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ALIGNMENT OF NEAR-SURFACE INCLUSIONS AND APPROPRIATE CRACK GEOMETRIES FOR GEOTHERMAL HOT-DRY-ROCK EXPERIMENTS[1]

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ABSTRACT

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Ubiquitous splitting of seismic shear-waves indicates that most rocks in the upper half of the crust are pervaded by stress-aligned fluid-tiled inclusions, called EDA-cracks. These inclusions are expected to be aligned perpendicular to the minimum compressional stress by stress relationships similar to those aligning industrial hydraulic fractures. At depths where the overburden stress is sufficiently large (typically below a few hundred metres), this minimum stress is usually horizontal, so that the EDA-cracks and hydraulic fractures are typically aligned vertically, striking parallel, or subparallel, to the direction of maximum compression. This is confirmed by the polarizations of the split shear-waves along raypaths at depth in the crust. At the free surface, however, the vertical stress is zero (or approximately zero) and cracks (and hydraulic fractures) at shallow depths in intact rock tend to be horizontal. Thus, the directions of minimum stress, and the orientations of hydraulic fractures, are likely to swing through 90" near the surface of the Earth. Since the behaviour of cracks and stress is often crucial to drilling operations, the rotation of the crack- and stress-geometry near-surface has important implications, particularly for optimizing hydrocarbon production and geothermal reservoir management. Consequently, evidence gained from experiments, for example in hot-dry-rock geothermal heat extraction, in inappropriate crack geometries at shallow depths, may not be valid when applied to other crack- and stress-geometries at depth in hot rock.

1. INTRODUCTION

Rocks with aligned cracks are effectively anisotropic to seismic waves (Nur and Simmons 1969; Crampin 1978, 1984), and the splitting (bi-refringence) of seismic shear-waves is the most diagnostic effect of anisotropy on seismic waves (Crampin

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1981). Consequently, observations of shear-wave splitting are giving us new ways to examine the *in situ* crack- and stress-geometry of the crust (Crampin 1987).

Shear-wave splitting is now recognized along almost all raypaths (within about 35” of the vertical) through the uppermost 10-20 km of the Earth’s crust, as a result of stress-aligned fluid-filled inclusions known to be present in most rocks in the crust (Crampin 1987). These distributions of aligned inclusions are known as extensive-dilatancy anisotropy or EDA (Crampin, Evans and Atkinson 1984; Crampin 1985). The inclusions may have a wide range of shapes from flat cracks and oblate spheroids to irregular inter-granular pore-space, and range in dimensions from a few microns in igneous and metamorphic rocks to submillimetre (and occasionally larger) in sedimentary rocks (Crampin 1987). However, because many of the seismic effects can be modelled by distributions of thin parallel (vertical) microcracks (Crampin 1987), it is convenient to call the inclusions themselves EDA-cracks. Figure 1 gives a schematic illustration of shear-wave splitting in the typical crack distributions below the near-surface stress anomalies. The geological and industrial implications of EDA have been reviewed by Crampin (1987).

The need to restrict analysis of shear-wave splitting to near-vertical raypaths is due to two phenomena. Firstly, shear-waves at the free surface need to be recorded within the shear-wave window: the cone of angles of incidence at the surface bounded by arcsin V_S/V_P ($\simeq$ 35” for a Poisson’s ratio of 0.25), as it is only within this window that shear-waves have waveforms similar to those of the incident waves (Evans 1984; Booth and Crampin 1985). Although these effects place restrictions on surface observations, shear-waves recorded subsurface in vertical seismic profiles (VSPs) avoid this constraint. However, the second more serious restriction requiring raypaths within about 30” of the vertical is that at depths where the inclusions are vertically aligned, the distinctive behaviour of split shear-waves (Fig. 1), is only seen for near-vertical raypaths (Liu, Crampin and Booth 1989).

Faster split shear-waves arriving from several kilometres below the surface are aligned parallel, or subparallel, to the direction of maximum horizontal stress (Crampin 1987). This regular behaviour of shear-waves at depth suggests that the alignments of EDA-cracks are comparatively uniform. However, EDA-cracks are expected to be aligned by the local stress-field. Since the directions of stress near the surface are anomalous, corresponding anomalies are expected in crack- and stress-geometry near the surface. This paper examines the expected distributions of EDA-cracks at shallow depths in the crust and their effect on shear-wave splitting, and discusses the possible implications of this for hydraulic fracturing.

2. The Stress Field in the Crust

Boundary conditions at the Earth’s surface usually ensure that the directions of principal stress are approximately horizontal and vertical, and the regional stress-field typically results in unequal principal horizontal stresses. The vertical component of stress (the pressure of the overburden) is zero (strictly one atmosphere) at the surface and increases with depth in the brittle crust, until it eventually becomes

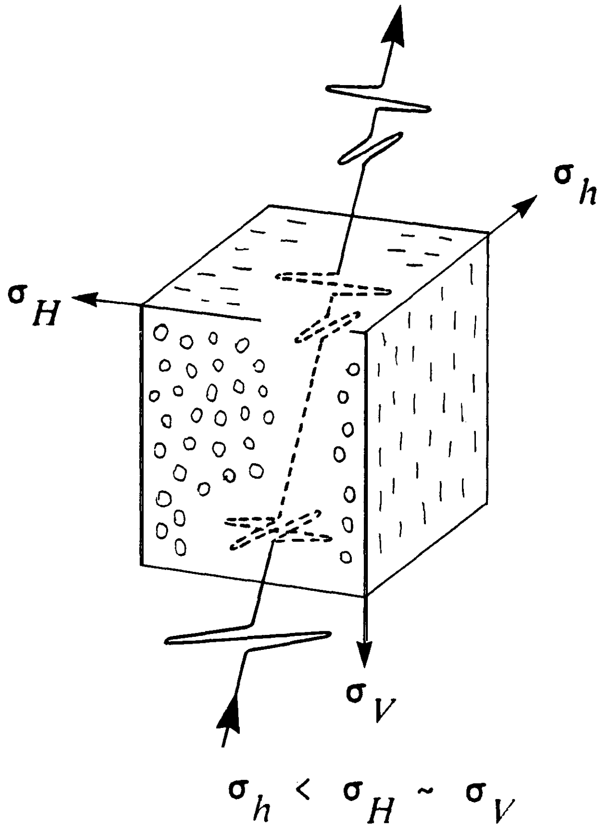

FIG. 1. Schematic illustration of shear-wave splitting, where the cracks are aligned perpendicular to the direction of minimum horizontal stress, σ_h, and σ_H and σ_V are the maximum horizontal and vertical stresses, respectively. A shear-wave entering a region of aligned cracks in the crust necessarily splits into (usually) two phases with different polarizations and different velocities. The direction parallel to the face of the cracks is more compliant than the direction normal to the face, so the phase polarized parallel to the face travels faster and is less attenuated than the phase polarized perpendicular to the crack face. Such shear-wave splitting inserts characteristic signatures into the three-dimensional shear-wavetrains which can be easily identified in polarization diagrams (projections of the particle motion for given time-intervals onto mutually perpendicular cross-sections).

an essentially lithostatic stress in the hotter, more ductile, lower crust. Thus, the direction of the minimum compressional stress may be vertical at the surface, but rotates to horizontal as the (vertical) overburden stress increases with depth.

In these circumstances, the orientation of EDA-cracks and hydraulic fractures, which are aligned normal to the direction of minimum stress, will also rotate with depth. The only exceptions to this rotation occur when the minimum horizontal stress is either equal to the maximum stress, or is effectively tensional (negative) at the surface. Both cases are unlikely. If the horizontal stress were effectively tensional at the surface, the minimum stress would be horizontal throughout the crust, in which case there would be no rotation of crack- and stress-geometries, and the vertical parallel alignment of cracks and stress typical in deeper rocks would persist up to the surface.

3. Cracks in the Crust

Hydraulic fracturing is the principal technique for opening cracks in the Earth, both naturally by geological processes (Fyfe, Price and Thompson 1978; Crampin 1987) and industrially (Hubbert and Willis 1957). Although extensively used, hydraulic fracturing is still not a well-understood process (Veatch 1983). In uniform intact porous rock, hydraulic pumping, whether by the naturally occurring processes releasing fluids into the rockmass, or by industrial processes, will tend to open planar cracks oriented perpendicular to the direction of minimum compressional stress. In uniform intact impermeable rock, pumping tends to open pre-existing planes of weakness (joints and fractures), which the polarizations of shear-waves suggest are typically less than 30” from the direction of minimum compressional stress (Crampin and Booth 1989). At the Fenton Hill, Los Alamos, hot-dry-rock experiment, for example, there was only one comparatively minor fracture set, of the five dilated by pumping, which had normals to the crack faces more than 30” from the direction of minimum compression (Fehler, House and Kaieda 1987).

The Earth’s crust, however, seldom consists of uniform intact rock, and in real rock the orientations of fractures will be distorted by rock fabric, bedding, incipient (and dilated) joints, cleavage planes, and other geological irregularities (Warpinski and Teufel 1987). In many circumstances, however, geologically-induced hydraulic fractures (the mechanism by which chemically-bound water is released into EDA-cracks by prograde metamorphic processes) appear to be aligned very closely to the principal axes of stress in uniform impermeable rock (Crampin and Booth 1989), with the implication that, unless dilated, joints and fractures visible in surface exposures are usually held closed in the subsurface by lithostatic stress.

4. Expected Orientation of EDA-Cracks and the Polarizations of Shear-Wave Splitting

Shear-waves being propagated through the stress-oriented distributions of EDA-cracks display characteristic 3D patterns of behaviour that allow the orientation of the crack distribution to be identified from the polarizations of the faster shear-wave. These 3D variations can be conveniently displayed in equal-area projections. These polar maps show the behaviour of the polarization of the faster shear-wave over a hemisphere of directions of propagation. Thus the symbol in the centre of the projections represents the horizontal polarization (as recorded by horizontal geophones) of a vertically-propagated faster split shear-wave. The symbols at the edge of the projection represent similar horizontal polarizations of nearly-horizontally-propagated faster split shear-waves at appropriate azimuths. The different crack geometries in the following figures lead to distinctive patterns of shear-wave polarizations in the equal-area projections which allow the alignment of the crack geometry (and hence stress geometry) to be identified if there are sufficient observations.

The upper row of diagrams in Fig. 2 shows the typical crack geometries expected in the crust when the two horizontal principal directions of stress are different ($(\sigma_h <$

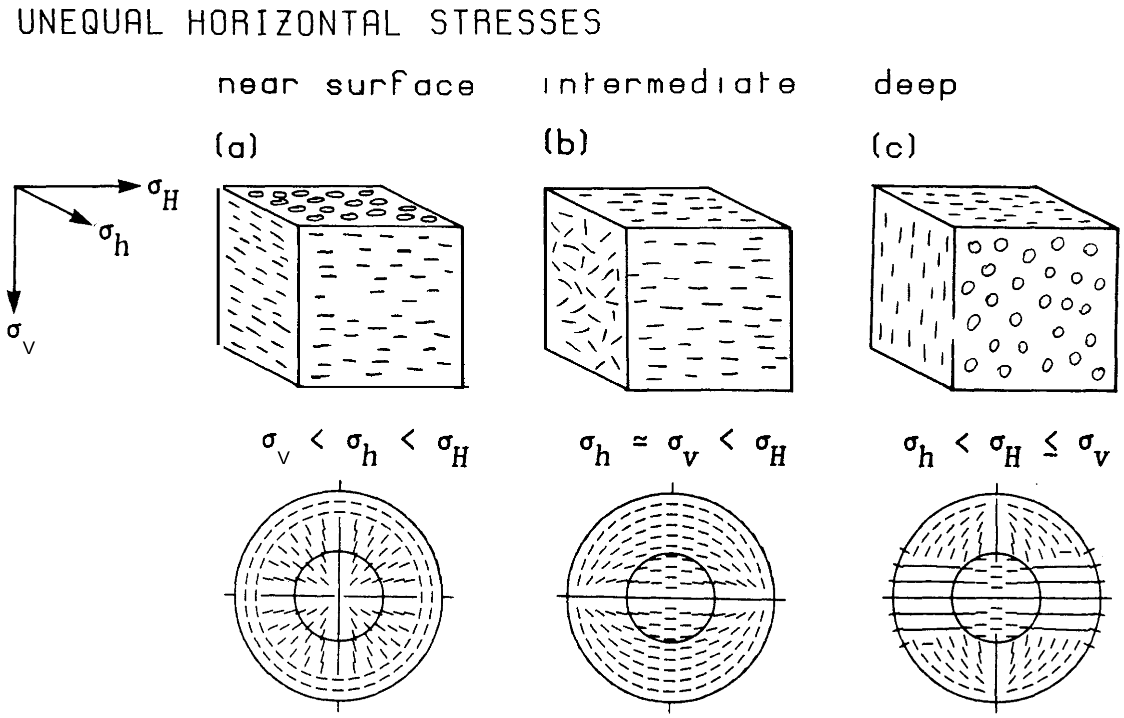

FIG. 2. Upper diagrams in each row are schematic illustrations of the expected orientations of EDA-cracks for a range of specified stress relationships in the crust when the two principal horizontal stresses are different. The stress relationships are: (a) $\sigma_v < \sigma_h < \sigma_H$; (b) $\sigma_h \simeq \sigma_v < \sigma_H$; and (c) $\sigma_h < \sigma_H \leq \sigma_v$. The less than sign '<' indicates stresses differing by a factor of 2 or 3. Lower diagrams are equal-area projections (polar maps) of the horizontal polarizations of the faster shear-wave for the upper hemisphere of directions through the particular EDA-crack geometry. The inner circle marks the limit of the shear-wave window (incidence angle 35.3°), where shear-waves recorded at the surface are similar to the incident waveforms (Booth and Crampin 1985).

σ_H) which is the usual situation, where σ_H and σ_h are the maximum and minimum horizontal stresses, respectively. The lower diagrams in Fig. 2 show the equal-area projections of the initial polarizations of the faster shear-wave through the appropriate crack geometries, as observed by horizontal geophones. The behaviour of polarizations within the shear-wave window displays characteristic patterns that can identify some details of the crack-geometry, including the orientation of the cracks, and hence the orientation and relative magnitude of the principal axes of the stress field acting on the rockmass.

The crack geometry in Fig. 2 is shown for three depths:

(a) Near the free surface where the vertical stress σ_v is the minimum stress, EDA-cracks and hydraulic fractures tend to be aligned horizontally. This leads to hexagonal symmetry (transverse isotropy) with a vertical axis of cylindrical symmetry. The corresponding equal-area projections show that the faster shear-wave is polarized radially (SV-waves) for wave propagation in near-vertical directions.

(b) At an intermediate depth, the vertical stress is equal to the minimum horizontal stress, and cracks and fractures tend to be parallel to the direction of maximum horizontal stress but randomly aligned in the plane normal to the maximum stress. This again leads to hexagonal symmetry, but with the axis of symmetry horizontal and parallel to the direction of maximum horizontal stress. The polarizations of the faster split shear-waves are now parallel to the direction of the maximum horizontal stress.

(c) At greater depths, where the vertical stress is larger than the minimum horizontal stress, cracks and fractures tend to be vertical, striking perpendicular to the direction of minimum horizontal stress, and parallel to the maximum horizontal compressional stress. The polarizations of the faster split shear-waves are again parallel to the direction of maximum horizontal stress. Thus, the polarization of the faster shear-wave is parallel to the strike of the EDA-cracks throughout the whole of the shear-wave window and is parallel to the direction of maximum horizontal compressional stress. This remarkable phenomenon has been observed whenever shear-wave splitting has been identified above small earthquakes (Crampin 1987).

Note that the critical intermediate stress depends on the magnitude of the minimum horizontal stress. In areas where the minimum horizontal compressional stress is small or is tensional, the vertical stress may always be greater than the minimum horizontal stress, so that the stress and crack configurations in Fig. 2c may persist to the surface. Note also that the only assumption made here is that the EDA-cracks are aligned perpendicular to the minimum compressional stress, and this direction can be identified from the polarizations of the split shear-waves (Crampin 1987).

Figure 3 shows similar crack configurations and patterns of shear-wave behaviour when the horizontal stresses are equal. Such equality is an intermediate phenomenon which has not been observed, and is likely to exist only at restricted depths in particular areas. The behaviour is shown, for completeness, for a similar range of stress relationships.

Figure 4 shows possible stress-induced cracking in laboratory conditions: (a) unstressed or lithostatic conditions, when there are no stress-induced crack alignments; (b) what is commonly (although misleadingly) called triaxial stress in rock physics laboratories, where a uniaxial stress acts on a sample in a uniform confining pressure; and (c) true triaxial stress, where the three principal stresses have different values. We see that the stress relationships in the crust (Fig. 2) commonly occur in many circumstances and could be simulated in the laboratory by the conditions in Fig. 4.

Stress is difficult to measure *in situ* and the detailed stress conditions even in the shallow, most accessible, crust are not well understood. There are a variety of techniques for estimating stress *in situ* which do not always give compatible results, but it does appear that the average direction of maximum compression is controlled by tectonic forces over large areas, although there is a large scatter (Zoback and Zoback 1980). Almost all shear-wave signals, propagated from below 1 km through

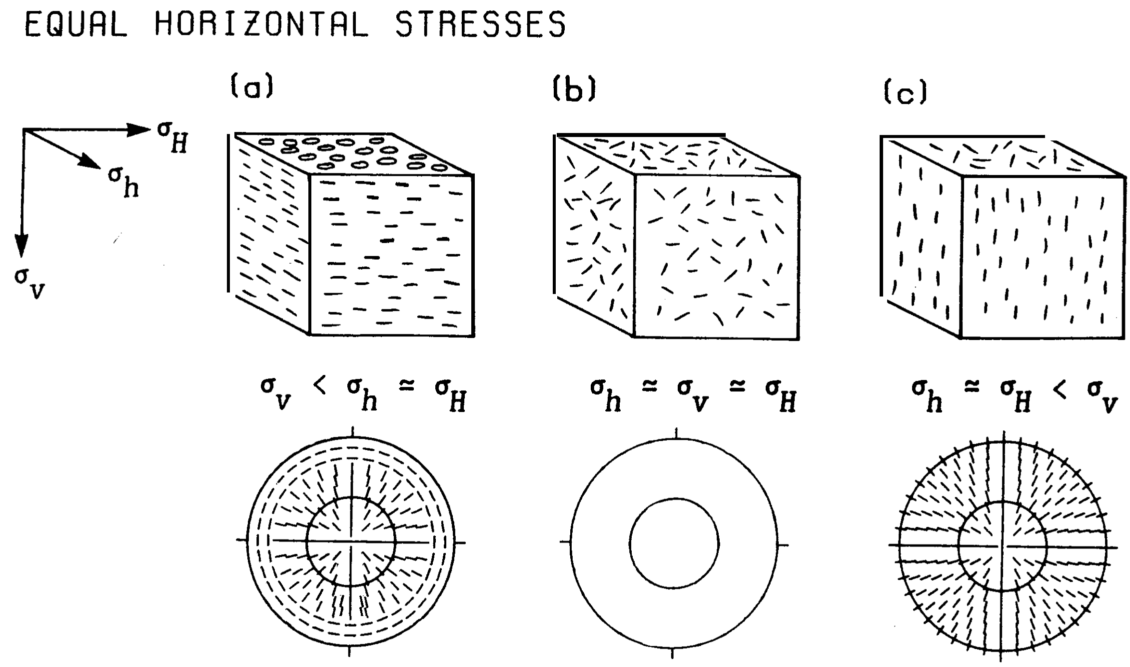

FIG. 3. Expected orientations of **EDA-cracks** and equal-area projections of shear-wave polarizations for a range of stress relationships when the two principal horizontal stresses are equal. The stress relationships are: (a) $\sigma_v < \sigma_h \simeq \sigma_H$; (b) $\sigma_h \simeq \sigma_v \simeq \sigma_H$; and (c) $\sigma_h \simeq \sigma_H < \sigma_v$. Notation as in Fig. 2. The blank equal-area projection indicates propagation through randomly oriented cracks where there are no preferrred shear-wave polarizations.

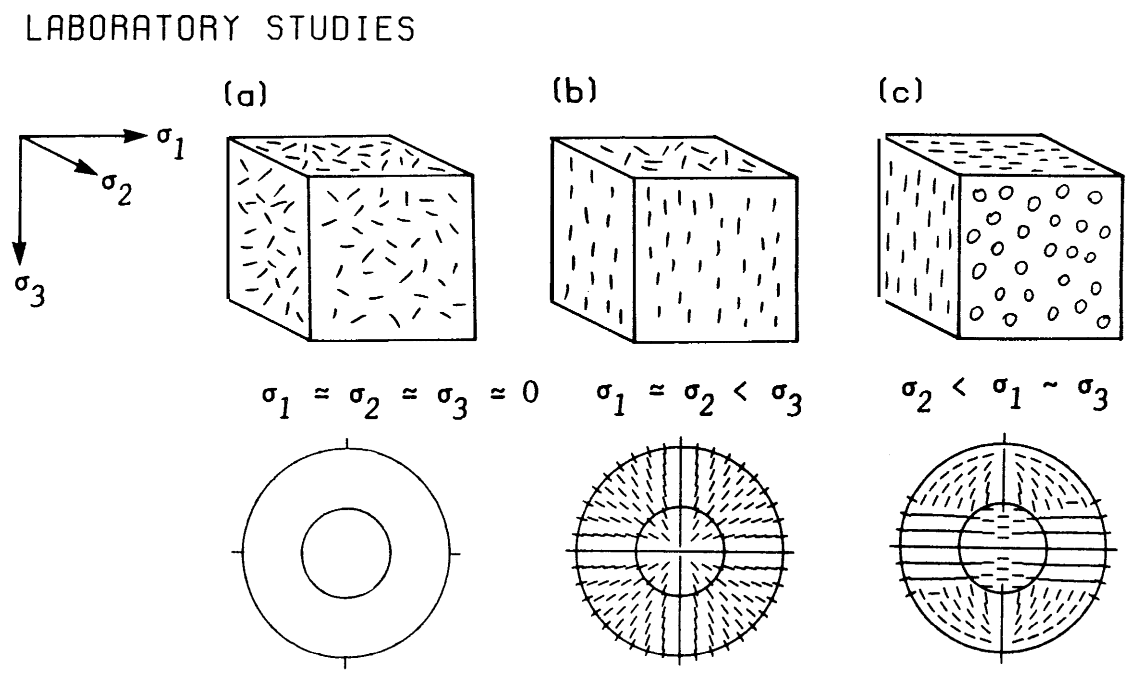

FIG. 4. Expected orientations of microcracks in laboratory experiments for a range of stress relationships: (a) $\sigma_1 \simeq \sigma_2 \simeq \sigma_3 \simeq 0$; (b) $\sigma_1 \simeq \sigma_2 < \sigma_3$; and (c) $\sigma_2 < \sigma_1 \sim \sigma_3$. Notation as in Fig. 2. The blank equal-area projection indicates propagation through randomly oriented cracks where there are no preferred shear-wave polarizations.

hard rock which have been examined to date, display shear-wave splitting caused by EDA-cracks with the pattern of polarizations parallel to the direction of maximum compression as in Fig. 2c. These include observations of shear-waves above small earthquakes in a wide variety of tectonic regimes in many countries including Turkey, Tadzhikistan U.S.S.R., Japan and California, and observations of shear-wave reflection surveys in sedimentary basins in North America, and in vertical-seismic-profiles in sedimentary basins and elsewhere (reviewed by Crampin 198'7). The only common exceptions to these patterns of polarization are in sedimentary sequences where, although the EDA-cracks are still approximately vertical, the shear-wave polarizations are modified by periodic thin-layer anisotropy with a vertical symmetry axis (Bush and Crampin 1987; Crampin 1988). This results in a structure with orthorhombic anisotropic symmetry where the polarization of the split shear-waves varies with both azimuth and angle of incidence.

Note that as the vertical stress σ_v increases with depth, the orientation of cracks in transition zones between the zones of well-defined crack geometry will be sensitive to local structural anomalies. The crack geometry in these transition zones, which may extend over several hundreds of metres in depth, is likely to be locally irregular and not well defined. In addition, hydraulic fractures are usually initiated from boreholes, and boreholes may substantially modify the stress for a metre or two into the rockmass by partially de-stressing. This usually imposes such a severe stress anomaly that spalling is induced, and breakouts occur in the borehole wall which can be used to estimate stress directions in the crust (Bell and Gough 1979; Zoback and Zoback 1980). Thus, a hydraulic fracture initiated at the wall of a well will not immediately encounter the *in situ* stress-field, and may twist as it encounters the unmodified stress away from the anomalies near the well and the changing relationships with the vertical stress above and below the point of injection. Such anomalies are most likely to occur in the transition zones between the critical stress relationships indicated in Fig. 2.

4. CRITICAL DEPTHS

One of the critical features of these crack and stress anomalies in shallow rocks, which largely controls the extent of the transition zones, is the depth at which the vertical stress equals the minimum horizontal stress. This critical depth depends on the regional stress, the local stress, and the type of the surrounding rock, and appears to vary quite widely. In particular, the critical depth may be comparatively deep. In the Canadian Shield, for example, equal vertical and minimum horizontal stresses are observed at 2.4 km depth (Herget 1986), so that the stress relationships characteristic of deeper levels would not be reached until at least 3 km.

Many laboratory experiments, and some field experiments which are too shallow for the local stress regimes, are subject to stress relationships and crack geometries that are not appropriate to the depths at which hot-dry-rock geothermal heat extraction is expected. This is because, except in areas of very high heat flow, heat extraction must be from heat exchange reservoirs below (at least) 3 km where the rock is sufficiently hot. At these depths, the minimum compressional stress is likely to be horizontal, and cracks will tend to be vertical, parallel to the maximum horizontal stress, as in Fig. 2c. If the stress orientations have not rotated to their more stable deeper alignment, the crack configurations induced by hydraulic fracture are likely to be much more irregular and difficult to predict. Consequently, the operation of hot-dry-rock extraction will be more difficult to plan and to optimize.

In some geothermal experiments, such as the hot-dry-rock project at Rosemanowes Quarry, Cornwall, the uniform shear-wave alignments from acoustic events induced by hydraulic pumping appear to persist even for shallow events, at least at the wavelengths of the shear-wave signals – about 150 m (Roberts and Crampin 1986). This implies that, in this region, the minimum compressional stress is small or tensional so that the vertical stress is always greater than the minimum horizontal stress and the crack orientations in the deeper rock (Fig. 2c) persist to very near the surface. This is confirmed by locations of acoustic events associated with the hydraulic fracturing which indicate that there are two parallel vertical (or near vertical) fractures which persist to at least 3 or 4 km depth (Pine and Batchelor 1983), and by various direct measurements of stress which indicate that the vertical and minimum horizontal stresses are equal at approximately 400 m (Green *et al.* 1987). This depth is presumably sufficiently shallow to have minimal effect on the shear-wave polarizations determined by the deeper stress relationships. Thus it does appear that the stress relationships deep in the crust persist to near the surface at Rosemanowes Quarry, so that hydraulic fracturing at depth is likely to be consistent with the shallower experiments.

It is difficult to evaluate the relevance of hot-dry-rock experiments in inappropriate crack geometries. Hot-dry-rock extraction strategies must open and manipulate cracks at depths of several kilometres in remote, essentially inaccessible, rock which can only be monitored by indirect techniques such as locating acoustic events and analysing shear-wave splitting. Televiewers and other well-logging techniques, such as sonic logs, and analysis of tube waves, sample only the immediate wall of the well, or the rock in the anomalous modified region within a metre or two of the borehole. These may suggest properties which are not applicable to the *in situ* rockmass beyond the modified region. Estimating the behaviour of rocks at depth is largely based on empirical experience, and successful hot-dry-rock techniques are likely to rely heavily on previous empirical experience. Experience based on the manipulation of cracks in hot-dry-rock experiments in inappropriate geometries may be seriously misleading when applied to the behaviour of cracks in deeper production zones. Boreholes in hard impermeable hot rock suitable for hot-dry-rock geothermal heat extraction are expensive to drill, and wells based on inappropriate evidence could be costly mistakes.

5. Conclusions

There are two conclusions.

(1) Laboratory experiments, simulating conditions below the critical stress condition, should simulate parallel cracks, which in cracked rock can only exist in conditions of (true) triaxial stress where $\sigma_2 < \sigma_1 \sim \sigma_3$.

(2) Hot-dry-rock experiments in shallow *in situ* rock should first establish that they are in stress and the crack geometries appropriate for deeper rocks where geothermal heat extraction is anticipated.

The stress relationship at depth is typically $\sigma_h < \sigma_H \leq \sigma_v$ leading to vertical cracks striking parallel to the maximum horizontal stress σ_H. The most direct way to test for this geometry is by monitoring shear-wave splitting in reflection surveys or, more reliably, in VSPs. Shear-wave VSPs, in any well intended for hot-dry-rock experiments, interpreted with synthetic seismograms (Crampin *et* al. 1986), would immediately yield the stress directions and orientations of EDA-cracks, and place constraints on the initial directions of hydraulic fractures in intact rock.

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