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Mapping Fracture Flow and Reservoir Stress Compartments with Passive Seismic Imaging

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Abstract

We will present examples of detailed mapping of induced hydraulic fractures, natural fractures stimulated by hydraulic fracturing, and reservoir stress compartments using several complementary passive seismic methods. The passive seismic results are compared and complemented with other data including reflection seismic, chemical tracers, and borehole images. Passive seismic data types utilized are microearthquake (MEQ) hypocenter locations and magnitudes, focal mechanism solutions, and Tomographic Fracture Images® (TFIs). TFIs are direct images of fractures as complex surfaces and networks (Figure 1).

Recent work is showing that MEQs represent only part of the seismic signal produced by hydraulic fracture treatments of unconventional reservoirs. In some (probably most) reservoirs MEQs represent only a small part of the signal. The additional energy in large part occurs as long-lasting, low-frequency phenomena without distinct first arrivals such as Long-Period, Long-Duration (LPLD) activity (Das and Zoback, 2013 a & b), Extended Duration Signals (EDS; Sicking et al, 2014), and perhaps other as-yet-undescribed seismic phenomena. EDS have been observed in surface passive seismic data. EDS likely represent fluid resonance in fractures similar to that described by Tary and van der Baan (2012) in downhole passive seismic data. Water/gas hammering in the induced and natural fracture system is also a likely source of such signals. (Water hammering is the cause of "singing pipes" in household plumbing.) Resonant signals occur at specific frequencies that are controlled by the length of the resonating fractures, path tortuosity, and other characteristics of the flow system. Resonant signals can be focused to reveal their location. Signals derived from fluid resonance have the advantage of directly revealing fracture flow paths.

Conventional MEQ location methods adapted from earthquake seismology cannot be used to image such emissions because they require discrete events with distinct, pickable P- and S-wave arrivals. Instead, we utilize total trace energy to accumulate all detectable coherent seismic activity in each voxel of an imaged volume. The method works as follows. After suppression of coherent noise in the trace data, Seismic Emission Tomography (SET) is used to produce a five-dimensional data volume. The dimensions are the X, Y and Z coordinates of the voxels, the time step (typically on the order of 100 milliseconds) and a measure of seismic activity (typically semblance or covariance). SET is well-established technology that is routinely used for studying tectonic and volcanic tremor and for locating microearthquakes with surface or shallow buried passive seismic arrays. Microearthquake hypocenter locations and relative magnitude and TFIs are computed from

the SET data volume via different workflows. Focal mechanism solutions are determined from the field data using polarities of strong microearthquakes.

TFI is an extension of SET. TFIs are computed by summing individual SET time steps over extended periods of time, such as the pumping time of a frac stage (Figure 1). Summation enhances spatially-stable signal and suppresses random noise. The data is then clipped to remove low-amplitude false structures. The remaining clouds are regions of high-cumulative seismic activity. Different processing flows can be used to image the most intensely active features directly connected to the wellbore, or all active feature throughout the imaged volume. Rock mechanics theory, laboratory experiments, and field studies show that large fractures are embedded in clouds of smaller fractures and acoustic emissions that become exponentially more intense near the main fracture surface. TFIs are produced by finding the highest-activity surfaces within the clouds which represent the main fracture surfaces for the aforementioned reasons. The precision and accuracy of the results have been checked repeatedly in a number of basins by various methods including PSDM reflection seismic data and seismic attribute data, chemical frac tracers, radioactive frac tracers, geochemistry, and borehole images.

The original raster TFIs can be converted to vector images - tessellated surfaces. Figure 1 is an example of a tessellated TFI. (A *tessellated surface* is a continuous surface composed of triangles that share common edges and vertices.)   The tessellated representations have numerous advantages including visualization, orientation statistics, reservoir stress interpretation, and Discrete Fracture Network (DFN) reservoir simulation (Lacazette et al, 2014).

The orientation and area of each triangle of a tessellated TFI can be computed so that area-weighted orientation statistics for the active fracture surfaces can be generated for both the induced fractures connected to the wellbore and the natural fracture network at the reservoir-scale. The orientation statistics are directly useful for determining the orientation(s) of reservoir flow paths, distinguishing auxiliary nodal planes from fault planes of focal mechanism solutions, and for calibrating stochastic DFN models. Also, auxiliary nodal planes are distinguished directly from fault planes when focal mechanism solutions coincide with images of active faults. The relative magnitude of seismic activity as a function of triangle orientation may also yield reservoir stress information. Tessellated TFIs can be incorporated directly into DFN hydrofrac and reservoir simulations as discrete features (Lacazette et al, 2014).

We will present examples of integrating TFI with MEQ locations and relative magnitudes, and with focal mechanism solutions to map reservoir stress compartments and study fault reactivation during hydrofracture treatment. We find cases in tectonically active environments where reservoir stress compartments exist at the scale of infill drilling. In these cases, adjacent wells can encounter radically different stress states and natural fracture abundances, with obvious implications for drilling and hydraulic fracture engineering.

Images of reactivated faults and clusters of hydraulically-conductive fractures reveal the paths and locations of frac diversion and frac hits on adjacent wells. Such features are imaged during fracing of the first well on a pad or development area. Early detection allows adjustment of frac programs and even development plans to better utilize or mitigate the effects of pre-existing natural fracture flow networks.

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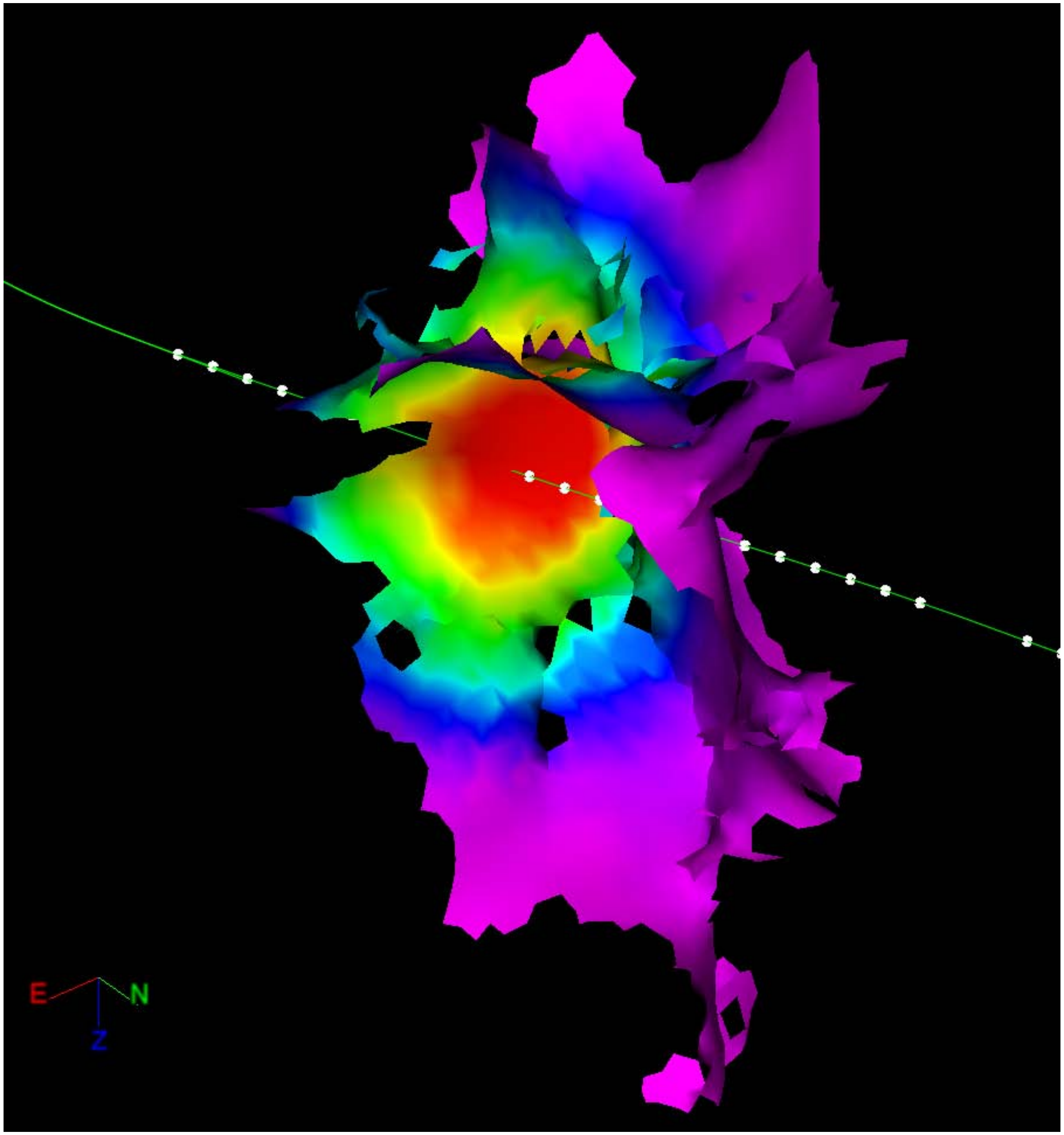

FIGURE 1. Near-well Tomographic Fracture Image of a hydraulic fracture stage in the Eagle Ford Fm., Texas. Color indicates intensity of cumulative seismic activity from red (high) to violet (low). Note that the fracture complexity increases and the activity decreases as the frac quenches in the natural fracture system.