 2. Magnitude vs. Distance Plot from a multistage horizontal hydraulic stimulation job in the Barnett Shale (Warpinski, 2009). As highlighted, high-magnitude events are interpreted as the result of fault reactivation. Copyright 2009, SPE; reproduced with permission of SPE; further reproduction prohibited without permission.

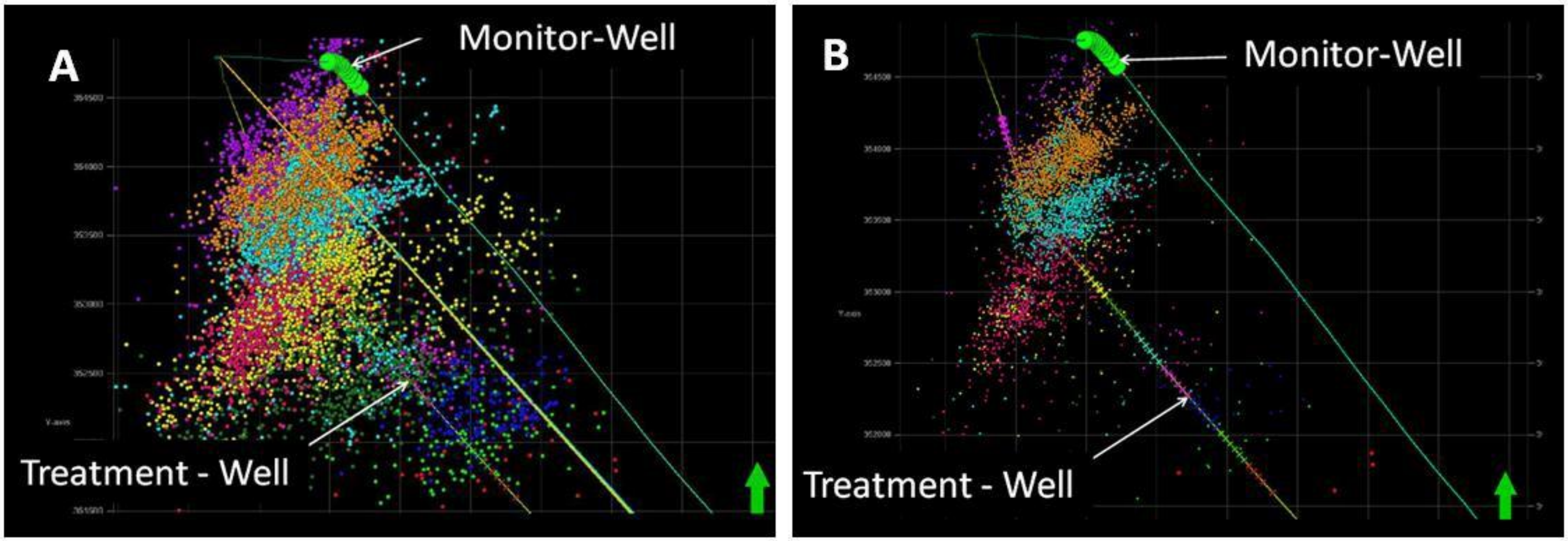

Figure 3. A. Map view of all events from a multistage hydraulic fracturing stimulation. B. Its associated filtered version based on an arbitrary magnitude value (internal Hilcorp's report). Each set of colored dots aggregates all microseismic events associated with an individual fracturing stage. By evaluating only the filtered version, it is very difficult to come up with a stimulation evaluation.

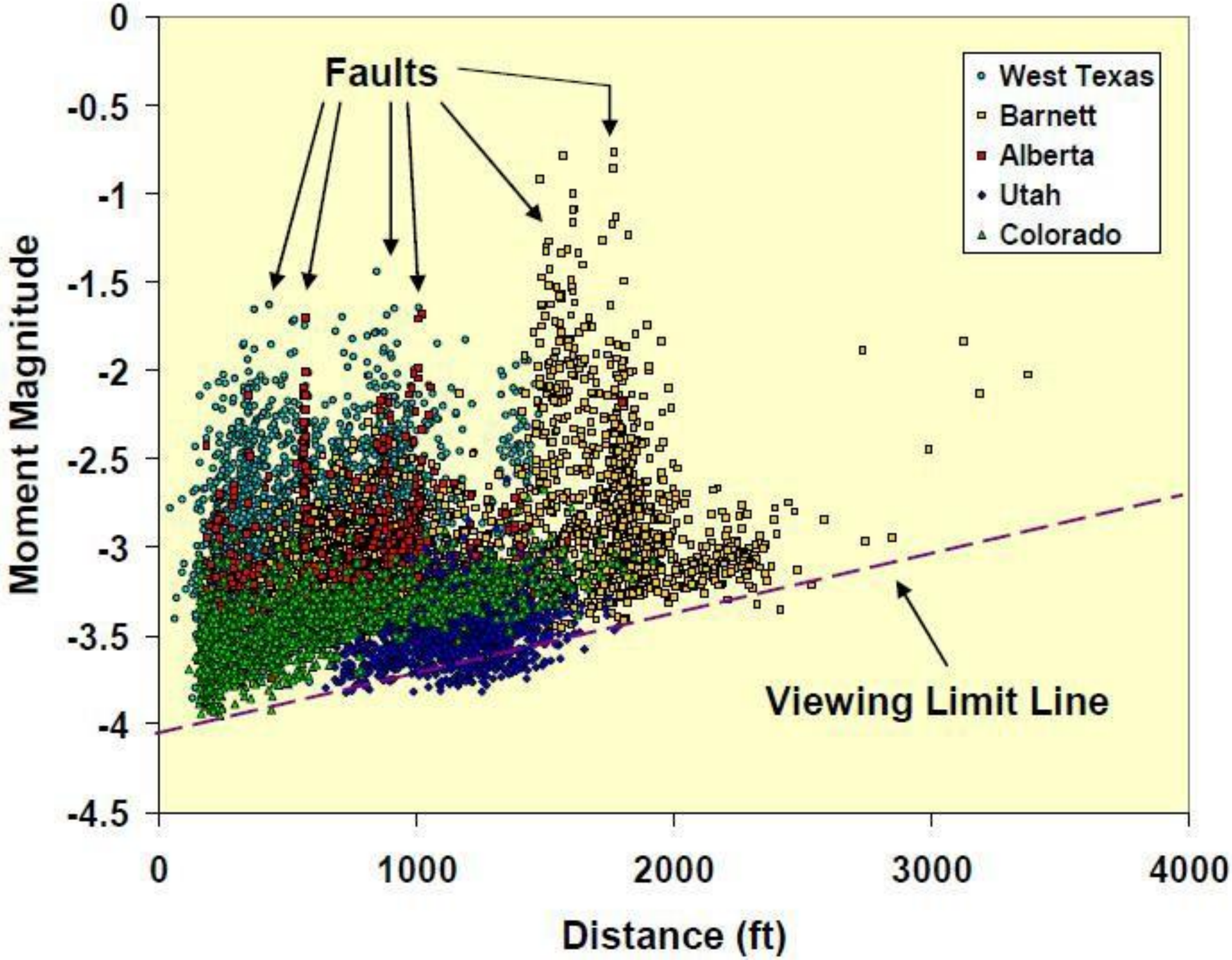

Figure 4. Magnitude vs. Distance Plot of microseismic events detected during a variety of treatments monitored at multiple geographical regions (Warpinski et al., 2008). Different multistage hydraulic fracturing stimulation treatments are each represented by a single color, based on the legend shown in the figure. Copyright 2008, SPE; reproduced with permission of SPE; further reproduction prohibited without permission.

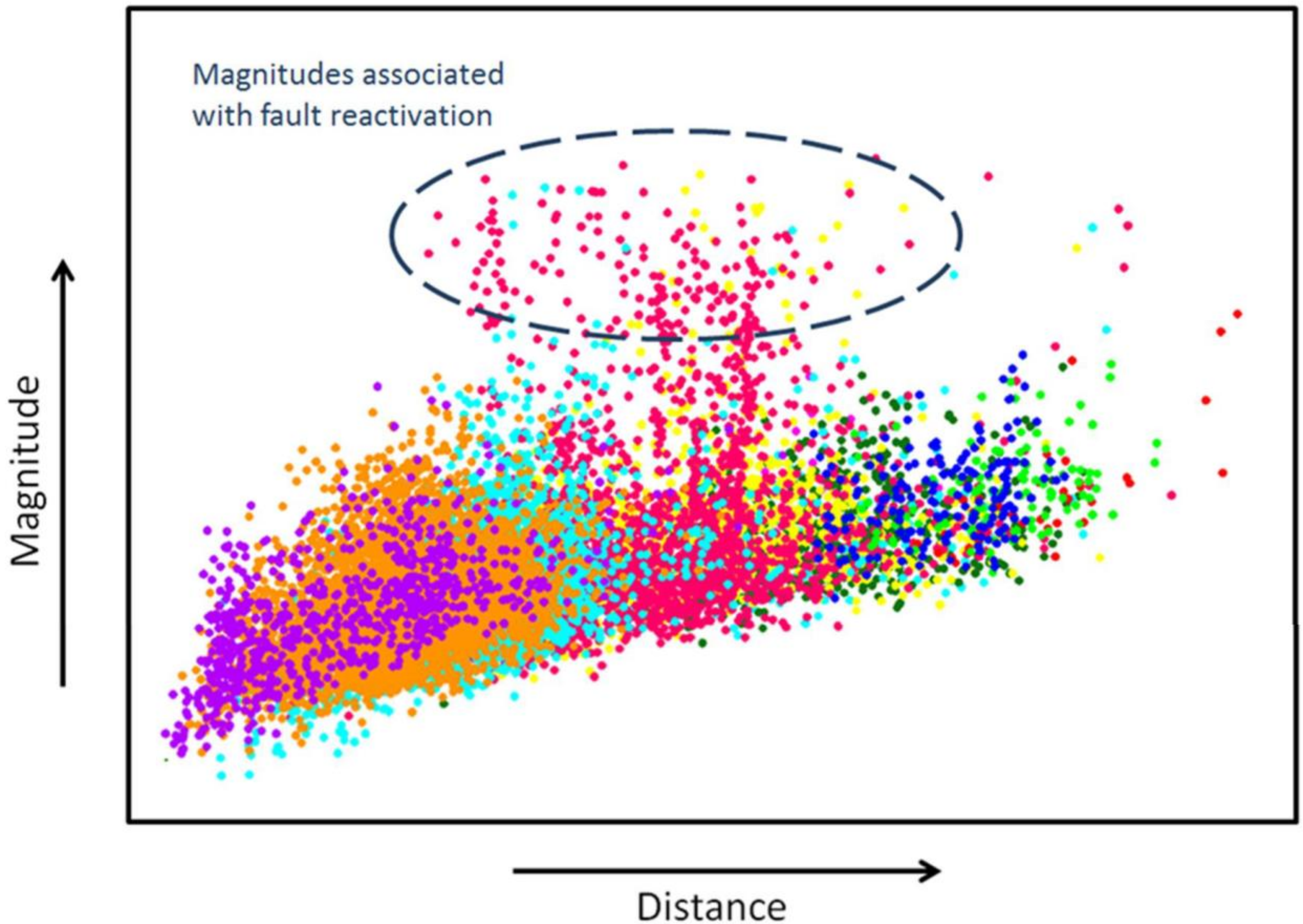

Figure 5. Magnitude vs. Distance Plot from a multi-stage hydraulic stimulation job monitored from a borehole for microseismic activity. Different colors represent event sets from different stages. Most of the stages generate microseismic events that predictably populate the graph (i.e., lower magnitude events can be detected near the monitor well, while farther from the monitor well, only relatively higher magnitude event can be detected). Stages yellow, cyan, and especially stage red, suggest fault reactivation due to their higher magnitude, as compared to magnitudes from other stages. Magnitude and distance increase, respectively, in the direction pointed by the arrows.

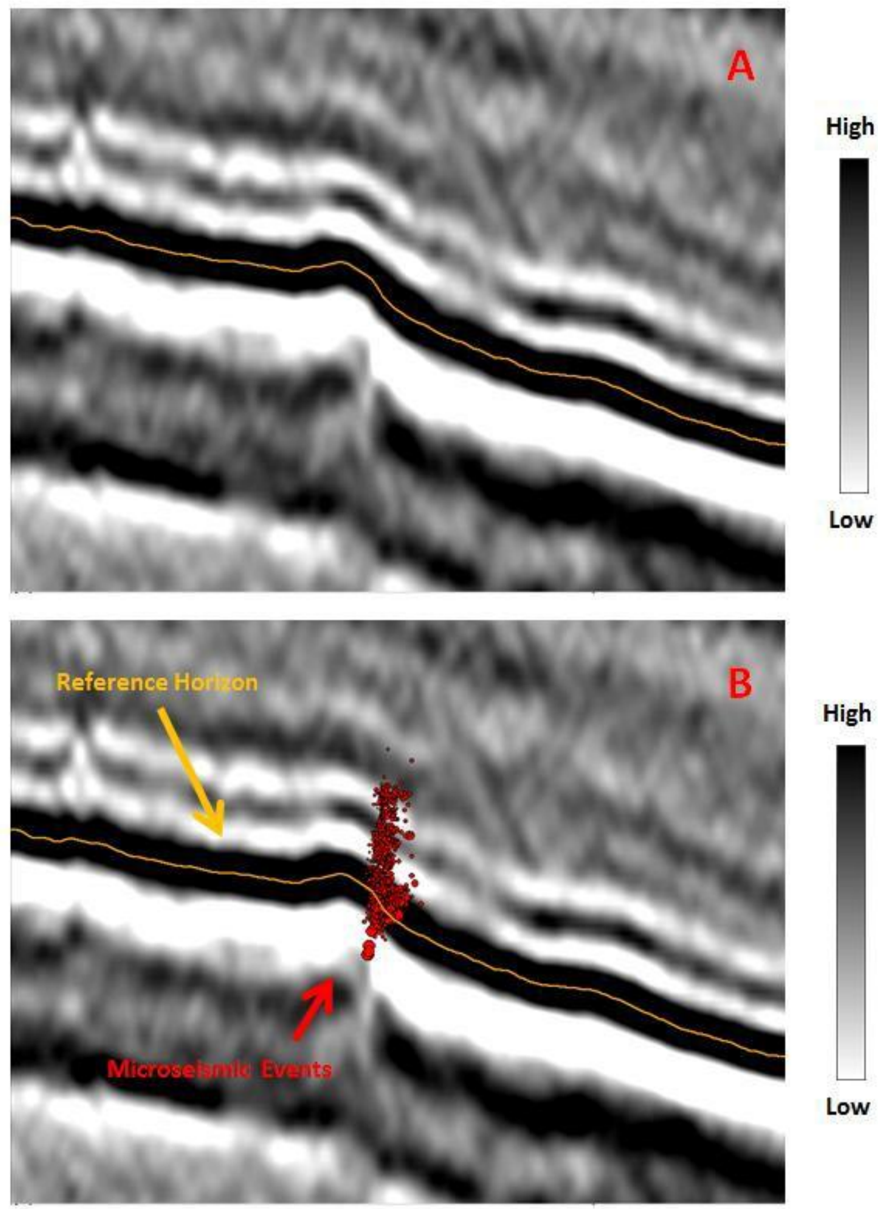

Figure 6. A. Vertical seismic section parallel to the azimuth of a treatment well monitored for microseismic activity (courtesy of Seitel, Inc.). B. Same seismic line overlaid by microseismic events from a stage interpreted as associated with a fault reactivation. Microseismic events align very well in depicting the trace for an antithetic normal fault dipping opposite to the dip of the reflectors (and beds).

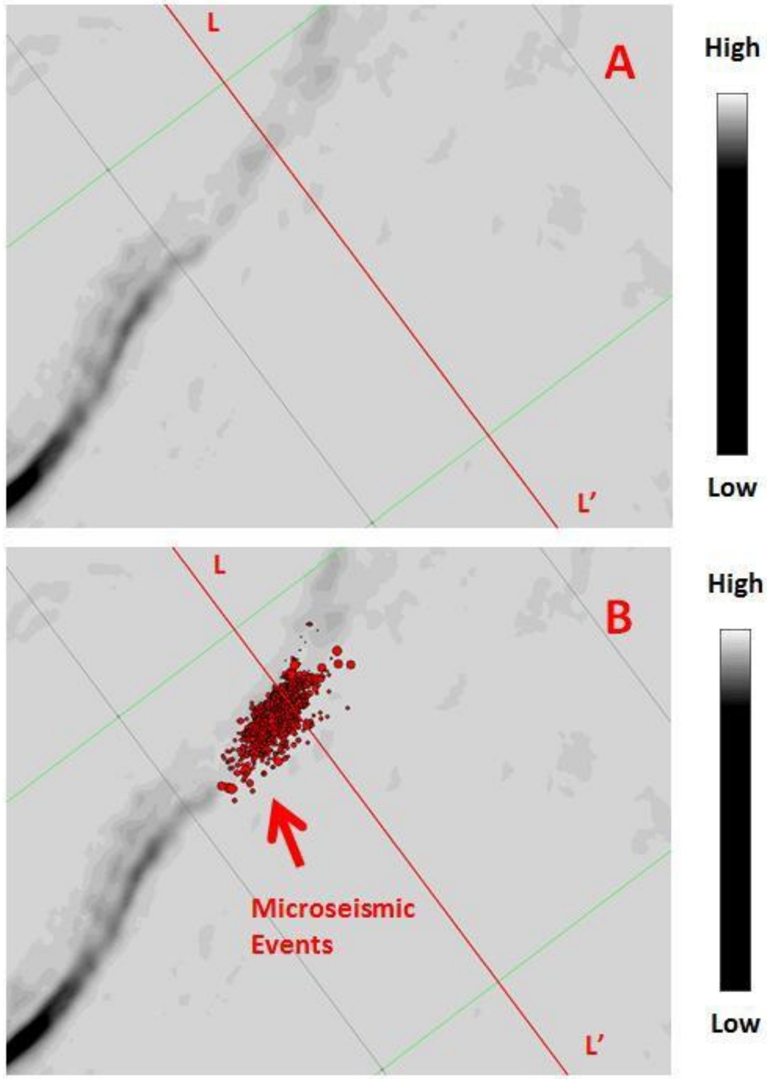

Figure 7. Similarity horizon slice extracted along the stimulated zone of interest monitored for microseismic activity. The original seismic data used as input into the Similarity algorithm is the property of Seitel Inc. Highly similar data are colored in grey shades while areas with low similarity values are tinted black as shown in the figure legend. Microseismic events from the hydraulic stimulation stage believed to have reactivated a fault are aligned very well with a Similarity anomaly that also represents a fault system trace. The treatment well is shown for reference purposes. The red line labeled L-L' represents the direction and length of the vertical seismic section shown in Figure 5.

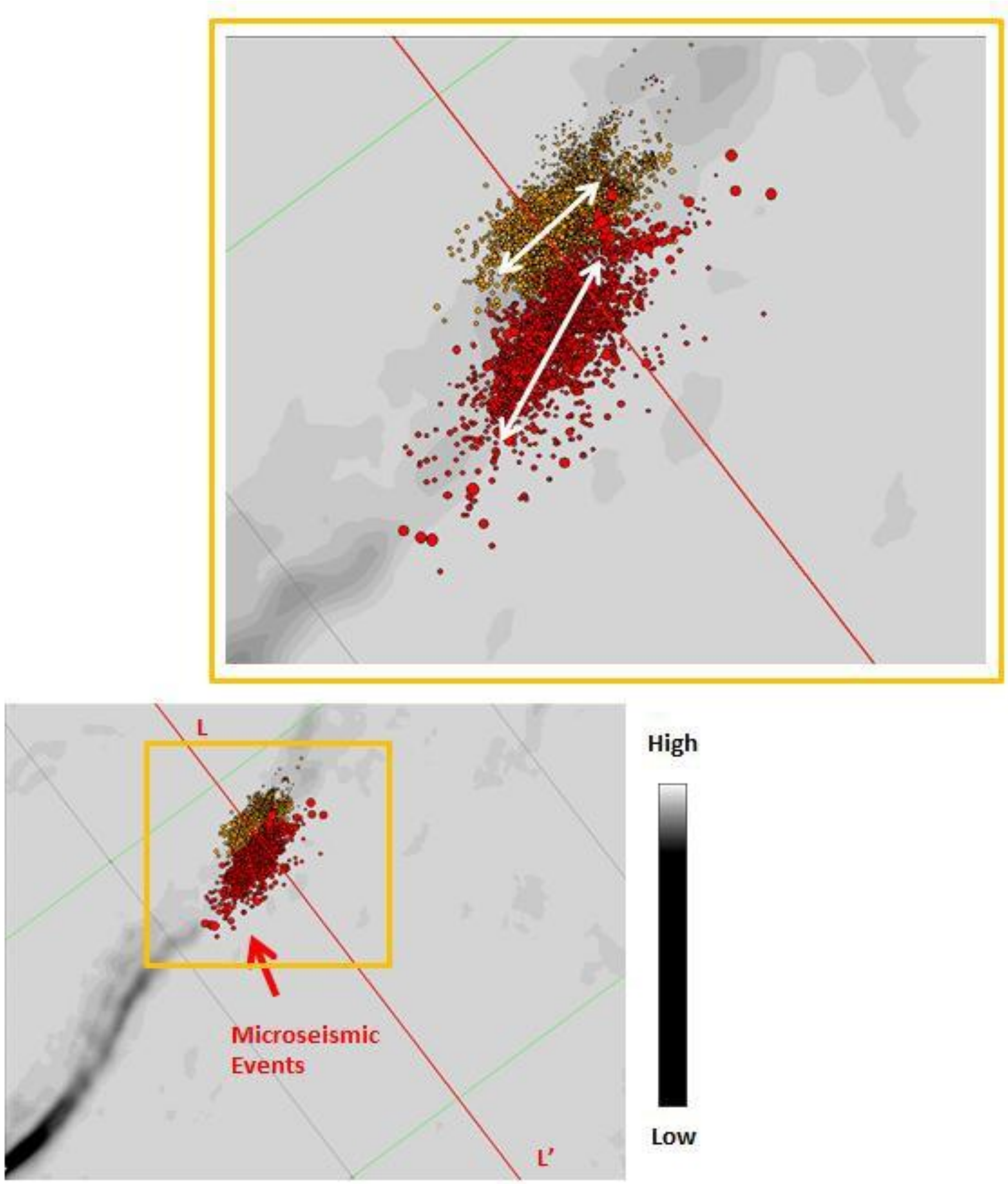

Figure 8. Close-up view of Figure 7 together with the addition of the microseismic events recorded during a subsequent hydraulic fracturing stage. White arrows highlight the associated azimuth interpreted from the microseismic events set associated with each stage.