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The Signature of Shearing Driven by Hydraulic Opening

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Abstract

Hydraulic-fracture microseismicity sometimes exhibits fairly uniform source mechanisms along the event cloud lengths. In layered rock, the uniform mechanisms are either dip-slip or strike-slip mechanisms or a mix of both. When combined with precise source locations, the patterns of mechanisms and locations sometimes reveal the following common characteristics: 1) the event locations outline simple linear or planar geometry and form distinct horizontal bands in depth separated by aseismic intervals, 2) the mechanisms are primarily shear, 3) one nodal plane is aligned close (<10°) to the hydraulic fracture and principal stress direction, and 4) opposite sense of motion is often observed, but not always, on the similarly aligned nodal planes. We present a number of examples of these observations from reservoirs of different rock types and varying stress regimes (e.g., Figures 1 and 2).

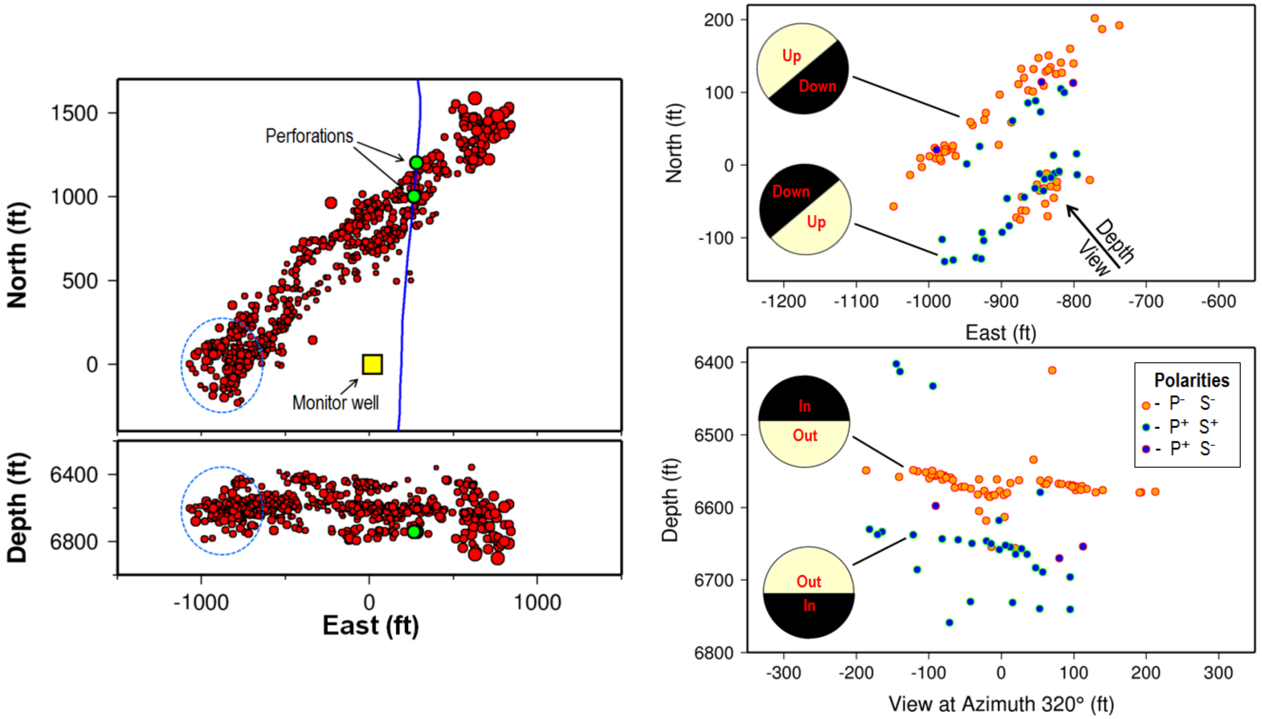

Figure 1. (left) A single stage from a Barnett-shale, horizontal-well completion. Event symbol size is proportional to magnitude. (right) The subset of events circled in plan and depth views at left, re-mapped after obtaining correlated, precise arrival times. Colors orange and blue distinguish two dip-slip mechanism families that largely separate in depth. The mechanism families were identified based on patterns of amplitude ratios and polarity reversals of P, SH and SV phases (Rutledge et al., 2013). The focal mechanism projections in plan view (right top) and viewing across strike (right bottom) indicate the first-motion quadrants. We interpret the horizontal nodal planes as the failure planes representing bedding-plane slip, of opposite sense, largely following continuous bedding surfaces.

These cases of shearing occurring preferentially on planes aligned close to the principal stress direction and the associated simple geometry of source locations suggest the microseismicity is closely associated with the hydraulic fracture. That is, the observed shearing is associated with the near-field stress/strain conditions of fracture opening, and is not, for example, a secondary effect of shearing on natural-fracture networks that reflects tectonic stress release through leak off and far-field pore pressure coupling. Further, the distinct depth bands revealed by the precise locations suggest the microseismic signal generation is controlled by the mechanical stratigraphy.

Based on the analog of natural tensile joint structures observed in layered rock, we associate the aligned strike-slip and dip-slip mechanisms with fringe crack breakup and bedding-plane slip on step-over features, respectively. Dip-slip mechanisms are common in shale stimulations (e.g., Figure 1). Considering the alternate, horizontal nodal plane as the fault plane, dip-slip events have been interpreted as bedding-plane slip accommodating the strain of vertical hydraulic fracture opening (Rutledge et al, 2013; Stanek and Eisner, 2013). Modeling studies of bedding-plane slip and the formation of jogs or step-overs of a tensile fracture along bedding suggest that the fracture growth is controlled by crack tip stresses and the mechanical properties of the layer interfaces (e.g., Helgeson and Aydin, 1991; Cooke and Underwood, 2001).

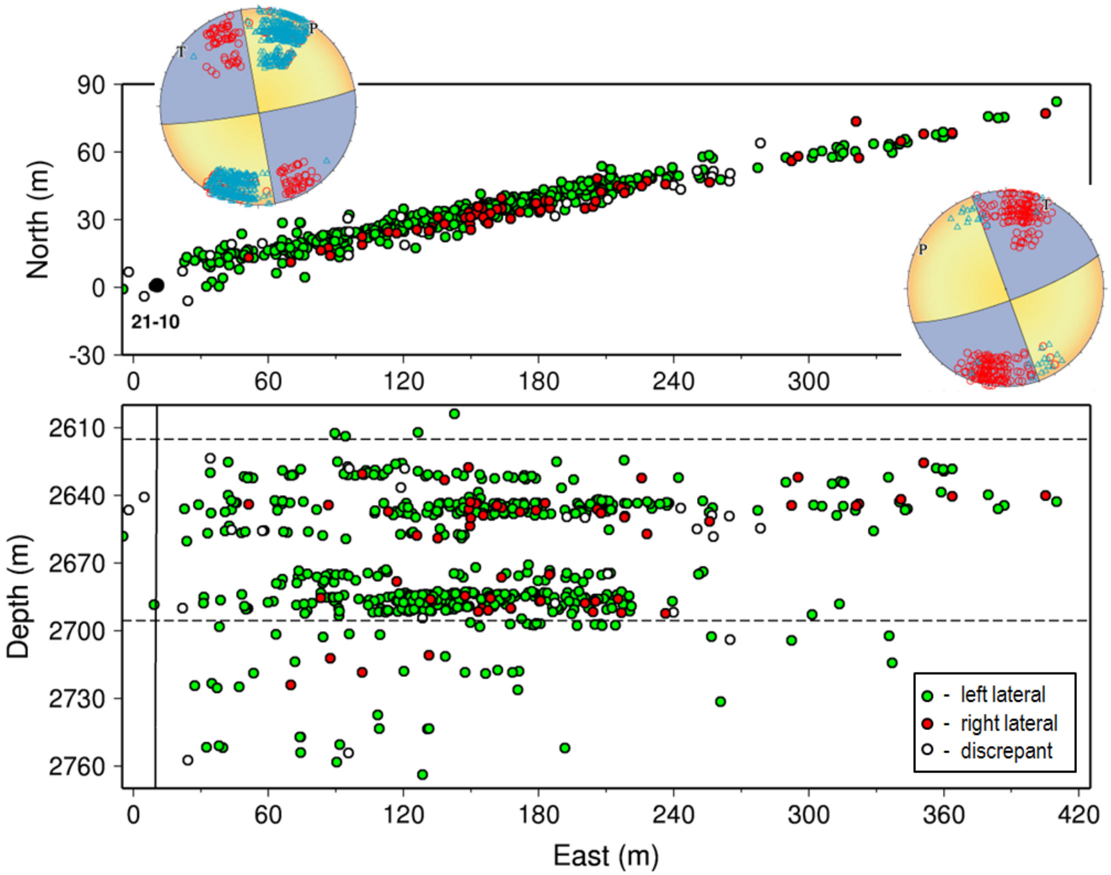

Figure 2. An example of precise source locations for a Cotton Valley tight-sands completion stage in well 21-10 and the composite fault plane solutions showing two families of strike-slip events with opposite sense of shearing on nodal planes aligned within 10° of the event trend and the direction of maximum horizontal stress (Rutledge and Phillips, 2003).

The observation of strike-slip events aligned in horizontal bands could be similarly associated with tensile joint behavior at layer interfaces. The alignment of strike-slip events is common in more heterogeneous layered reservoirs such as tight-sand resources where gas is produced from sequences of low-permeability sands interbedded with shales (e.g., Figure 2). Natural joint structures in sedimentary sections often form fringe cracks near layer boundaries where the parent tensile crack breaks up into a set of en echelon cracks or twist hackles (Figure 3) (Simón et al, 2006). As the crack tip line approaches a bedding plane, the stresses can be rotated locally about an axis perpendicular to bedding (Pollard et al., 1982). The tensile parent fracture cannot re-orient in the local stress field resulting in the twisting and breakup of the joint into the echelon fringe cracks. Breakup is initiated by a strike-slip shearing parallel to the crack line near the bedding interface, representing a tearing mode (mode III) deformation (Younes and Engelder, 1999). Assuming these same structures are created by injection-driven hydraulic fractures, the aligned bands of strike-slip events would represent the breakup. To generate a microseismic signal, this interpretation would require that the shearing accompanying breakup is critical, occurring at rupture velocities approaching the rock shear velocity, and thereby represents a destabilization of the largely slow, aseismic tensile growth of the parent fracture. From common magnitude scaling relationships, and for typical monitoring geometry, downhole detection of microseismic signals is limited to source lengths of about 1 m. Thus, for signal detection, the proposed interpretation also requires that crack-line breakup occurs at similar or greater length scales.

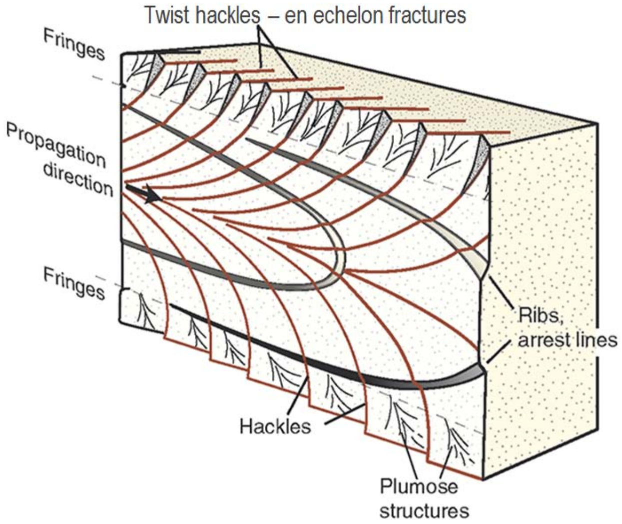

Figure 3. Schematic features of plumose joint structures with en echelon fringe cracks.

Both Roche and Van Der Baan (2013) and Langenbruch and Shapiro (2014) have shown that elastic heterogeneity associated with stratigraphy can explain the banding of events for the case of the Cotton Valley formation (Figure 2) in terms of variations of differential stress and brittleness indices. The association of echelon fringe zones and bedding surfaces in nature implies that the variation of mechanical properties can also include a local stress rotation, or control a temporal rotation as the crack tip line interacts with the strength/stress discontinuity (Pollard et al., 1982). Our interpretation of microseismicity generated by bedding plane slip and fringe fracture breakup may provide a general model for describing the prevalent alignment of shear planes with principal stress. In this sense the microseismicity provides a direct picture of tensile fracture growth through a reservoir, highlighting the deformation at and near bedding boundaries as the hydraulic fracture rips through or along layer interfaces. Understanding these processes is important in imaging the reservoir accessed and drained by injection stimulation.

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