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Prediction of Fracture Direction using Shear Acoustic Anisotropy

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Abstract: Several new methods have been developed to measure the direction of shear acoustic anisotropy in core samples and relate it to the directions of in situ stresses. Hydraulic and natural fractures propagate in the direction of the maximum horizontal in situ stress. Knowledge of the direction of fracture propagation is important for optimal field development in hydraulically-stimulated and naturally-fractured reservoirs due to the highly elliptical drainage and waterflood patterns around fractured wells.

Aligned microfractures have been found to cause shear-wave birefringence or splitting of shear waves into two orthogonally polarized waves. Observation of this shear-wave birefringence in oriented core samples can be used to accurately predict the direction of maximum horizontal in situ stress. The relief of the in situ anisotropic stress field on the rock core during coring creates an anisotropic distribution of microcracks in the core sample. A majority of the stress relief microfractures are aligned with strikes parallel to the direction of the minimum horizontal stress (i.e., cracks opening in the direction of the maximum horizontal stress).

Planar shear acoustic waves propagated in the core along the vertical axis of the formation are polarized into a fast shear wave with polarization parallel to the aligned microfractures and a slow shear wave with polarization perpendicular to the aligned microfractures. Using two shear acoustic transducers whose polarizations are parallel and rotating the core azimuthally, we can see the change in velocity of the vertically propagating shear wave as the direction of polarization is changed (Sprunt and Smallwood, 1986b).

Similar to the observation of optical birefringence of minerals in the microscope with cross-polarized lenses, shear-wave extinction patterns can be observed by rotating the core between two cross-polarized acoustic transducers (Yale, 1987). This acoustic extinction is so strong that the stress direction can be found with excellent resolution.

Shear acoustic anisotropy has many advantages over present methods used to find fracture direction. As a laboratory technique, shear acoustic anisotropy is easier, less expensive, and allows many more samples to be measured than does the anelastic strain relaxation technique. Tests have shown shear acoustic anisotropy to have much greater accuracy and resolution than the horizontal velocity anisotropy. Shear acoustic anisotropy also predicts the direction of fractures by measuring the direction of the in situ stresses. This has advantages over tiltmeter surveys and the passive borehole seismic technique in that fracture direction can be predicted before fracturing.

INTRODUCTION

Hydraulic stimulation and natural fractures enhance oil and gas recovery in tight formations but cause strongly anisotropic flow and drainage patterns. Knowledge of the azimuthal direction of these fractures, therefore, becomes very important for effective reservoir management. Fracture direction is important for well placement, especially during in-fill drilling, due to elliptical drainage patterns around fractured wells. Wells should be spaced more closely together perpendicular to the fracture direction than parallel to it in order to optimize recovery. Effective hydraulic fracture stimulation designs are influenced by fracture direction. The size of the fracture treatment can depend on fracture azimuth, especially if there are geologic structures that need to be intersected or avoided by the stimulation fracture.

Knowledge of fracture direction, however, is probably most important in waterflood and other enhanced oil recovery (EOR) projects. Waterflood patterns designed without knowledge of fracture direction may result in extremely premature breakthrough of the injected fluids, whereas waterflood patterns that take advantage of the fracture direction can increase sweep efficiency greatly. For example, in a standard 5-spot pattern, the line between a producer and injector might be NE–SW or NW–SE. If the fracture direction is close to either of these directions, then injected fluids will travel along the fracture and break through into the producer very early, sweeping a very small portion of the reservoir. However, if the injectors lie along a line parallel to the fracture direction and the producers along another line parallel to the fracture direction, then the fractures will act as a line injector. This would increase sweep efficiency over that achieved in a nonfractured reservoir.

DETERMINATION OF FRACTURE DIRECTION

Most hydraulic fractures and many natural fractures are near vertical and their azimuth of propagation is parallel to the direction of maximum horizontal in situ stress. This is because most tensile fractures open normal to the minimum in situ stress, which is generally equivalent to the minimum horizontal stress. Horizontal fractures occur only when the overburden stress is the minimum of the three stresses, and this generally occurs only in very shallow reservoirs in tectonically active areas. The fracture direction, therefore, can be predicted before stimulation fractures are generated by measuring the direction of the maximum horizontal in situ stress.

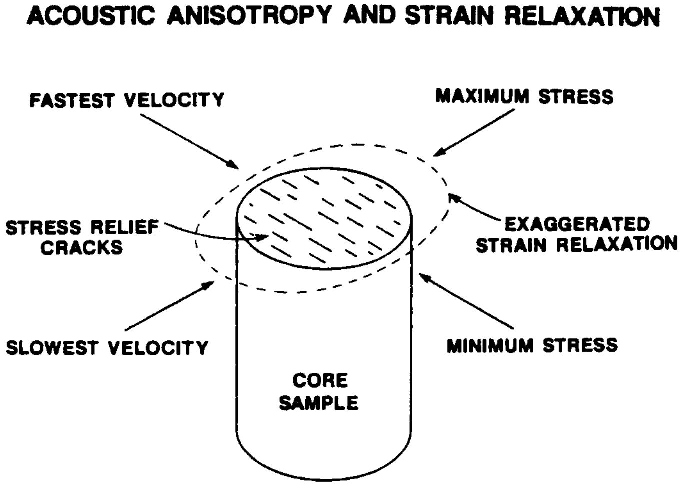

Figure 1. Acoustic anisotropy is caused by stress relief microcracks that are aligned parallel to the minimum stress direction. The acoustic velocity is slowest parallel to the maximum stress and fastest parallel to the minimum stress. The relief of in situ stresses causes an anisotropic strain relaxation with more strain occurring in the maximum stress direction.

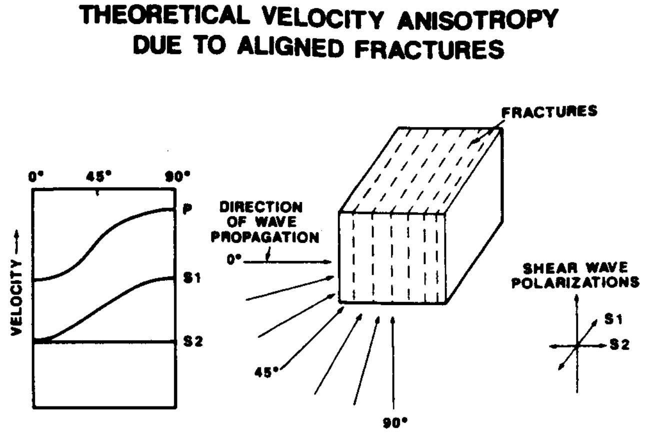

Figure 2. The acoustic velocity as a function of the direction of wave propagation is shown on the left for P waves and S1 and S2 waves. The shear wave polarizations are such that when propagating at 90°, S1 waves have polarizations parallel to the fractures and S2 waves have polarizations perpendicular to the fractures.

When a core sample is removed from the formation, it expands when the in situ stresses on it are relieved. In the horizontal plane, the greatest expansion takes place in the direction of the maximum horizontal in situ stress. In many rocks this stress relief leads to time-dependent viscoelastic (sometimes referred to as anelastic) strains that can be larger than the elastic portion of the strain (Voight, 1968; Teufel, 1982, 1983; Blanton, 1983; Lacy, 1987). It has been suggested that much of the viscoelastic deformation may be due to the creation of microfractures in the core (Teufel, 1983; Plumb et al., 1984; Engelder and Plumb, 1984; Lacy, 1987). The relief of an anisotropic stress field leads to an anisotropic distribution of microcracks with more microcracks having strikes perpendicular to the direction of the maximum horizontal in situ stress (see Figure 1).

The anelastic strain relaxation (ASR) method (Voight, 1968; Teufel, 1982, 1983) measures that portion of the anelastic or viscoelastic strain that occurs after the core has been removed from the core barrel. ASR infers the maximum horizontal stress direction from the direction of maximum horizontal strain. ASR tests must be done within hours of removing the core from the reservoir. This requires the tests to be done in the field and only on those core samples near the bottom of the core barrel (i.e., the portion of the core most recently cut).

As an alternative to ASR, several laboratory techniques have been tried to determine the maximum horizontal stress direction from the direction of stress relief microfractures. These methods include horizontal acoustic velocity anisotropy, differential strain analysis, and differential thermal expansion (Teufel, 1983; Engelder and Plumb, 1984; Griffin, 1985; El Rabba and Meadows, 1986; Sprunt and Smallwood, 1986a; Lacy, 1987). Of these three methods, horizontal compressional velocity anisotropy is the simplest. It involves measuring the variation in the velocity of horizontally propagating acoustic waves as the azimuth of propagation is changed. The direction of minimum velocity corresponds with the direction of maximum horizontal stress (see Figure 1).

SHEAR ACOUSTIC ANISOTROPY

Several similar theories have been proposed (Anderson et al., 1974; Garbin and Knopoff, 1975; Crampin, 1978, 1984; Hudson, 1980; Schoenberg, 1983) to explain the velocity anisotropy caused by a single set of parallel cracks or fractures. Theoretically the velocity of horizontally propagating compressional (P) waves and vertically polarized shear (S1) waves increases as their direction of propagation changes from normal to a set of vertical fractures to parallel to a set of vertical fractures (see Figure 2). The velocity of the P and S1 waves parallel to the fractures should be equal to the velocity in an unfractured rock. Conversely, the velocity of horizontally polarized shear (S2) waves will change little as the direction of propagation is varied from normal to parallel to the fracture set.

These theories confirm the horizontal compressional velocity anisotropy observed by Yale (1980), Teufel (1983), Plumb et al. (1984), Sprunt and Smallwood (1986a), and Lacy (1987). In addition, the theories suggest that a set of parallel fractures will polarize shear waves that propagate parallel or subparallel to the fractures (i.e., the 90° direction in Figure 2). This "shear-wave birefringence" causes shear waves of any polarization to be split into two waves with orthogonal polarizations. One wave with faster velocity will have a polarization parallel to

SHEAR WAVE BIREFRINGENCE

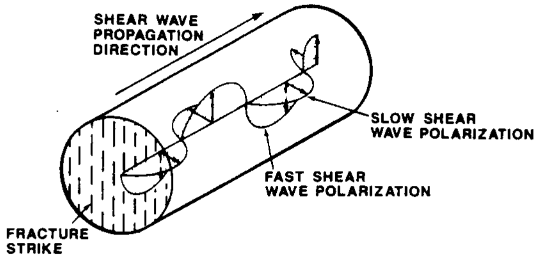

Figure 3. Aligned fractures or microfractures will cause a shear wave birefringence such that shear waves of any polarization will be split into a fast wave parallel to the fracture strike and a slow wave perpendicular to the fracture strike when the waves are propagating along the fractures.

SHEAR ACOUSTIC ANISOTROPY TECHNIQUES

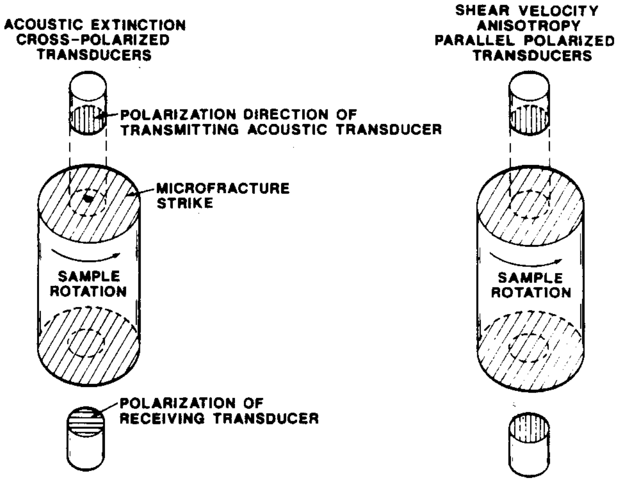

Figure 4. The acoustic extinction technique propagates plane polarized shear waves along the vertical axis of the core and receives them at a shear transducer, which is cross-polarized with respect to the transmitter. The transducer polarizations remained fixed as the sample is rotated between them. The vertical shear velocity anisotropy technique is similar, except that the polarization directions of the two acoustic transducers are parallel.

the fracture strike and the other slower wave will have a polarization perpendicular to the fracture strike (see Figure 3). The result is similar the the optical birefringence observed in minerals. Light with any polarization is polarized into two orthogonal waves parallel to the preferred directions of the mineral.

We have developed a set of techniques called "shear acoustic anisotropy" that utilize this shear-wave birefringence to determine the direction of maximum horizontal stress from core measurements and thus predict the azimuth of propagation of fractures (Sprunt and Smallwood, 1986b; Yale, 1987). One method, called vertical shear velocity anisotropy, entails cutting two parallel surfaces on an oriented core sample and propagating a shear acoustic wave in a direction that is parallel to the vertical direction of the formation (see Figure 4). The transmitting and receiving planer shear transducers are aligned so that their directions of polarization are parallel ("parallel polarized transducers"). Rotating the core sample relative to the transducer polarization, we observe the variation in shear velocity through the core as the direction of polarization of the shear waves varies with azimuth (Sprunt and Smallwood, 1986b). When the direction of polarization of the transducers is parallel to the microfracture direction, the shear velocity is at a maximum, and when the transducer polarization is perpendicular to the microfracture direction, the velocity is at a minimum. When the transducer polarization is oriented at any other angle with respect to the fractures, two orthogonally polarized shear waves are propagated in the core and "shear-wave splitting" is observed at the receiving transducer. The polarization direction where the shear velocity is at a minimum is the maximum in situ stress direction.

This vertical shear velocity anisotropy is much more sensitive and accurate than the horizontal compressional velocity anisotropy method. As shown in Figure 4, the acoustic path remains constant in the shear velocity anisotropy case, whereas in the horizontal compressional velocity anisotropy (see Figure 1) the path varies as the direction of propagation rotates around the core. This can lead to variation in velocity due not only to fractures but to lithologic and porosity variations between the different paths. One problem, however, is that the magnitude of the shear anisotropy is generally small. Few rocks show vertical shear velocity anisotropies greater than 10% and most fall between 1% and 5%.

ACOUSTIC EXTINCTION

To avoid the problems associated with small anisotropies, we developed a method analogous to the cross-polarized optical microscope (Yale, 1987). By cross-polarizing the transmitting and receiving shear transducers and then rotating the core between the transducers (see Figure 4) we produce "acoustic extinction" patterns similar to the optical extinction patterns created in an optical microscope with cross-polarized lenses. Energy generated at the transmitting transducer has its polarization split and rotated as it enters the rock so that the energy is polarized parallel and perpendicular to the microfracture direction. If the microfractures are not exactly parallel to the transmitter or receiver polarizations, then there will be some component of motion in the polarization direction of the receiver and a signal will be received (see Figure 5). As the core rotates, the microfracture direction will align itself with the polarization direction of one of the trans-

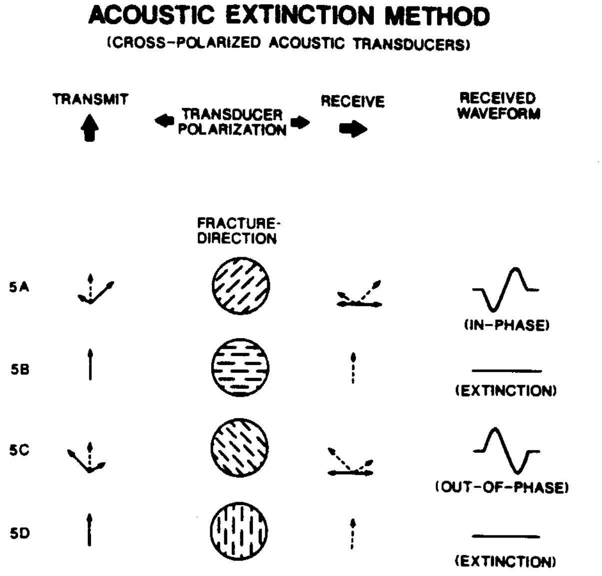

Figure 5. The arrows under TRANSMIT and RECEIVE indicate the polarization directions of the transmitting (left) and receiving (right) shear acoustic transducers. Underneath these arrows, the dotted arrows are the polarizations of the shear waves impinging upon the rock or receiver, and the solid arrows are the shear-wave polarizations of the energy in the rock or receiver. The longer arrow corresponds to the fast shear wave, the shorter arrow to the slow shear wave.

ducers. At that orientation, the energy is polarized only into one wave as it enters the rock and this wave will have no component of motion in the direction of the receiving transducer (see Figures 5b, 5d). This will be an acoustic extinction direction as no energy will be received.

As with optical extinctions, there will be four orthogonal extinction directions as the core is rotated through 360°. These directions will be parallel and perpendicular to the direction of the microfractures that are causing the anisotropy. There are two ways to determine which of the directions is the maximum stress direction. One method is to measure the velocities of shear waves with polarizations parallel to the four extinction directions using parallel polarized shear transducers (see Figure 4). The extinction direction of slowest velocity will correspond to the maximum stress direction.

A second method is illustrated in Figure 5 and uses the phase of the received waveform using cross-polarized shear transducers. Figure 5a shows that when the microfracture direction is between 0° and 90° relative to the polarization of the transmitting transducer, then the phase of the received signal is in phase with respect to the transmitted signal. When the microfracture direction is between 90° and 180°, then the phase of the received signal is out of phase with respect to the transmitted signal (see Figure 5c). Therefore, that extinction direction (Figure 5b) that falls between an in-phase signal (Figure 5a) and an out-of-phase signal (Figure 5c) will be parallel to the microfracture direction.

The phase of the signal is due to the first motion direction of the fast wave. As shown in Figure 5a, the transmitted wave is decomposed into a fast wave with polarization northeast (parallel to fracture strike) and a slow wave with northwest polarization (perpendicular to the fracture strike). When these two waves impinge upon the receiver, the fast wave has a component of first motion east and the slow wave a component of first motion west (see Figure 5a). The first motion direction of the receiver is east, so the first arriving fast wave is in phase with respect to the transmitted signal. In Figure 5c, the opposite is true. With the fracture strike northwest, the fast wave has polarization northwest and the slow wave northeast. The fast wave therefore has a westerly component of motion relative to the receiver so that the overall signal is out of phase with respect to the transmitted signal.

The acoustic extinction technique is more powerful in determining the maximum stress direction than the vertical shear velocity anisotropy or horizontal compressional anisotropy methods. Generally the signal at extinction is 5 to 50 times smaller than the signal 45° from extinction. Over 50 percent of the signal decay is within 10° of the anisotropy direction. The direction can be resolved more accurately when a signal amplitude variation of 500–5,000% is being observed over 90° than when a 1–5% velocity variation over 90° is observed. The parallel polarized vertical shear velocity anisotropy method, however, is still used for determining which extinction direction is the maximum stress direction. In some cases, noisy signals make phase measurements difficult, so velocities must be determined at each extinction point to determine stress direction. In other cores, comparing phase data with velocity data gives us a double check on which extinction point is the maximum stress direction. We have been able to measure in situ stress directions in cores with anisotropies as small as 0.1%. The acoustic extinction technique is sensitive enough to find the anisotropies in aluminum that are induced during the extrusion or rolling processes.

RESULTS

Shear acoustic anisotropy, horizontal velocity anisotropy, anelastic strain relaxation, differential strain analysis, and differential thermal expansion are all based on the assumption that a set of oriented microcracks forms with strikes perpendicular to the maximum horizontal in situ stress. Plumb et al. (1984) correlated microcracks seen in thin section with the horizontal velocity anisotropy observed in cores. Teufel (1982) showed that the horizontal velocity anisotropy disappears as a hydrostatic pressure on the core increases. This also suggests the anisotropy is due to microcracks, which close at high pressure. Very few of the core samples that we have analyzed for acoustic anisotropy have shown any preferential grain or mineral alignment. We have conducted tests that show that as long as the acoustic path is within 30° of the normal to the bedding planes, then the anisotropy is not affected by bedding planes. Acoustic anisotropy has been observed in almost every rock sample we have tested, including sandstones, carbonates, and shales.

Although the theories assume a single set of aligned microfractures, we know that in real rock this is not the case. Generally the differential between the maximum and minimum horizontal stress may be only 10–40% of the average compressive stress on the rock in situ. This suggests that there should be a set of randomly aligned background microcracks with only 10–40% more microcracks aligned parallel to the minimum stress direction than in any other direction. This is supported by the small differences between velocities parallel and perpendicular to the maximum stress direction (3–10% compressional anisotropy, 1–6% shear anisotropy). Anelastic strain relaxation data also show that the entire core expands with incrementally more expansion in the direction of the maximum horizontal stress.

The signal strength variation during extinction suggests that even rocks with small shear velocity anisotropies polarize 80–99% of the shear energy entering the rock. The rock acts as a very efficient polarizer even though there may only be 10% more microcracks in one direction than in other directions. Some rocks show complicated horizontal velocity anisotropy, suggesting two or more sets of aligned microfractures. However, even in these samples the acoustic extinction method identifies a single direction, that direction being the dominant microfracture direction.

Acoustic anisotropy has been found to be useful in areas where the differential stress is small and/or there are large numbers of natural (tectonic) fractures and microfractures. In such areas, other techniques have had problems. The strain relaxation technique has had problems in naturally fractured reservoirs (Griffin, 1985; El Rabba and Meadows, 1986). In naturally fractured reservoirs, strain relaxation can occur perpendicular to the natural fractures as these fractures open up upon relief of the in situ stress. This sometimes causes the strain relaxation data to suggest an in situ stress direction that is oriented 90° from the true stress direction (Griffin, 1985; El Rabba and Meadows, 1986). Griffin (1985) found that horizontal velocity anisotropy and differential strain analysis were correct in one naturally fractured reservoir where the strain relaxation was in error.

In direct comparisons on the same cores, we found the strain relaxation technique was 90° in error in 42% of the cores from six wells through naturally fractured formations, whereas the shear acoustic anisotropy was only in error in 7% of the cores (see Table 1). The true maximum stress direction was known from a variety of tests in other wells in the areas. This suggests that although the magnitude of the anelastic strain relaxation was greater perpendicular to the natural fractures, the total density of stress relief microfractures was greater in the maximum horizontal stress direction. Even in a few cores with visible natural fractures, the shear acoustic anisotropy technique gave the correct in situ stress direction.

Table 1: Acoustic anisotropy versus strain relaxation error due to natural fractures.

	Acoustic anisotropy	Strain relaxation
Field A (4 wells)	4 of 43	10 of 23
Field B (2 wells)	1 of 34	4 of 10

Note: This table represents the number of cores out of the total number of cores measured where the data were 90° from the true stress direction. Acoustic anisotropy measurements were performed on all strain relaxation samples as well as additional cores.

Often small differential strains from anelastic strain relaxation and small velocity differences from horizontal velocity anisotropy are interpreted as indicative of small differential horizontal stresses in situ (Teufel, 1982, 1983; Griffin, 1985). We have found, however, that some cores that show very small velocity anisotropies have very strong extinction patterns. We suggest that this is due to two sets of perpendicular microfracture patterns in the core. If the density of the two sets of microfractures is similar, then the velocity anisotropy and strain relaxation suggest a small differential stress. The two sets of perpendicular microfractures, however, enhance the acoustic extinction patterns. These observations have been made in formations that have a set of natural fracturing parallel to the present-day stress field and a set of stress relief microfractures perpendicular to the stress field. The acoustic extinction method appears to be able to distinguish between low differential stress regimes and dual fracture sets.

CONCLUSIONS

We have tested our shear acoustic anisotropy techniques on cores from several wells and have compared the data to other techniques for determining fracture direction. The direction determined from acoustic anisotropy has been within 15° of other fracture direction measurements such as anelastic strain relaxation, tiltmeter surveys, core fracture descriptions, overcoring of minifracs, and horizontal velocity anisotropy (see Table 2).

Shear acoustic anisotropy has many advantages over present methods used to determine fracture direction. Because it is a laboratory technique, it is easier, less expensive, and allows many more samples to be measured than field techniques such as anelastic strain relaxation. Shear acoustic anisotropy is also not time dependent as is anelastic strain relaxation. Core samples 20 years old have been found to have shear acoustic anisotropy. Tests

Table 2: Comparison of acoustic anisotropy with other fracture direction techniques.

	Acoustic anisotropy	Strain relaxaton	Core fractures	Other
Well A	269°	283°	280°	272° PW
Well B	101°	91°	95°	105° TS
Well C	37°	44°	39°	38° MF

Note: All data are in degrees azimuth. The three wells represent three different fields. PW = compressional wave anisotropy, TS = tiltmeter survey, and MF = overcoring of minifrac test.

show shear acoustic anisotropy has greater accuracy and resolution than horizontal velocity anisotropy, and the tests require much less time than differential strain analysis or differential thermal expansion. As predictive techniques, shear acoustic anisotropy and anelastic strain relaxation can determine hydraulic fracture direction before the fractures are propagated. In fractured and low differential stress regions, we believe shear acoustic anisotropy to be a more reliable technique for predicting hydraulic fracture direction than anelastic strain relaxation.

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