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Shear-wave splitting showing hydraulic dilation of pre-existing joints in granite

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Summary. The polarizations of split shear-waves from acoustic events in a hot dry rock geothermal reservoir change by about 7° before and after hydraulic fracturing. The polarizations change from parallel to the direction of maximum compressional stress to parallel to joints exposed in surface outcrops. This indicates that hydraulic pumping dilates pre-existing planes of weakness at small angles to the stress directions in hard impermeable granite. The possibility of this happening in other rocks has serious implications for the use of hydraulic fracturing to measure *in situ* stress. This study demonstrates that shear-wave splitting may be used to monitor the detailed behaviour of the crack- and stress-geometry in *in situ* rock.

Key words: Shear-wave splitting, Hydraulic fracturing, Crack-anisotropy, Stress orientations

Introduction

Shear-wave splitting (bi-refringence), diagnostic of some form of seismic anisotropy, is now observed along almost all shear-wave raypaths recorded subsurface or within the shear-wave window at the surface (Crampin 1987). These include raypaths in a wide variety of rocks and a wide range of geological and tectonic regimes in the uppermost 10 or 20 km of the Earth's crust. A characteristic feature of the splitting is that the polarizations of the leading split shear-waves are usually parallel to the direction of (local) maximum compressional stress. The splitting has been attributed to the effects of extensive-dilatancy anisotropy (EDA), the distributions of stress-aligned fluid-filled micro-cracks and preferentially oriented pore-space that are known to exist in most rocks and have been aligned by stress perpendicular to the minimum compressional stress (Crampin et al. 1984). Since the minimum compressional stress is usually horizontal once below the immediate surface layers. the cracks are typically aligned vertical, striking parallel to the direction of the maximum horizontal stress (Crampin 1985).

Roberts and Crampin (1986) identified shear-wave splitting in records of acoustic events generated by hydraulic fracturing at Rosemanowes Quarry in the Camborne School of Mines hot dry rock (HDR) geothermal experiment in Cornwall. The hydraulic injection excited many thousands of small events, which were recorded by vertical accelerometers in shallow boreholes and hydrophones in the extraction well (Batchelor 1984). Some of the larger events were also recorded by a small surface network of three-component seismometers operated by the British Geological Survey which was designed to monitor local seismic activity. This network, shown in Figure 1, included four three-component stations (triangles). one of which, CRQ, was in the quarry itself and was too noisy to record useful signals. Roberts and Crampin showed that the polarizations of the split shear-waves recorded by the three-component surface instruments were parallel at each station and that the delays between the split shear-waves displayed the three-dimensional pattern of behaviour expected for propagation through parallel vertical cracks. Thus. the shear waves at Rosemanowes quarry appear to follow the classic behaviour expected in studies of shear-wave splitting in the crust. However. several anomalous features remained unexplained.

The polarizations of the leading split shear-waves (shown in the equal-area rose-diagrams in Figure 2) at two of the three-component stations, CME and CTR, are parallel to the directions of joints and fractures observed at surface outcrops and not parallel to the direction of maximum compressional stress as is usually found elsewhere (Crampin and Booth 1985). The direction of compressional stress, measured by overcoring at the nearby South Crofty Mine (Pine et al. 1983), is some 25" anticlockwise from the average of the joint directions which range from N- 18°W to N 40°W (Pine and Batchelor 1983). The polariz-

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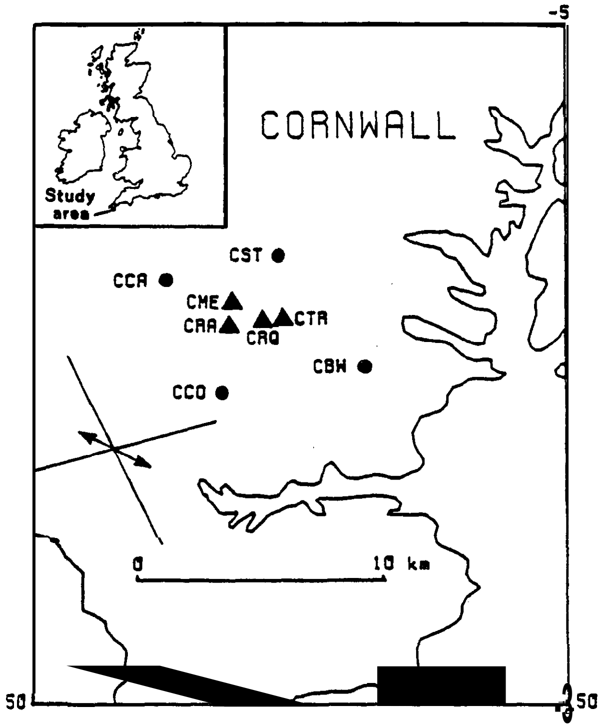


Fig. 1. Map showing locations of the surface network of seismic stations around the Rosemanowes Quarry (CRQ) with three-component stations marked with triangles (after Roberts and Crampin 1986). Arrows mark the directions of maximum compressional stress at the nearby South Crofty mine and lines mark the directions of joints at surface outcrops (Batchelor 1984).

are different from CME and CTR and are parallel to, the stress.

This paper interprets these anomalies and, by analyzing a few small early acoustic events before the main hydraulic pumping sequence had begun, shows that the pumping opened pre-existing joints previously transparent to seismic waves and not parallel to the direction of maximum compressional stress. There are several important implications of these results.

The Hypothesis

Figure 3a shows the rose-diagrams of Figure 2 on a map of the locations of the micro-acoustic events, and Figure 3b shows vertical cross-sections of the foci of the events. The stations with polarizations parallel to the joint directions (CME and CTR) are close to the epicentres and close to the alignment of the cluster of epicentres. Since the foci of the events are principally between 1 and 3.5 km, the raypaths to stations CME and CTR have a large proportion of their pathlength close to the locations of the acoustic events and close to the modifications to the crack geometry introduced by the hydraulic pumping. Station CRA, with polarizations parallel to the stress directions, is located perpendicular to the alignment of the cluster of epicentres. This means that for most of their pathlength the raypaths

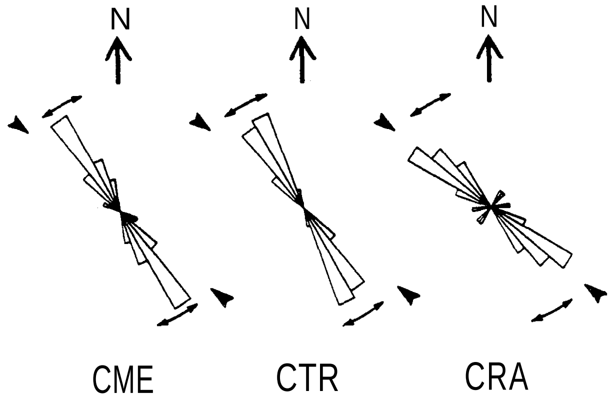
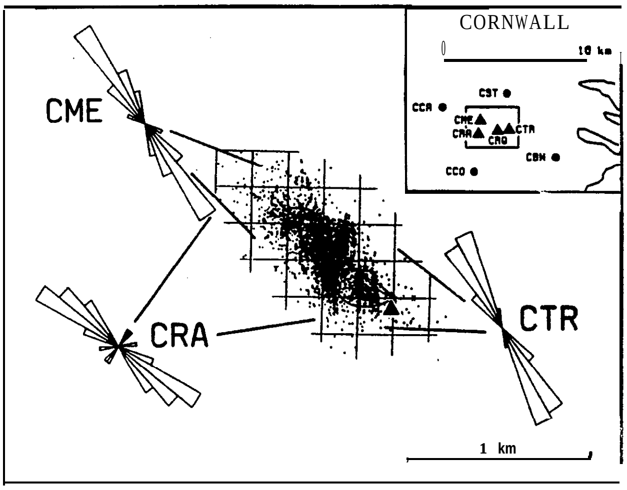


Fig. 2. Equal-area rose-diagrams showing the polarizations of leading split shear-waves from over 40 acoustic events recorded by the three three-component stations during the main hydraulic pumping operation at Rosemanowes Quarry. The solid arrowheads are the direction of maximum compressional stress at N 310°E and the double headed arrows mark the range of joints observed at surface outcrops (both from Batchelor 1984).

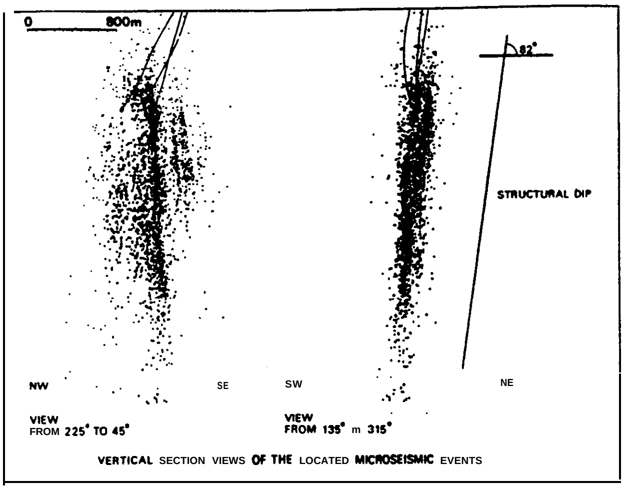
of the shear waves to CRA are away from the immediate neighbourhood of any modifications introduced by the pumping. It has been found elsewhere that the polarizations of the leading split shear-waves are generally parallel to the direction of maximum horizontal stress (Crampin 1987). Thus, the polarizations at CR4 are typical of shear waves observed elsewhere and it is the polarizations at CME and CTR that are anomalous.

An hypothesis to explain these observations is that the hydraulic pumping dilated pre-existing planes of weakness parallel to the joints and fractures observed at surface outcrops. The opening of such fractures would modify the immediate stress orientations. Since fluids do not transmit shear stress, principal stresses in the vicinity of large approximately-planar parallel fluid-filled hydraulic fractures are necessarily normal and tangential to the plane of the fractures. Thus, if hydraulic fractures are dilated at an angle from the stress direction, as in the hypothesis, the axes of stress between and in the immediate neighbourhood of the fractures will be re-oriented parallel and perpendicular to the fractures. Since fluid-filled inclusions are the most compliant elements in the rockmass, any modification of the stress will alter the strain and modify the geometry of the fluid-filled EDA-cracks. Shear waves travelling through this modified zone to CME and CTR would display the alignments of the re-oriented EDA-cracks parallel to the joint directions, whereas shear waves travelling through the unmodified rock to CRA would display polarizations parallel to the unmodified axes of stress as is observed.

The cross-sections of the acoustic events in Figure 3b show some indications of fractures with such alignments, but the locations are difficult to interpret because concentrations of foci appear to be distributed in columns rather than planes. This may be associated with the shearing identified by



(a)



(b)

Fig. 3(a). The equal-area rose-diagrams of Figure 2 on a map showing the locations of small acoustic events determined by the subsurface instruments (from Green et al 1987). The curved lines show the paths of the deviated wells at Rosemanowes Quarry. The two lines radiating from each rose diagram show the approximate range of raypath azimuths sampled at each station, being approximately parallel (CME and CTR) and orthogonal (CRA) to the distribution of epicentres. **(b)** Cross-sections of the locations of the acoustic events viewed from N 255°E, left hand side, and N 135°E, right hand side (from Batchelor and Pine 1986)

Table 1. Small events stimulated by tests of pumping equipment

Event No.	day	mon	year	h m s	Depth (km)
1)	14	10	1982	17 14 36	*
2)	19	10	1982	22 23 38	1.58
3)	19	10	1982	22 24 07	*
4)	19	10	1982	22 24 08	*

Small events after main pumping sequence started at 1000 hours on 4th November 1982.

5)	4	11	1982	18 38 56	*
6)	4	11	1982	202949	*
7)	4	11	1982	21 59 04	1.88
8)	4	11	1982	23 5259	2.52

*Too small to locate

Pine and Batchelor (1984) as the reason for the fracturing extending downwards rather than upwards. The absence of clearly delineated planes in the cross-sections may also be due to the expected errors in location being greater that the gaps between the hydraulic fractures. The micro-acoustic events were located with the assumption of an isotropic halfspace (Batchelor 1984). Neglecting the known (weak) anisotropy (Roberts and Crampin 1986) is unlikely to alter the relative locations, but could re-orient the overall azimuthal alignment and the overall dip by few degrees (probably by up to about 10°, see examples in Doyle et al. 1982). The 82” dip in the vertical cross-section in Figure 3b is similar to the spurious anisotropy-induced dips in Doyle et al. 1982.

If the hypothesis is correct and hydraulic pumping at Rosemanowes Quarry dilates pre-existing joints at an angle to the directions of stress. it would be expected that before hydraulic pumping had modified the crack orientations, the polarizations at CME and CTR would display the alignments of the unmodified EDA-cracks parallel to the stress directions. If such changes can be recognized it would confirm the hypothesis.

Analysis of early events

Roberts and Crampin (1986) reported one acoustic event on 19th October 1982 (Event 2. Table 1) large enough to be located by the surface network, which was stimulated when the pumping equipment was being tested two weeks before the main hydraulic fracturing sequence began on 4th November 1982. Search of the magnetic tapes identified three other events (Table 1) stimulated by the pump tests, which were too small to be located and had been neglected by Roberts and Crampin. Table 1 also lists the first four events excited by the main fracturing operations including two events too small to be located.

Figure 4 shows three-component seismograms of these early events at CME, the only station which recorded all eight events. Figure 5 shows polarization diagrams of the horizontal motion of the initial shear-wave onset at all three stations. The polarization diagrams of these early events in Figure 5 show the abrupt changes in direction or ellipticity of the particle motion, characteristic of shear-wave splitting in cracked rock, and are very similar to those observed by Roberts and Crampin (1986) for the later shallow events above the injection point. This further investigation is a detailed analysis which indicates that the polarizations of the early events in Figure 5 have small but distinct differences from those of the later events in Figure 2.

The particle motion in Figure 5 shows a variety of behaviour probably associated with differences in focal depth. Roberts and Crampin (1986) found that events below the injection point appeared to have different focal mechanisms from those above.

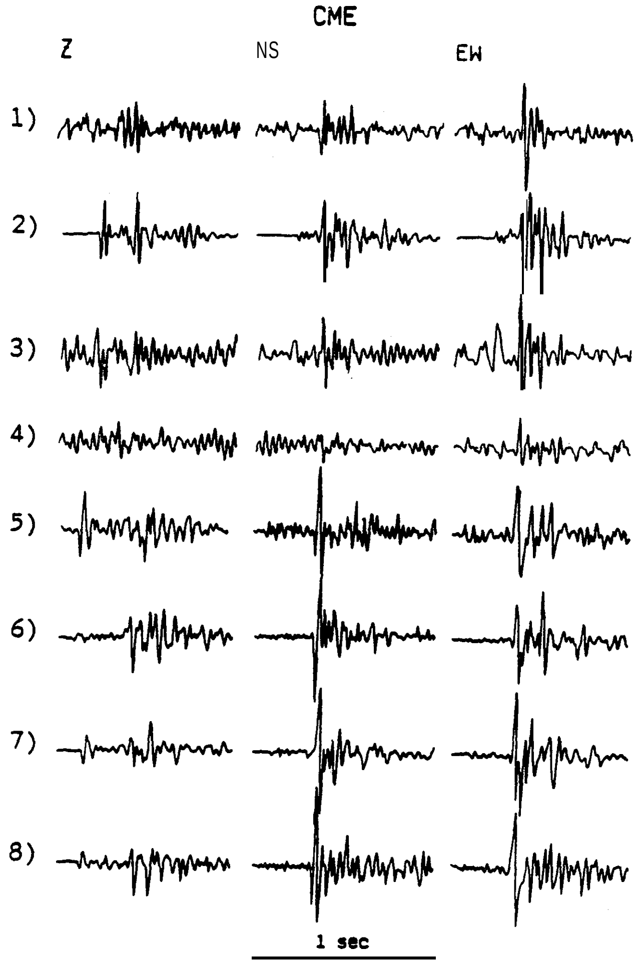


Fig. 4. Three-component seismograms at CME of the events in Table I

The initial pattern of polarization at CTR and CRA begins with nearly linear motion so that the initial polarization can be determined usually within ± 5° At CME, however, except for Event 6 (Table 1), the motion radiated from the source has too little motion in the direction of the leading split shear-wave for the initial polarization to be clearly above the noise level. Consequently, the polarizations at CME are more subjective and less reliable than those at CTR and CRA. It is worth noting that clear patterns of polarization can be seen in recordings even with low signal to noise ratios. This is because the pattern of shear-wave polarizations is determined by the details of the relative amplitude and phase of the two horizontal components, and this is unlikely to be seriously disturbed by uncorrelated, or differently correlated, noise from whatever source.

Figure 6 shows the rose-diagrams of Figure 2 with the polarizations of the early events superimposed as solid petals. Table 2 summarizes the alignments in Figure 6. The polarizations of the early events are within a standard deviation of the directly measured stress directions at CRA and 5° outside a deviation at CTR. The later events at CRA indicate no change in orientation, whereas the later events at CTR show a difference in orientation significant at the 99% level and within the range of orientations of the joints at surface outcrops. The (unreliable) early polarizations at CME show a tendency towards alignment with the stress directions (which could be increased by a less conservative choice of polarization directions in Figure 5). In view of the uncertainties associated

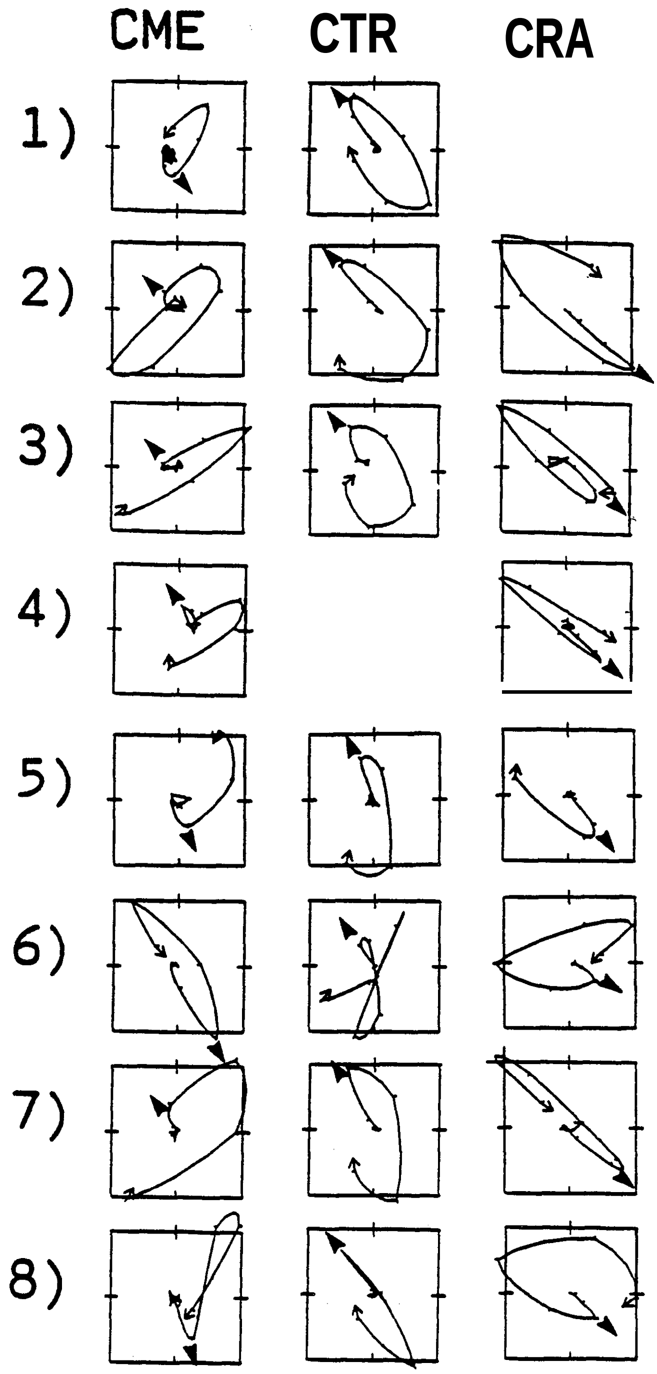


Fig. 5. Horizontal polarization diagrams of the initial shear-wave onset. The length of record shown has been varied for clarity. The arrowheads mark the estimated takeoff angles of the initial shear-wave motion, which are believed to be better than ±5° except for Events 1 to 5 at CME

Table 2. Summary of alignments in Figure 6

Stress direction at South Crofty Mine: N 50.2°W (Pine et al. 1983)			
Range of directions of joints at surface outcrops: N 18°W to N 40°W (Pine and Batchelor 1983).			
Shear-wave polarizations	CME	CTR	CRA
Early events	N 38.0°W ± 8.7	N 37.1 °W ± 7.7	N 47.3°W ± 4.1
Later events	N 34.0°W ± 7.3	N 29.8°W ± 5.7	N 46.4°W ± 20.4
Difference between early and late events	4” ± 16	7.3” ± 13.4	0.9” ± 24.5
Students T test for significance of two populations	Not significant	Difference in alignment significant at 99% level	Difference in alignment negligible at 99% level

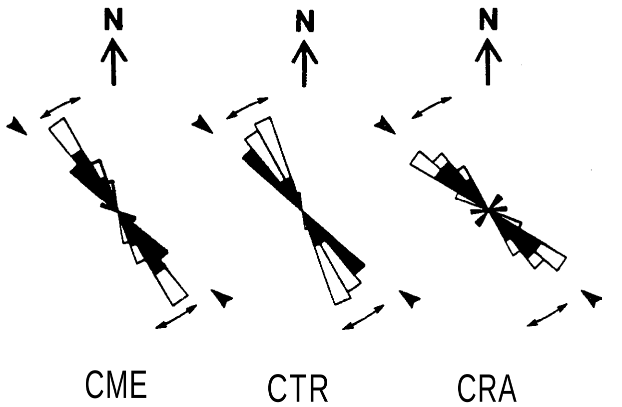


Fig. 6. The equal-area rose-diagrams of Figure 2 with the same notation and the polarizations of the early events in Figure 5 superimposed as solid petals. Note the difference in scale with over 40 polarizations in the open petals and eight or less in the solid petals

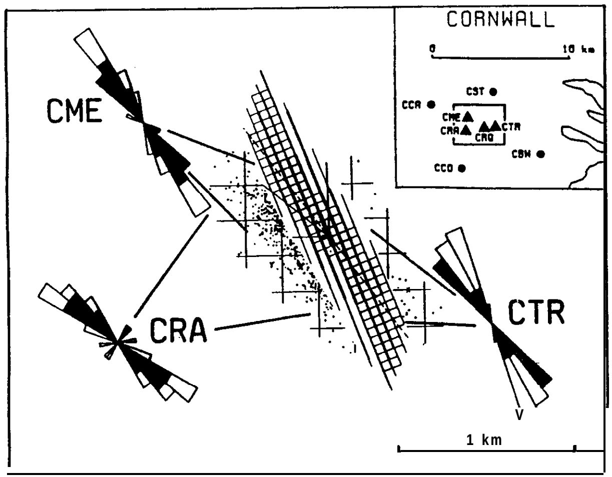


Fig. 7. The map of Figure 3a with the polarizations of the early events from Figure 6 (solid petals) and the FRIP joint pattern (Pine and Cundall 1985) superimposed

with stress measurements in *in situ, we* suggest these alignments confirm the hypothesis that the hydraulic pumping at Rosemanowes Quarry opened pre-existing planes of weakness at a small angle to the compressional stress.

Discussion

We suggest that within the limits of the available data the hypothesis is confirmed. Before hydraulic pumping the polarizations at CTR, CRA (and CME) are parallel to the EDA-cracks which strike parallel to the local direction of maximum compressional stress. After fracturing, waves propagating through the modified rockmass for a large part of their raypath to CTR (and CME) display the new polarizations parallel to the joint directions. The polarizations at CRA, propagating away from the modified rockmass, retain the original polarizations parallel to the local stress directions.

Hydraulic pumping opening joints not parallel to the stress have been postulated before at Rosemanowes Quarry. Cundall (1980, 1982) developed a two dimensional finite element Fluid Rock Interaction Program (FRIP) modelling a regular grid of square prisms separated by joints where laminar flow may occur. Figure 7 shows the map and rose-diagrams of Figure 3 with the early shear-wave polarizations and the FRIP model superimposed. The FRIP result (Pine and Cundall 1985) shows cracks opening parallel to the joints with an overall distribution similar to the distribution of the small acoustic events.

Hydraulic fracturing is commonly used to estimate directions and magnitudes of stress in *in situ* rock (Zoback et al. 1977). The demonstration that fractures may dilate planes of weakness not parallel to the stress suggests that such stress orientations may be in error in some circumstances by at least up to about 10” with corresponding errors in the determination of the magnitude of the stress. The geometry of EDA-cracks appears to be very sensitive to the stress acting on the rock. Similar stress-induced changes to EDA-cracks have been identified before and after both large (Peacock et al. 1988; Crampin et al. 1989) and small earthquakes (Booth et al. 1989). The ability to monitor the detailed changes in the crack- and stress-geometry by analysis of shear-wave splitting is a powerful technique with applications to reservoir and production engineering,

There are several important implications of the results of this paper.

I) Hydraulic pumping may dilate pre-existing planes of weakness, at least in hard impermeable rocks, which may be at least 10" away from the direction of maximum compressional stiess. The maximum limits of such deviations are not known, and it also is not known whether such deviations can exist in porous sedimentary rocks. The implication is that the possiblity of such deviations cannot be neglected and that stress determinations by hydraulic fracturing must be interpreted with caution.

2) Such "off-stress" hydraulic fractures may t-e-orient EDA-cracks between the fractures, but the re-orientations appear to occur only in the immediate vicinity of the disturbed rock.

3) The joints visible in surface outcrops may be transparent to seismic waves at depth until they are dilatated by hydraulic pumping.

4) It appears that EDA-cracks are comparatively mobile and rapidly reflect modifications to the stress regime acting on the rockmass.

5) Shear-wave splitting is sensitive to the detailed behaviour of such stress-induced modifications to crack-geometry, and may be used to monitor the changes in stress and cracks. Such techniques may give us a better understanding of the detailed behaviour of the *in situ* rockmass during the extraction of hydrocarbons.

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