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Microseismic Monitoring of Fracture Networks During Hydraulic Stimulation: Beyond Event Locations

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Abstract

The successful exploitation of tight-gas reservoirs requires fracture networks, sometimes naturally occurring, often hydraulically stimulated. Borehole microseismic data acquired in such environments hold great promise for characterising such fractures or sweet spots. The loci of seismic events delineate active faults and reveal fracture development in response to stimulation. However, a great deal more can be extracted from these microseismic data. For example, inversions of shear-wave splitting data provide a robust means of mapping fracture densities and preferred orientations, useful information for drilling programs. They can also be used to track temporal variations in fracture compliances, which are indicative of fluid flow and enhanced permeability in response to stimulation. Furthermore, the frequency-dependent nature of shear-wave splitting is very sensitive to size of fractures and their fluid-fill composition. Here we demonstrate the feasibility of using such analysis of shear-wave splitting measurements on data acquired during hydraulic stimulation of a tight-gas sandstone in the Cotton Valley field in Carthage, West Texas.

Introduction

The passive monitoring of microseismic events provides a cheap and effective means for monitoring spatial and temporal variations in reservoir properties. These microearthquakes occur naturally due to regional tectonic stresses, but can be also induced through exploitation activities such as hydraulic stimulation, enhanced petroleum recovery and fluid extraction. Such monitoring offers insights into the dynamic state of stress in a reservoir - invaluable information for developing effective strategies for drilling, injection and production programs.

Microseismic data acquired from passive seismic monitoring of petroleum fields are ideally suited to the study of seismic anisotropy. Unlike conventional reflection seismology, raypaths are not generally sub-vertical and hence directional variations in velocity are more easily assessed. Perhaps the most unambiguous indicator of anisotropy is shear-wave splitting (Silver and Chan, 1991; Teanby et al., 2004a; Wuestefeld et al., 2010). Shear-wave splitting measurements can be used to assess fracture properties, which are sensitive to spatial and temporal variations in the stress field (e.g., Teanby et al., 2004b; Al-Harrasi et al., 2010). Microseismic data are generally rich in frequency content so there is also much potential to look at frequency-dependent wave phenomena. It has been shown that frequency-dependent shear-wave splitting is sensitive to crack size, aspect ratio, and fluid properties (Chapman, 2003; Al-Harrasi et al., 2011). Cumulatively, shear-wave splitting is sensitive to a range of crack or fracture parameters and is a potentially valuable tool for reservoir management and exploitation.

Here we show how shear-wave splitting measurements made on microseismic monitoring data can be used as a tool for fracture characterization in tight-gas reservoirs (TGR). While such monitoring is common during hydraulic fracture stimulation, processors seldom do anything more than locate events. Such data are ideally suited to measuring fracture-induced anisotropy, both in naturally occurring 'sweet spots' and fractures resulting from stimulation. Such measurements are relatively rare, but the emerging picture is one of fracture-induced anisotropy where a number of factors control both spatial and temporal variations (e.g., Teanby et al., 2004b; de Meersman et al., 2009; Verdon et al., 2010a; Wuestefeld et al., 2011). Here we will develop a work flow and demonstrate its application to real data from a TGR in Carthage Texas: the Cotton Valley field (Rutledge and Phillips, 2003).

Seismic anisotropy and shear-wave splitting

Studies of anisotropy are useful as they provide insights into lithologic fabric and the alignment of grain boundaries, pores, cracks and fractures. For example, anisotropy due to mica alignment will be sensitive to in the degree of compaction in shales (Vernik and Liu, 1997; Caddick, et al., 1998; Valcke, et al., 2006), which can be useful in assessing shale gas and cap rock sealing properties. The preferred orientation of cracks, fractures and joint-sets will also lead to anisotropy (Thomsen, 1995; Hall and Kendall, 2003). P-waves propagate faster parallel to the fractures than along the fracture normals, and are hence sensitive to permeability anisotropy. In general, anisotropy results from a superposition of various effects. Indeed one of the difficulties in its interpretation is discriminating between competing mechanisms (Kendall et al., 2007).

Perhaps the easiest way of detecting anisotropy using microseismic data is through evidence of shear-wave splitting (Figure 1). Two orthogonally polarised and independently travelling shear waves will propagate in anisotropic media. The delay time between the fast and slow shear-waves ($\delta\tau$) is proportional to the magnitude of the anisotropy, and the ray-path length through the anisotropic region. The polarisation of the fast (ϕ) and slow shear-waves are indicators of the anisotropic symmetry of the medium. Measurements of these two splitting parameters ($\delta\tau$ and ϕ), coupled with observations for a range of propagation directions can be used to characterise the anisotropy. One of the advantages of using microseismic data to study anisotropy is that the sources are often well distributed around the receivers.

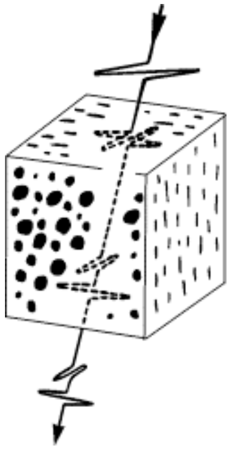

Figure 1: A shear wave entering an anisotropic medium (in this case caused by aligned vertical fractures) will be split into two orthogonally polarized shear waves. The delay time (δt) between the two shear waves is proportional to the magnitude of the anisotropy and its extent. The polarization of the fast shear wave (ϕ) is an indicator of the symmetry and style of anisotropy.

Passive seismic monitoring of a reservoir will routinely record many 1000s of events and manual analysis of shear-wave splitting is therefore impractical. Teanby et al. (2004a) and Wuestefeld et al. (2011) have developed a semi-automated workflow for estimated shear-wave splitting using S-wave travel-time picks and a cluster analysis to assess the robustness of the solutions.

Evidence of shear-wave splitting in microseismic datasets has been documented in a number of reservoirs. These include: North Sea chalk reservoirs (Valhall (Teanby et al., 2004b) and Ekofisk (Jones et al., in prep, 2012)); carbonate reservoirs in west-central Oman (Al-Anboori and Kendall, 2010; Al-Harrasi et al., 2010) and southern Saskatchewan (Weyburn) (Verdon et al., 2010b; 2011a); and siliciclastic reservoir of Cotton Valley in Carthage, Texas (Wuestefeld et al., 2012).

Fracture inversion

Observations of shear-wave splitting are sensitive to fracture sets and as such can be inverted for fracture parameters. However, the challenge lies in separating fracture effects from other anisotropy effects. In Verdon et al. (2009) we outline an inversion approach that uses rock physics modelling to select the best-fit fracture geometries and sedimentary fabrics to match shear-wave splitting observations. The approach has been demonstrated using a passive seismic dataset collected during hydraulic fracture stimulation (Verdon et al., 2010a). Tests with synthetic data show that the success of these inversions is highly dependent on the range of arrival azimuths and inclinations that are available. It is therefore possible to determine in advance which structures are detectable with shear-wave splitting, and which are not. With such an approach to survey design it is also possible to identify potential trade-offs between parameters than can affect the accuracy of such inversions.

Verdon and Kendall (2011) generalize the inversion to detect the presence of two fracture sets. With one dataset, their analysis reveals a set of conjugate fractures that allow CO2 migration through carbonate reservoir. A second dataset reveals a single fracture set that is stimulated through hydraulic injection.

Temporal variations in shear-wave splitting have been observed in a number of datasets, including those acquired in volcanic settings (Gerst and Savage, 2004), mining settings (Wuestefeld et al., 2011), producing oil reservoirs (Teanby et al., 2004b), and during hydraulic stimulation of tight-gas reservoirs (Wuestefeld et al., 2012). The magnitude of the splitting generally rises as the fracture density increases. These measurements are very sensitive to changes in the normal compliances of fractures, and hence the ratio of normal to tangential compliance (B_N/B_T). This can lead to a rotation in the polarization of the fast shear-wave (e.g., Gerst and Savage, 2004), a less intuitive effect. As fluid ingresses into the formation, the permeability increases as fractures interconnect, leading to a rise in the B_N/B_T ratio. Figure 2 shows these effects as changes in the P-wave anisotropy and shear-wave splitting.

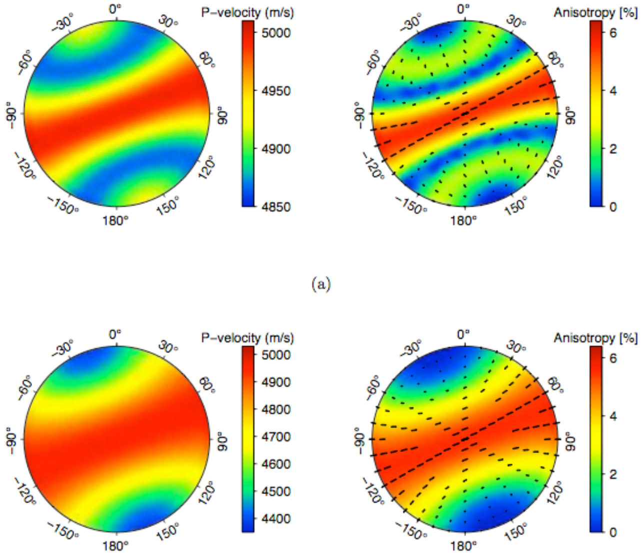

Figure 2. LHS – P-wave velocity plotted on an upper-hemisphere projection. Vertically propagating P-waves plot at the center and horizontally propagating P-waves plot around the edge. RHS – the magnitude of shear-wave splitting (δt) as a function of direction, again plotted on an upper-hemisphere projection. The black ticks show the polarization of the fast or leading shear-wave (ϕ). The top two hemispheres are for a model where the B_N/B_T ratio is 0.1 and represents the case of isolated cracks or fractures. The lower two hemispheres are for a model where $B_N/B_T=0.9$ and represents the case of connected cracks/fractures (e.g., improved permeability). Changes in B_N/B_T can lead to significant changes in the style and magnitude of anisotropy in a given direction.

Frequency-dependent shear-wave splitting

In a similar way, observations of frequency dependent anisotropy can be used to invert for fracture size, density and orientation. In the past, we have successfully applied such an inversion to a dataset from a carbonate reservoir (Al-Anboori and Kendall, 2010; Al-Harrasi et al., 2011). Our results show large meter-scale fractures in the gas-producing reservoir and micrometer scale cracks in the sealing shale. These results agree with independent measures of crack/fracture size in this reservoir. Such analysis is ideally suited to detecting 'sweet spots' in TGRs and monitoring fracture stimulation.

In many reservoirs fracture orientation, density, size and connectivity control reservoir production. Studies of source mechanisms and shear-wave splitting provide insights into fracture orientation and density, but offer little information about fracture size and connectivity. Recent work by Chapman and co-workers (e.g., Chapman, 2003; Maultzsch et al., 2003) has shown that the frequency dependence of shear-wave splitting can be very sensitive to these parameters. At low seismic frequencies a material with aligned inclusions will behave like a homogeneous anisotropic medium, but at higher frequencies the inclusions will behave as discreet scatterers. Poroelastic effects are more subtle. For example, aligned fluid filled fractures in a porous medium will exhibit frequency-dependent anisotropy. At high frequencies, the inclusions will be isolated and the effective anisotropy will be smaller, whereas at low frequencies, the inclusions are effectively interconnected and the anisotropy will be larger.

Microseismic data are typically rich in frequency content, making it ideal for studies of frequency-dependent wave phenomena. The frequency content in datasets is somewhat variable with depth and lithology, but is generally between 10-400Hz. The analysis of frequency-dependent shear-wave splitting has been described in Al-Harrasi et al. (2011). The data are filtered with a one-octave passband (i.e., a constant ratio of high to low frequencies of 2). The splitting parameters are then estimated for each frequency-band. The results presented in Al-Harrasi et al. (2011) reveal a lithology dependent variability in the nature of frequency-dependent splitting.

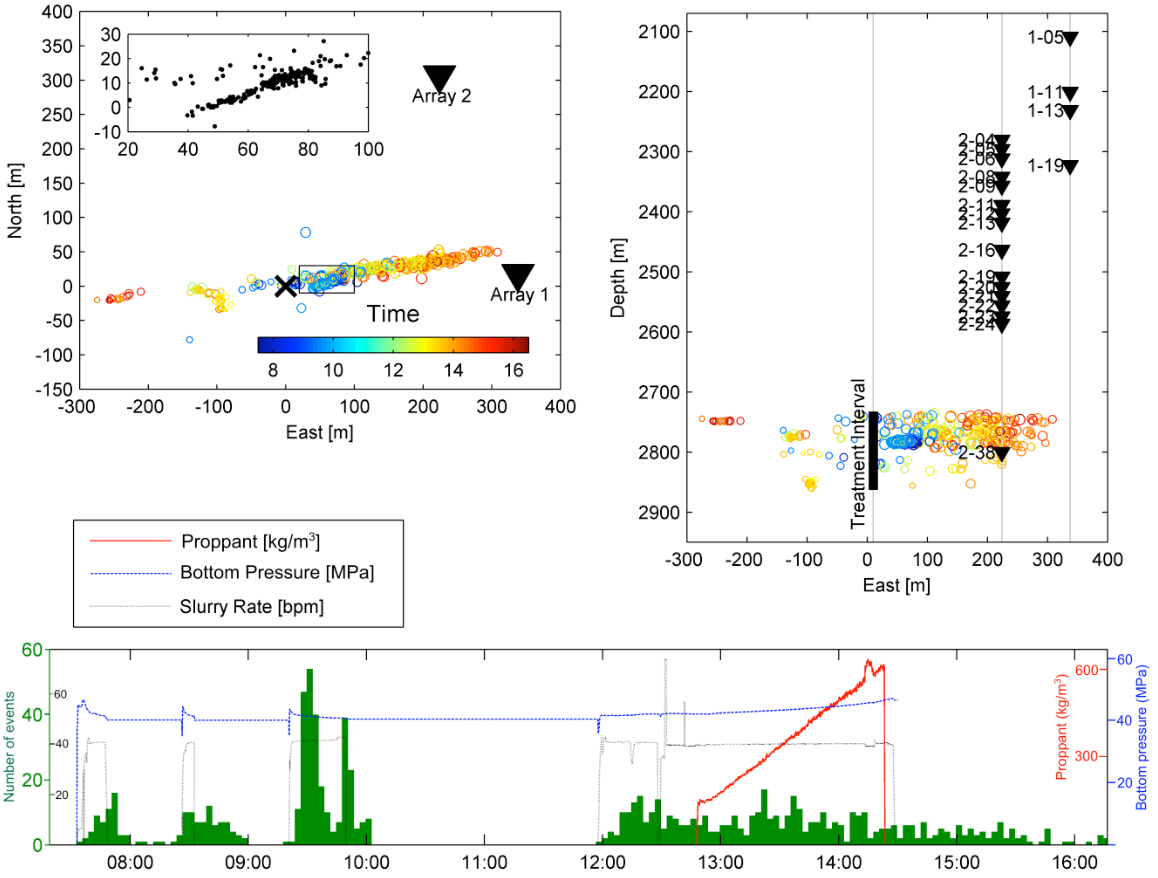

Figure 3. The top panel shows the evolution of seismicity in a roughly 9-hour time period during stimulation. The treatment interval is shown in map view (LHS) by the black ‘x’ and in depth (RHS) by the black vertical bar. Sensors are deployed in two arrays and are marked by black inverted triangles. The lower panel shows cumulated proppant density (red), slurry rate (grey) and pumping pressure (blue) during stimulation. The green histogram shows seismicity in 3 minute bins.

The Cotton Valley Dataset

The Cotton Valley formation consists of silicastic sandstones with intermittent shale and carbonates horizons over a total thickness of approximately 325m (Rutledge and Phillips, 2003). The reservoir is typical of low-permeability gas resources that require hydraulic fracture stimulation for economic production. The current understanding of the fracture process assumes that tensile opening dominates at the fracture tip, while shear failure occurs simultaneously along the entire fault length (e.g. Rutledge et al., 2004). In another deep hydraulic fracturing experiment, Ake et al. (2005) found that 89% of the events were strike-slip, while the remaining events where roughly equally divided between normal and thrust faulting events. More recent studies have found evidence for a non-double-couple component in event mechanisms associated with hydraulic fracturing (e.g., Sileny et al, 2009).

Figure 3 shows the recording geometry of the monitoring array and the seismicity recorded over a 9-hour period during stimulation. The bulk of the seismicity trends along an azimuth of 80^{o} from North, but the inset in the top left frame shows a secondary cluster trending with an azimuth of 65^{o} from North.

Our shear-wave splitting workflow (Figure 4) has been applied to microseismic monitoring data recorded in the Cotton-Valley field. As such datasets are rather large, the bulk of the analysis must be automated. Our ultimate aim is near-real time characterization of fractures. Each component of the analysis has been demonstrated in isolation, but never linked in a coherent workflow.

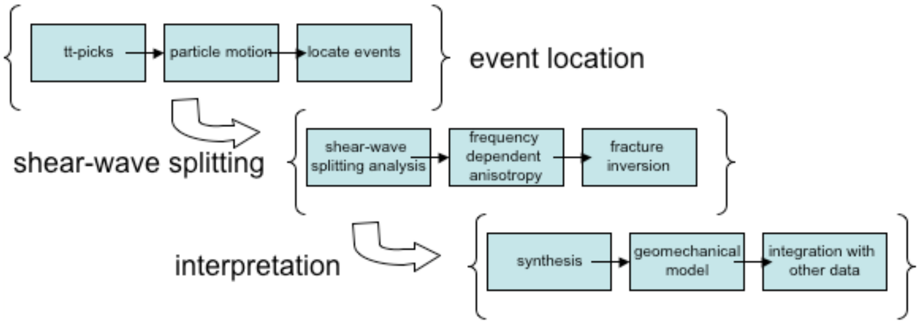

Figure 4: A suggested workflow for the analysis of microseismic data acquired during the monitoring of hydraulic stimulation. The first step in the analysis is event locations. Various location algorithms exploit the array-properties of downhole recordings on sensor strings (cf., Jones et al., 2010). The second step involves shear-wave splitting measurements and their inversion for fracture parameters. Cumulatively, this approach will lead to insights into the spatial and temporal variations in the distribution of fracture corridors in tight gas reservoirs, and provides valuable constraints on plausible geomechanical models that can be integrated into other datasets.

Results

We have analyzed shear-wave splitting in over 16,000 seismograms recorded by the Cotton-Valley array using the automated method of Wuestefeld et al. (2010). The results are inverted for fracture parameters using the methodology of Verdon et al. (2009). This method finds the rock physics model that best fits the data by inverting for fracture parameters (strike and density) and Thomsen's anisotropy parameters γ and δ (Thomsen, 1986). We note that δ is unconstrained and that we cannot estimate ε using shear-waves. The γ term is a measure of the background shear-wave anisotropy caused by sedimentary fabric. We assume an orthorhombic anisotropy model, with a single set of vertical cracks in an anisotropic rock matrix of sedimentary layers. The inversion gives a dominant crack strike of N68E, an average crack density of 0.024, and a γ of 0.12. For further detail, see Wuestefeld et al. (2012).

However, closer inspection of the results reveals clear temporal variations (Figure 5), which initially correlate with the cyclical rise and fall in seismicity. However, the biggest changes occur during the injection of slurry and proppant in the final 4 hours of monitoring. The fracture density rises from <0.02 to 0.04. More recent work by Verdon and Wuestefeld (submitted, 2012) invert these measurements for B_N/B_T ratios and find a clear linear trend in the B_N/B_T ratio, which varies from ~0.5 to ~1.5 as the proppant is injected into the formation during the final five hours of monitoring. In the early parts of the stimulation the strike parallels that of the main frac. But as injection continues the inverted fracture strike rotates to nearer N65E, presumably as new fractures develop.

Laubach (1988) found two distinct fracture trends in this area: one set of natural and coring induced cracks with a mean strike of N83E, and a second set of natural cracks that strikes between N65E and N74ºE. The interplay between these two sets of natural fractures may lead to fracturing as a series of tensile and shear failures in en-echelon ruptures.

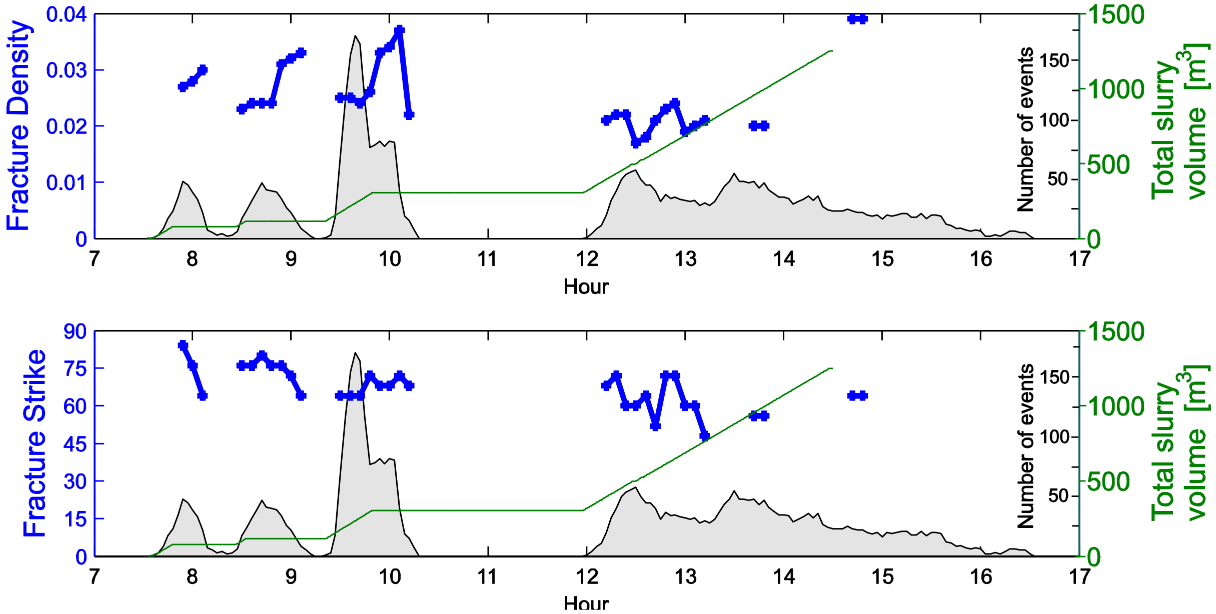

Figure 5. Temporal variations in fracture density (top) and strike (bottom), as inferred from shear-wave splitting measurements (shown in blue). Seismicity during each time window used in the inversion is marked in grey and the cumulative injected slurry is marked in green.

The data show clear frequency dependent effects (see Figure 6), the analysis of which are on going. The aim is to invert these observations for fracture size, as per Al-Harrasi et al. (2011). The challenge with the Cotton-Valley data is to decouple effects of increasing fracture density and permeability from fracture size. Preliminary estimates suggest fractures on the order of 10 of cms to meters in size, but this is very dependent on the assumed relaxation time for the fluid.

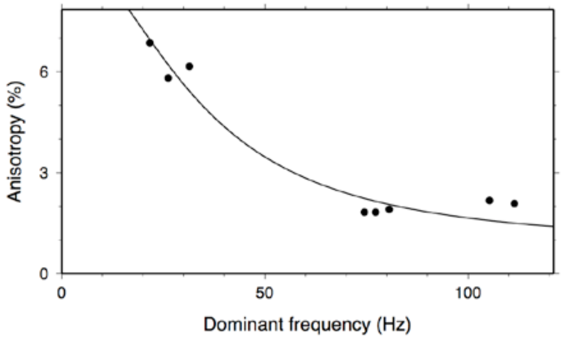

Figure 6. An example of frequency dependent shear-wave splitting in the Cotton-Valley data. The percent anisotropy is determined from normalizing the magnitude of splitting by the ray path length. There is a clear decrease in the magnitude of the splitting with increasing frequency. The solid line corresponds to the best fitting poroelastic model, assuming a relaxation time of 0.1 ms (Chapman, 2003). The inversion suggests a fracture size of ~100cm, but this estimate is very sensitive to the assumed relaxation time, which is not well known.

Conclusions

We have developed a framework for estimating shear-wave splitting in microseismic data using an automated approach, where the rate-limiting step is the speed of event location. Given sufficient ray coverage in azimuth and inclination, clusters of splitting measurements can be inverted for fracture properties such as density and orientation, including those for multiple fracture sets. Furthermore, these inversions can be used to track temporal variations in splitting, which are intimately related to variations in fracture density and fracture compliances. Early results suggest that these measurements may serve as a proxy for changes in permeability and fluid migration. Finally, the frequency dependent nature of shear-wave splitting is sensitive poroelastic effects and can be used to estimate fracture size.

We have started applying this integrated methodology for measuring and interpreting shear-wave splitting to a dataset from Carthage, West Texas – the Cotton Valley field. The dominant polarization of the fast shear-wave alignment is oblique to the trend of the main fracture (65^o versus 80^o in azimuth). We attribute this to a series of en-echelon ruptures, which connect pre-existing joints and cracks. We also observe a clear increase in the magnitude of the splitting that correlates well with the volume of slurry pumped into the formation. This is interpreted in terms of fracture stimulation in a halo surround the main frac. Early results suggest that these changes correlate with an increase in the fracture compliance ratio (B_N/B_T), which can be interpreted as a change in permeability and fluid ingress into the formation. There is also a clear frequency-dependence in our shear-wave splitting measurements. However, more work is required to further interpret these in terms of fracture size.

Cumulatively, these results suggest that shear-wave splitting measurements made on microseismic data acquired during hydraulic facture stimulation may provide a useful tool for assessing the efficacy of fracture stimulation in tight-gas reservoirs.

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