Predicting flowpaths of hydraulic fracture fluid with curvature data

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Abstract

Many reservoirs throughout the world rely on fractures to connect pores in an otherwise impermeable rock and it is common for engineers to induce or reinforce such fractures for improved well performance using hydraulic fracturing techniques. Under ideal conditions, hydraulic fracturing would affect all parts of the reservoir rock equally, but information derived from micro-seismic monitoring of such treatments suggests that the effects are localized, most likely along naturally occurring fractures. A priori knowledge of the locations of such naturally occurring fractures could lead to significant savings on the design of such treatments, increased efficiency of such treatments, or both. We present a case history in which the flowpaths of the hydraulic fluids follow orientations and locations corresponding to anomalies on maps of most-negative curvature.

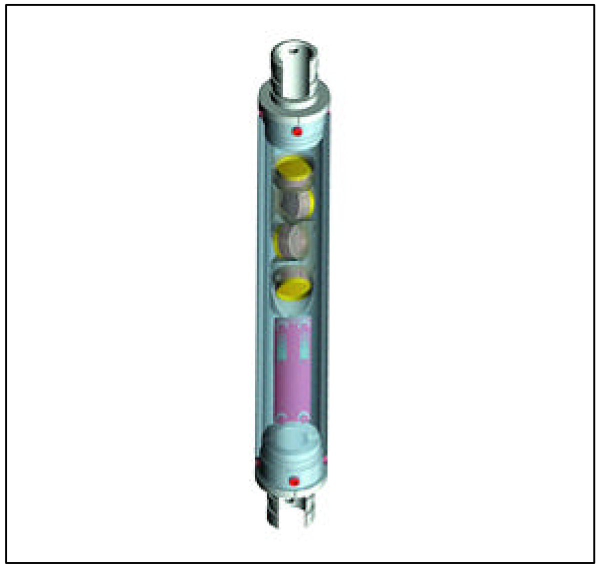

Figure 2: Downhole multicomponent micro-seismic array

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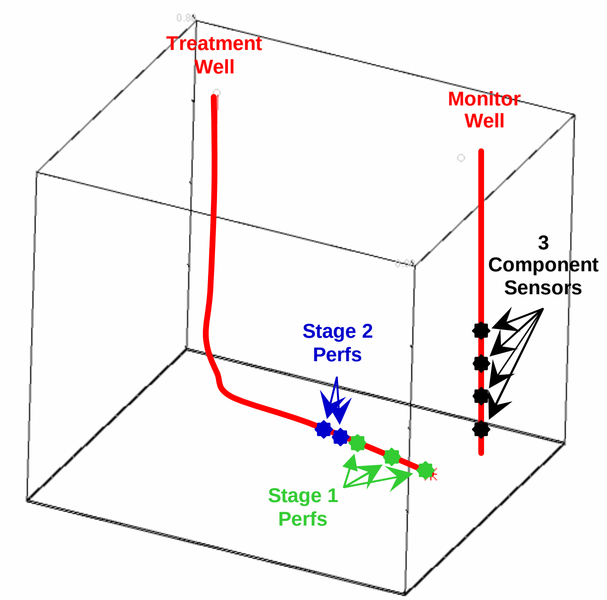

Figure 1: Hydraulic fracturing and micro-seismic monitoring

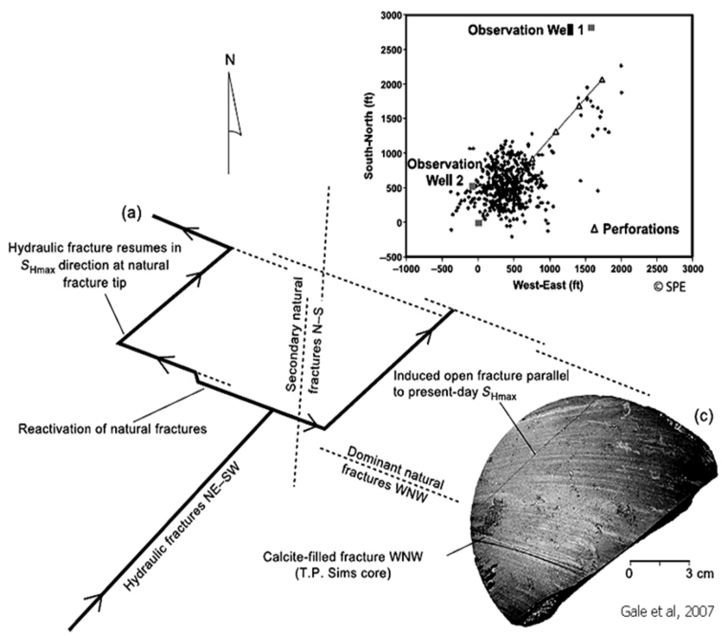

Figure 3: Hydraulic fracture growth paths

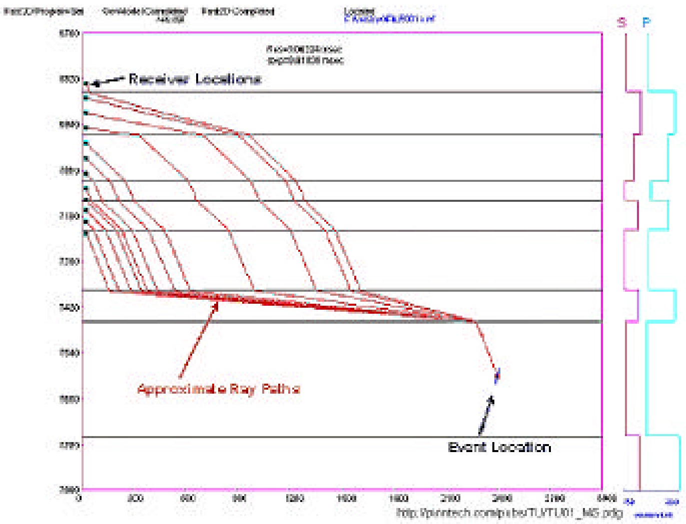

Figure 4: Fracture event location by micro-seismic monitoring.

Hydraulic fracturing

The Barnett shale of the Fort Worth Basin, USA, has produced substantial amounts of natural gas from a porous (4-6%) but impermeable mudstone. Permeability is created by natural and/or induced fractures which connect those pores. Current completion practices consist of drilling long offset horizontal wells (> 1000 m), casing the wellbores, perforating those wellbores, and pumping fluids containing sand grains as propants into the formation in one or more stages (Figure 1). When the pressure in the fluids exceeds the failure strength of the rock, the fluids follow hydraulically induced fractures which initially occur along planes along an orientation parallel to the direction of present day maximum horizontal stress (Figure 3). When such fractures intersect naturally occurring fractures in which the stress to reopen them is less than the failure stress of the rocks, the fluids and fracturing will follow those fractures until stress conditions again result in the opening of new induced fractures.

Micro-seismic monitoring

The occurrences of the fractures created or opened by this process are recorded through an array of three-component geophones (Figure 2) placed in one or more nearby wells to record the small (micro) seismic events which occur when such fractures open (Figure 1). The arrivals on these passive seismograms may then be analyzed to determine the locations of the fractures (Figure 4).

Curvature

In our case, we have compared the results of such a hydraulic fracture treatment as shown by the micro-seismic data to high resolution most-negative curvature computed from a three-dimensional seismic survey which surrounds the treated well and found that the subtle synclines identified correspond closely to the locations of the micro-seismic events. Curvature is a measure of the tightness of folding of a surface and may be either positive (anticlinal) or negative (synclinal). As folding becomes tighter, the magnitude of curvature becomes greater. Figure 5 shows a vertical seismic line intersecting a horizon with the maximum curvature displayed on it. Maximum curvature is an attribute that displays the tightest folding at a point, regardless of orientation or polarity. In this case, positive values are displayed in reds and yellows and negative values in blues and violets. A single, isolated positive trend represents an anticline and a single, isolated negative trend represents a syncline. Parallel trends indicate a flexure or a fault. Curvature values are a function of lateral resolution and higher resolution brings out narrower and more subtle trends (Figure 6).

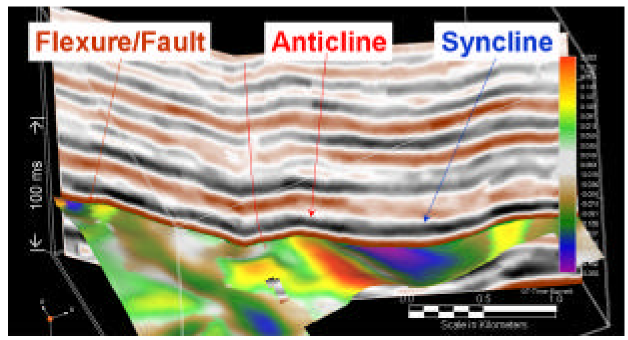

Figure 5: Vertical seismic section and long wavelength maximum curvature

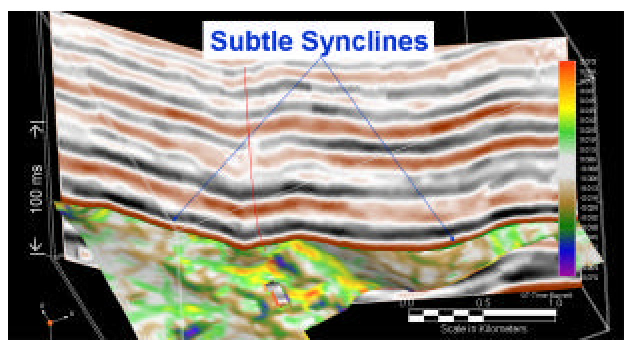

Figure 6: Vertical seismic section and high resolution maximum curvature

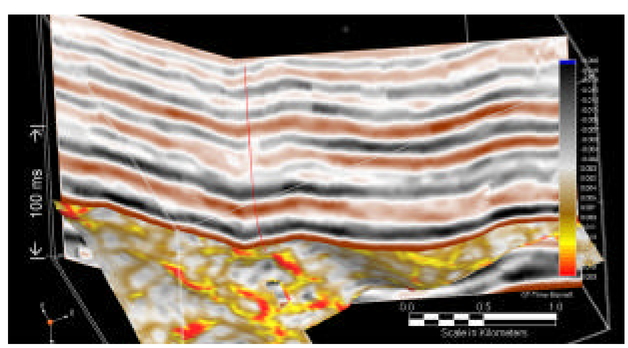

Figure 7: Vertical seismic section and high resolution most negative curvature

Corollaries of the maximum curvature are the most-positive curvature and the most-negative curvature, which highlight anticlines and synclines, respectively. In our case, most-negative curvature (Figure 7) provides the optimum correlation to the locations of fractures caused by hydraulic fracturing and illuminated by micro-seismic events.

Interpretation

In our case, the treatment well was perforated in five locations in anticipation of a two-stage hydraulic fracture operation. The first stage used the three perforations nearer the toe of the well and the second stage used the two perforations nearer the heel of the well (Figure 8).

Figure 9 shows the final results of the Stage 1 treatment. As discussed previously, fractures should open along a direction parallel to the maximum horizontal stress.

It is clear that, in this case, the fractures initially form in a direction parallel to the curvature anomalies (NNE) as indicated in reds and yellows. Additionally, in areas which have no curvature anomalies, shown in gray, there are no fractures occurring. Near the northern edge of the area of fracturing, the bearing of the fractures changes from NNE to the orientation of maximum horizontal stress (NE). The location of this trend corresponds to a weak (brown) curvature anomaly.

Conclusion

Based on these results, analysis of the curvature data could have predicted the likely paths that the hydraulic fracture fluids would follow and would have allowed a redesign of the fracture program that would be more effective and/or less expensive

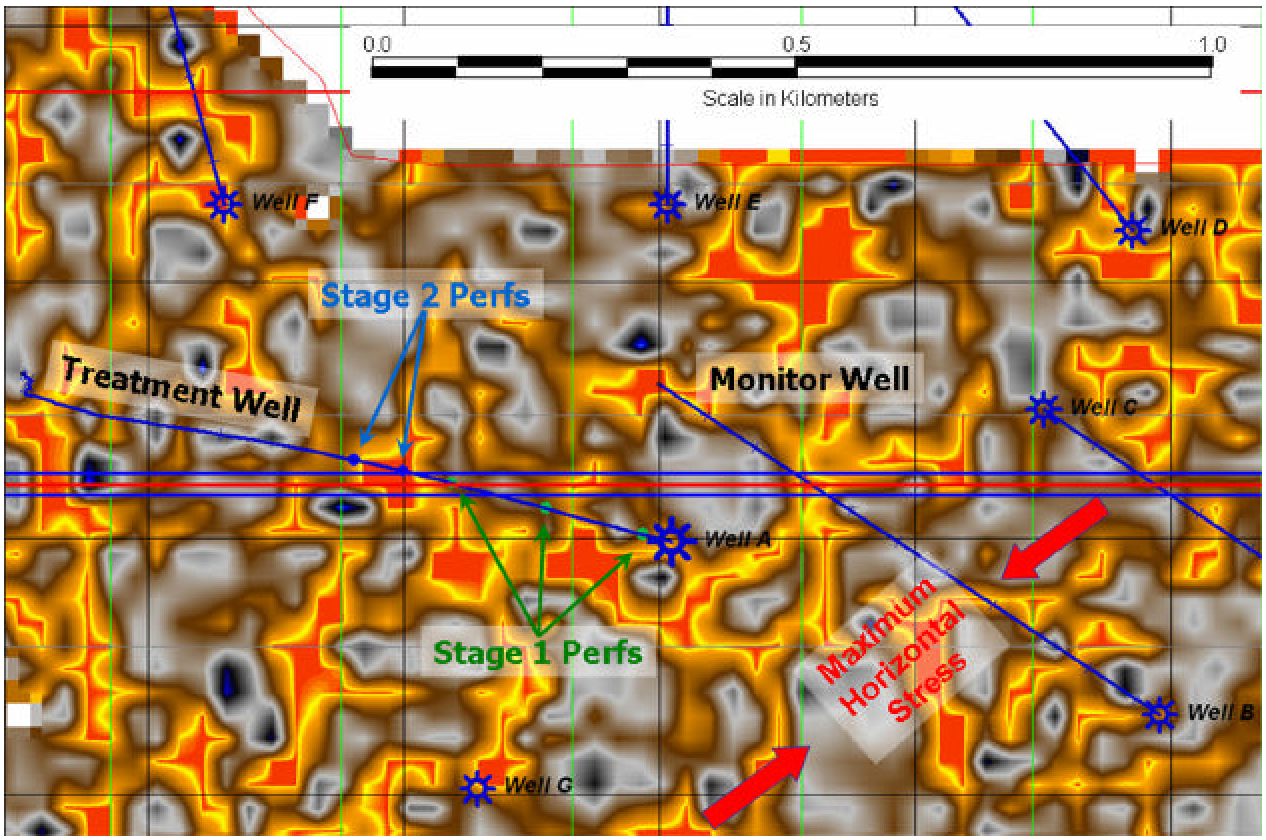

Figure 8: Barnett Shale most-negative curvature/ micro-seismic monitoring key elements

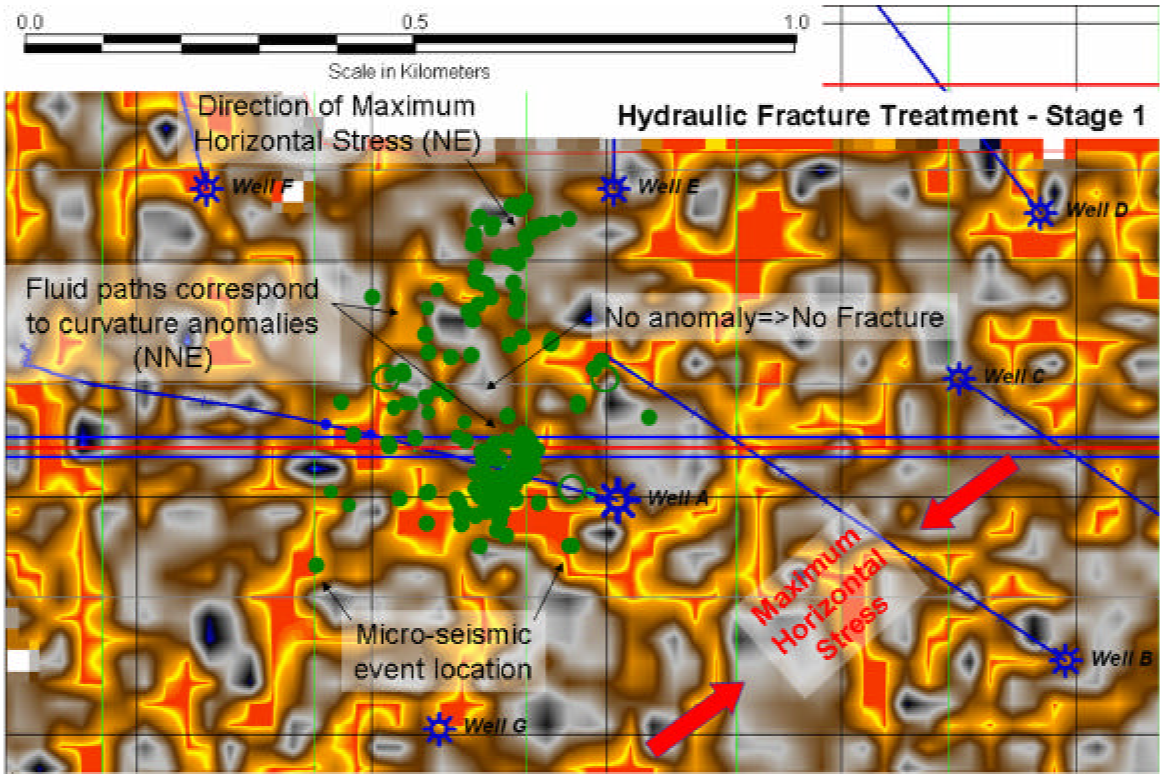

Figure 9: Stage 1 hydraulic fracture results

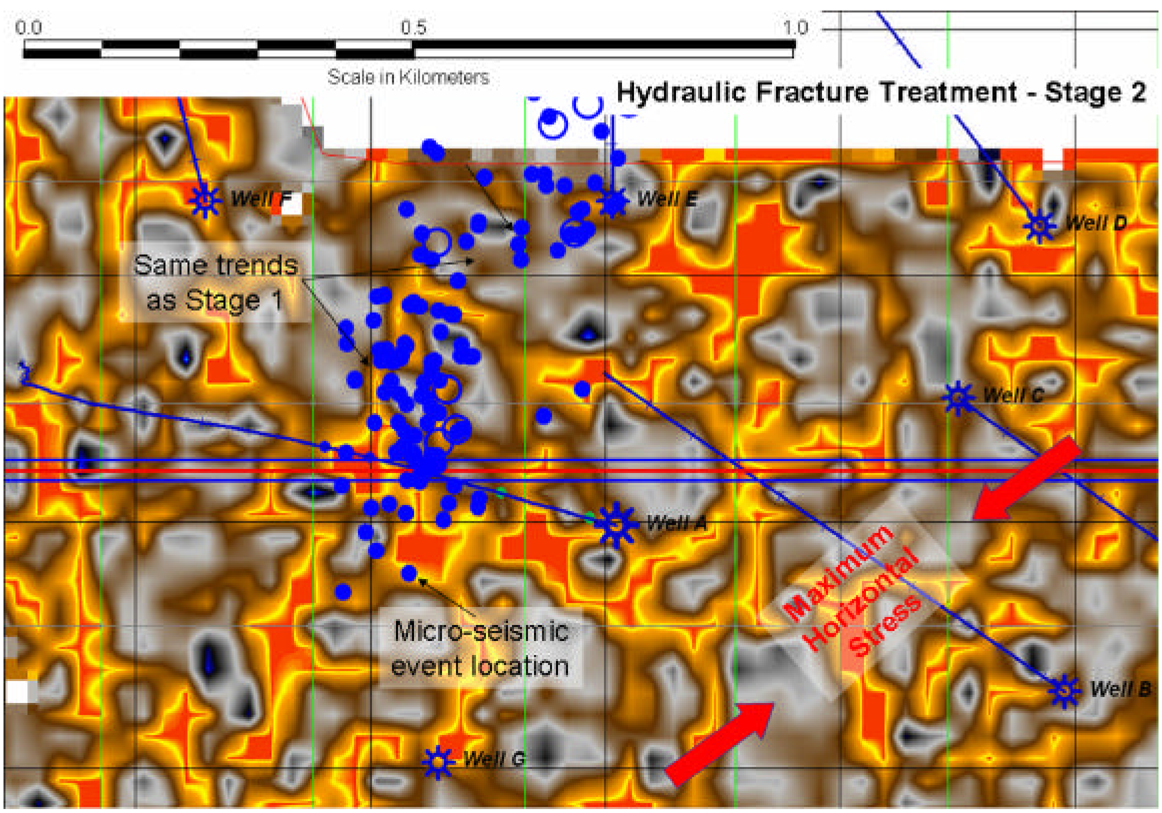

Figure 10: Stage 2 hydraulic fracture results