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ARGUMENTS FOR EDA

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ABSTRACT

The hypothesis that there are distributions of stress-aligned fluid-filled cracks, microcracks and preferentially oriented pore space pervading most rocks in at least the upper half of the crust, known as extensive-dilatancy anisotropy or EDA, was introduced to explain the apparently stress-aligned polarizations of split shear waves typically observed along most raypaths of seismic shear waves in the Earth's crust. There have been a number of advances in our understanding of seismic azimuthal anisotropy since EDA was first suggested in 1984, and this article reviews the current understanding of the hypothesis. There are a number of phenomena that can cause effective seismic anisotropy leading to shear-wave splitting, and there have been several claims that the observed splitting in particular cases is caused by alignment of crystals and fabric rather than the alignment of cracks. Although other causes of shear-wave splitting may be important locally, there is mounting evidence that stress-aligned shear-wave splitting occurs in most rocks and can be explained by the presence of EDA cracks. This paper reviews the current arguments for EDA in the Earth's crust.

INTRODWTION

Shear-wave splitting is now widely observed in the Earth's crust, with the polarizations of nearly vertically propagating shear waves usually aligned subparallel to the direction of the local maximum horizontal stress. The hypothesis of extensive-dilatancy anisotropy (EDA) that there are distributions of stress-aligned fluid-filled cracks, microcracks and preferentially oriented pore space present in most rocks has been suggested as the cause of this phenomenon (Crampin et al., 1984; Crampin, 1987; Crampin and Lovell, 199 1). There have been a number of advances in our understanding of shear-wave splitting which have resulted in changes in interpretation of shear-wave splitting. It seems useful to restate the current understanding of the EDA phenomenon as the explanation for the shear-wave splitting widely observed in at least the uppermost half of the Earth's crust. The terminology for seismic anisotropy is that suggested by Crampin (1989).

THE EDA HYPOTHESIS

Initial understanding

The original hypothesis of EDA was introduced (Crampin et al., 1984) to provide a mechanism for the shear wave splitting which at that time had only been observed in the vicinity of local earthquakes (Crampin et al., 1980a; Booth et al., 1985; Buchbinder, 1985; Crampin and Booth, 1985; Crampin et al., 1985; Crampin et al., 1986a; amongst others). The polarizations of the leading, faster split shear waves within the shear-wave window above the earthquakes were observed to be scattered by ±10° to ±20° about a direction parallel to the direction of maximum horizontal compression (Crampin and Booth, 1985; Crampin and Evans, 1986). The shear wave window is the area on the surface above the earthquake where raypaths subtend angles of incidence less than about 35” (Booth and Crampin, 1985), where the waveforms recorded at the free surface are similar to the incident waveforms. It was suggested (Crampin et al., 1984) that the splitting was the result of propagation through the known distributions of fluid-filled microcracks and microinclusions in igneous and metamorphic rocks (Fyfe et al., 1978), which are aligned by the stress field near earthquakes. It was supposed that these EDA cracks were usually small (submillimetre in diameter) and either individually isolated, or in isolated groups, without large-scale permeability. Similar effective seismic anisotropy had already been observed in the laboratory when a sample of granite was subjected to uniaxial stress (Nur and Simmons, 1969).

Subsequent understanding

By the time the EDA hypothesis was published, it had already become clear that shear-wave splitting occurred not only above small earthquakes in igneous and metamorphic

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rocks but also along most shear wave raypaths in a great variety of rocks, including porous and permeable rocks in sedimentary basins in reflection surveys (Crampin, 1984a, 1985a; Crampin and Atkinson, 1985) and VSPs (Crampin, 1986; Crampin et al., 1986b). At the annual SEG meeting in Houston in 1986, several oil companies reported shear wave splitting in almost all three-component reflection surveys in sedimentary basins (Alford, 1986; Lynn and Thomsen, 1986; Willis et al., 1986; amongst others). The splitting was generally assumed to be due to large fractures within fractured reservoirs, although the shear-wave splitting was also visible in reflections from layers above the reservoirs, so that exclusive dependence of splitting on large fractures seemed unlikely. Shear-wave splitting was also seen in great thicknesses of poorly consolidated sediments above earthquakes in Tadzhikistan (Crampin et al., 1986a), where once again large open fractures are unlikely. In all cases, the polarizations of the faster split shear wave are aligned approximately parallel to the direction of horizontal compressional stress in the rock mass or, more strictly, orthogonal to the direction of minimum stress.

It was clear that effective stress-aligned seismic anisotropy occurred throughout most porous and permeable sedimentary rocks, including some fractured reservoirs, as well as igneous and metamorphic rocks. Consequently, the concept of EDA was extended to include large fractures and preferentially oriented pore space and cracks and microcracks in permeable rocks (Crampin, 1987; Crampin and Lovell, 1991).

Current understanding

It is now becoming recognized that fractures in the crust are a fractal phenomenon whereby the frequency distribution of fracture size is scale invariant. The evidence comes from well logs (Leary, 1991), from the decay of S-wave coda observed at 2.5-km depth, where surface attenuation is absent (Leary and Abercrombie, 1993a) and from the spectra of S-wave coda, again observed at 2.5-km depth (Leary and Abercrombie, 1993b). Such fractures cluster as part of a fractal domain of brittle shear fractures. These will have a different response to seismic shear waves and a different response to fluid flow from EDA cracks and it is not yet clear whether the lower limit to the fractal crack size includes the distributions of EDA microcracks.

Is is suggested that the most useful definition of EDA cracks is to restrict the definition to those fluid-filled fractures, microcracks and preferentially oriented pore space that show some response, even a statistical response, to temporal changes in the physical parameters. This would include stress, temperature, pressure and pore-fluid composition, which affect the behaviour of fluid-filled cracks in in situ rocks. Since the seismic effects of these various fluid-filled openings, despite the wide range of possible shapes and dimensions, can be simulated by distributions of flat penny-shaped cracks, it is convenient to refer to this range of individual inclusions as EDA cracks.

Arguments for EDA

It is difficult to obtain direct evidence for EDA cracks in the in-situ rock mass. Table 1 lists 23 phenomena that affect the behaviour of cracks in in-situ rocks, each of which is controlled or affected either directly or indirectly by the local stress field acting on the rock mass. Once the in-situ rock is approached by drilling or mining, the existing stress is at least partially released and a new stress anomaly imposed by stress-relief fractures in the sample or by compressive stress around the borehole wall, so that the in-situ crack geometry is lost. The particular difficulties of scaling stress reactions in laboratory samples to in-situ conditions has long been recognized (Cuisiat and Haimson, 1992). This means direct physical examination of rock samples in the laboratory, or examination of the borehole wall by logging devices such as televiewers, sees a modified version of the in-situ crack geometry and extrapolation to in-situ conditions must be treated with great caution. Since the various reactions of the phenomena controlling the cracks have time constants ranging from substantial numbers of years for some geological and tectonic processes to the instantaneous elastic response, restoring in-situ conditions of temperature and pressure to core samples cannot reliably reinstate the original crack geometry. Note that in this paper I use crack geometry to mean all physical parameters of the cracks, as listed in Table 1.

Table 1. Phenomena controlling the behaviour of in-situ cracks.

EXTERNAL CONDITIONS			
1)	Lithostatic stress;	2)	Deviatoric stress;
3)	Temperature;	4)	Properties of the rock mass including;
INTERNAL CONDITIONS			
5)	Pore-fluid pressure;	6)	Compressibility of pore fluid;
7)	Viscosity of pore fluid;	8)	Debris (clay) in crack void;
9)	Vapour/liquid ratio in pore fluid;	10)	Properties of pore fluid (including dihedral angle) at high temperature and pressure;
DYNAMIC CONDITIONS			
11)	Rate of strain;	12)	Rate of crack growth;
13)	Rate of crack healing;		
CRACK PARAMETERS			
14)	Orientation;	15)	Crack density;
16)	Aspect ratio;	17)	Dimensions;
18)	Distribution of orientations;	19)	Geometry (parallel, biplanar, etc.);
20)	Nature of crack face (smoothness, roughness, etc.);	21)	Connectedness to other cracks (degree of isolation);
22)	Connectedness to surrounding pore space;	23)	Ratio of throat-width (of surrounding pore space) to crack radius.

The difficulty in direct examination means that arguments for EDA have to be indirect. Several arguments supporting EDA are given below and summarized in Table 2.

1) Shear-wave splitting, diagnostic of some form of azimuthal anisotropy, is seen in most rocks, and fluid-filled cracks and inclusions are common in most rocks (Fyfe et al., 1978; Sheppard, 1990; Marquis and Hyndman, 1992):

Prograde metamorphism releases chemically bound water from the majority of rocks so that most igneous and metamorphic rocks contain fluid-filled microcracks and other fluid-filled inclusions (Fyfe et al., 1978; Shepherd, 1990; Marquis and Hyndman, 1992). Parallel planes of gas bubbles would have seismic effects similar to those of parallel cracks. Sedimentary rocks contain fluid-filled pore space from their time of deposition. Such fluid-filled microcracks are the most compliant elements of the rock mass, and there are a variety of processes ranging from elastic opening and closing to subcritical crack growth (Atkinson, 1984) that will result in statistical alignments relative to the local stress field. This has been demonstrated in the laboratory by the action of uniaxial stress on samples of granite (Nur and Simmons, 1969) and on sedimentary samples (Rai and Hanson, 1988). Such fluid-filled openings are expected in almost all igneous, metamorphic and sedimentary rocks.

2) Polarizations of leading split shear waves within the shear wave window at each recording site are typically subparallel to the direction of maximum horizontal compressional stress. This can only be caused by propagation through hexagonal anisotropic symmetry with a horizontal symmetry axis, or a very similar symmetry structure, and parallel vertical fluid-filled EDA cracks are the only common source of such symmetry orientations in the crust (Crampin and Lovell, 1991):

The near parallelism of shear wave polarizations at most individual recording sites places severe constraints on the possible class of anisotropic symmetry and symmetry orientation causing the splitting. The only form of anisotropic symmetry that will produce parallel polarizations of the leading split shear waves over a solid angle large enough to span the shear-wave window (diameter at least 70°) is hexagonal symmetry (or a simple modification thereof), and to span the shear wave window the axis of symmetry needs to be aligned subhorizontally (Crampin, 198 1). Most orientations of most anisotropic symmetry systems lead to complicated patterns of shear-wave polarizations within the shear-wave window and this is usually not observed.

Fluid-filled microcracks are expected to be aligned, like hydraulic fractures, perpendicular to the direction of minimum compressional stress (Crampin, 1990). Once below the level where the vertical stress (the overburden) equals the minimum horizontal stress this minimum stress is typically horizontal (Crampin, 1990), so that the fluid-filled microcracks at depth are expected to be aligned vertically, parallel to the direction of maximum horizontal stress. Such alignments possess hexagonal anisotropic symmetry with a horizontal symmetry axis and would lead to the observed shear-wave polarizations.

It is a most important argument for EDA that shear waves indicate near hexagonal symmetry with a near horizontal axis symmetry. Although some crystals such as quartz and calcite and some fabrics such as rock cleavage and slaty cleavage do possess hexagonal symmetry, most do not, and those that do would be unlikely to be oriented with a horizontal axis of symmetry by the current stress field. Since crystals or fabrics are less compliant to realignment than fluid-filled cracks at the low temperatures in the upper crust, any such materials that do not have similar symmetry would be expected to be aligned by palaeostresses and not by current stress directions as is suggested by the shear-wave observations (Crampin and Evans, 1986; Crampin and Lovell, 1991). Thus, although there may be local exceptions (see Arguments against EDA, below), it appears that the only interpretation of rose diagrams showing parallel polarizations within the shear-wave window that is generally applicable is stress-aligned fluid-filled EDA cracks.

There are two related stress-aligned structures of fluid-filled EDA cracks with similar seismic effects to the hexagonal symmetry of parallel vertical EDA cracks. These are 1) biplanar systems of vertical cracks and 2) mixtures of matrix and crack-induced anisotropy, where matrix anisotropy refers to the anisotropy of horizontal bedding or to the lithology of rocks such as shales, both of which typically possess tranverse isotropy with a vertical symmetry axis.

1. The average polarization and time delay of biplanar or multiplanar systems of vertical cracks can frequently simulate those of parallel vertical cracks for directions of propagation within the shear-wave window (Liu et al., 1993a), although it might be expected that multiplanar systems of cracks are not common at depth (Crampin and Lovell, 1991).
2. Mixtures of matrix and crack-induced anisotropy may also have parallel polarizations for directions of propagation within the shear-wave window (Wild and Crampin, 1991) and are discussed in Item 4, below.

The direct effect of stress on an intact rock mass would also yield hexagonal symmetry. However, such alignment of the symmetry axis would require a comparatively strong deviator stress of perhaps- hundreds of MPa (Dahlen, 1972) and such high deviatoric stresses are not expected throughout most rocks where shear-wave splitting is observed (Zoback and Zoback, 1980). The strongest argument against direct stress-induced anisotropy in the crust is that fluid-filled cracks are pervasive and, since they are the most compliant elements of the rock mass, the geometry of the cracks will be the first elements of the rock mass to be modified when the rock is strained. This means that the rock mass is likely to display stress-aligned crack-induced anisotropy at much lower levels of stress than those needed for direct stress-induced anisotropy.

3) shear-wave splitting has similar percentages of differential shear-wave anisotropy in most rocks (Crampin

and Lovell, 1991) and the upper limit of observed anisotropy (usually 5%) is probably due to the limited cracking that can occur in an intact rock mass before fragmentation occurs:

Despite the wide range of rock types in which shear-wave splitting has been observed, the characteristics of splitting are similar with similar polarizations and a comparatively narrow range of differential shear-wave anisotropy, usually between 1% and 5%, although larger percentages of anisotropy are sometimes reported in partially destressed near-surface rocks (Crampin et al., 1980b; Liu et al., 1993b). These similarities suggest (but do not of course dictate) that the cause of the splitting is the same in all rock types. Stress-aligned fluid-filled microcracks are the only source of effective seismic anisotropy common to almost all rocks.

The limited range of differential shear wave anisotropy at depth observed in a wide range of rock types (1% to 5%) is equivalent to a limited range of effective crack densities, usually $0.01 \leq \varepsilon \leq 0.05$. Note that the percentage of differential shear wave anisotropy is usually about ε x 100 for a V_p/V_s ratio of 1.732 (Crampin, 1993) with $\varepsilon = Na^3/v$, where N is the number cracks of radius *a* in volume v.

A crack density of $\varepsilon = 0.05$ (shear-wave anisotropy about 5%) is equivalent to a crack of diameter 0.7 in each unit cube. A crack density of $\varepsilon = 0.1$ has a crack diameter of 0.93 in each unit cube, and this is clearly near the critical crack density at which an intact rock fragments, as very close cracks begin to coalesce to form through-going fractures. Thus, the upper limit of crack densities ($\varepsilon = 0.05$, with occasional excursions to 0.1) is probably due to the limit of the number of fractures for an intact rock mass to remain intact. If this limit is exceeded, the rock mass fragments and the pore fluid would disperse and, once dispersed, the cracks would tend to close and crack-healing occur which would lead to a lower crack density of open cracks. The only occasion when substantially larger crack densities (up to $\varepsilon = 0.4$) have been claimed for field observations are reported by Crampin et al. (1980a) for observations on the surface of limestone pavements, where the pavements are characterized by massive jointing and the rock cannot be considered as intact. Any other form of seismic anisotropy such as aligned crystals or direct stress-induced anisotropy would probably not be subject to such a limited range of differential shear-wave anisotropy.

4) Particle motion of synthetic seismograms propagating through theoretical simulations of cracked rock can match observed particle motion with considerable accuracy (Bush and Crampin, 1991; Slater et al., 1993; Yardley and Crampin, 1993):

Polarizations of leading split shear waves aligned subparallel to the direction of maximum horizontal compression appear to be almost universal within the shear wave window above small earthquakes in igneous and metamorphic rocks (Crampin and Lovell, 1991). The only common exception appears to be in sedimentary basins, where the crack anisotropy combines with the matrix anisotropy to produce orthorhombic symmetry. The matrix anisotropy may be due to aligned grains (lithologic anisotropy), or nearly (P)eriodic sequences of (T)hin (L)ayers (Postma, 1955), which I shall refer to as PTL anisotropy (Crampin, 1989). Both types of matrix anisotropy lead to hexagonal symmetry with a vertical symmetry axis (tranverse isotropy) and similar seismic properties; hence, for convenience, both types of tranverse isotropy will be referred to as PTL anisotropy. The combination of PTL anisotropy with a vertical symmetry axis and crack anisotropy with a horizontal axis leads to orthorhombic symmetry (Wild and Crampin, 1991) with three mutually perpendicular planes of mirror symmetry (Crampin, 1984b). Such orthorhombic combinations of anisotropies do not display parallel shear-wave polarizations throughout the whole of the shear-wave window. This is because all anisotropic symmetry systems except hexagonal possess directions of propagation called shear-wave singularities, where the two shear-wave phase-velocity surfaces touch and the two group-velocity surfaces have complicated interactions with each other including orthogonal shear-wave polarizations either side of the singular direction (Crampin, 1991a). The singularities in combinations of PTL and EDA anisotropies are in near-vertical directions with the shear-wave window (Wild and Crampin, 199 1) where they may cause irregular behaviour.

Combinations of PTL and crack anisotropy were first proposed by Bush and Crampin (1987) in an attempt to match nonparallel shear-wave polarizations in a multioffset VSP in the Paris Basin. The final model of combined anisotropies accurately simulated the observed shear-wave polarization diagrams (hodograms) at five offsets and azimuths (Bush and Crampin, 1991). Such modelling is not strictly unique, but matching synthetic to observed polarization diagrams is a rigorous test which demonstrates the validity of the combination of anisotropies and the presence of stress-aligned fluid-filled EDA cracks in the Paris Basin. At present, such detailed matching has only been possible in areas of uniform "layer cake" stratigraphy (Liu et al., 1993b; Slater et al., 1993; Yardley and Crampin, 1993). Complicated geology leads to complicated waveforms which are difficult to match with synthetic seismograms when there is inadequate knowledge of the complications.

5) Temporal changes in the behaviour of shear-wave splitting are believed to have been observed before and after earthquakes (Booth et al., 1990; Crampin et al., 1990; and possibly Liu et al., 1993c) and before and after hydraulic pumping (Crampin and Booth, 1989):

Temporal changes in behaviour of shear wave splitting have been observed before and after the $M = 6$ North Palm Springs Earthquake of 8th July, 1986 (Peacock et al., 1988; Crampin et al., 1990), and before and after two events in the Enola Earthquake Swarm, Arkansas, 1982 (Booth et al., 1990) [and possibly after an event near Parkfield (Liu et al., 1993c)]. The behaviour of the shear w-aves in these sequences could be simulated by increasing the aspect ratio of EDA cracks before the earthquakes and relaxing the ıspect ratio to the original value at the time of, or just before, :he earthquake occurred (Booth et al., 1990). The behaviour s similar to that of uniaxially strained samples in the labora- :ory which dilate as newly-created microcracks increase in ıspect ratio (Brace et al., 1966). The geometry of existing :luid-filled EDA cracks in the crust would be modified by nuch lower stresses than those needed to open new microc- :acks in strained samples in the laboratory. A paper in this ssue presents a further possible example of temporal :hanges before small earthquakes (Liu et al., 1993c).

Aster et al. (1990) could not reproduce the results of Peacock et al. (1988) and Crampin et al. (1990) on the same lata sets using an automatic technique to analyze shear-wave splitting. However, see the discussion in the next section on trguments against EDA.

The search for further examples of temporal changes in shear wave splitting before and after earthquakes faces two lifficulties: the need for closely-spaced three-component net- works recording digitally at relatively high sampling rates usually at least 100 Hz) and the need to site such networks within the shear-wave window over a swarm of small earth- ıuakes close to the epicentre of an impending large earth- ıuake. Appropriate networks are still comparatively scarce ınd the siting conditions are stringent. Consequently, no other suitable data sets have yet been identified. Monitoring solated swarms of small earthquakes may be an appropriate ılternative (Crampin, 199 1 b).

Another example of temporal changes is seen in the polari- :ations of shear waves from acoustic events at a depth of 1.5 cm recorded before and after a hydraulic pumping test in the Camborne School of Mines Hot-Dry-Rock geothermal :xperiment (Crampin and Booth, 1989). The changes in rnlarization were small (between 7° and 10°), but shear vave polarizations are relatively stable phenomena Crampin, 1981) and the results are believed to be signifi- :ant, although appropriate statistical tests would be difficult o devise. The results suggest that before the dilation of ncipient joints by pumping, the fluid-filled EDA cracks are ıligned parallel to the in-situ stress field. After the joints ıave been dilated by pumping and the stress field modified, he EDA cracks close to the joints are realigned parallel to he joints. Possibly processes for such realignment, which ıave been demonstrated in the laboratory, are the elastic pening and closing of microcracks (Nur and Simmons, 969) and subcritical crack growth (Nemat-Nasser and Horii, 982). Apart from the change in orientation of the EDA racks implied by the changes in shear-wave alignment in he hot-dry-rock experiment, a further implication is that efore the joints were dilated by pumping, joints above 1.5 m were held closed by the overburden pressures and were ransparent to seismic-wave propagation. This transparency f joints and fractures may be one of the reasons why field bservations of shear-wave polarizations often show remark- ble parallelism in areas of great complexity (Booth et al., 985; Crampin et al., 1986a).

It was recognized by Crampin (1978) that any temporal changes in shear-wave splitting would be diagnostic of some form of crack-induced anisotropy. Fluid-filled EDA cracks are the most compliant elements of the rock mass, and the immediate effect of any stress-induced strain of the rock mass will be to modify the geometry of the EDA cracks and, consequently, modify the behaviour of shear wave splitting. In enhanced oil recovery procedures, the hydrocarbon indus- try recognizes that the seismic (P-wave) response of the intact rock mass can be modified by small changes to the geometry of the pore space during steam floods and in situ combustion (Greaves and Fulp, 1987; De Buyl, 1989; Justice et al., 1989). Shear waves are much more sensitive than P-waves to the internal geometry (principally pore-fluid velocity and viscosity) along the raypaths (Crampin, 1985b), and any phenomenon that changed the f-wave response would be expected also to change the shear-wave response, although this has not yet been demonstrated in enhanced oil recovery processes. The change in P-wave response is thought to be caused principally by changes to the pore-fluid velocity and viscosity and, possibly, pressure-induced changes to aspect ratio. Such changes would also modify the response to shear-wave splitting.

6) Differential shear-wave anisotropy, indicating aligned cracks, correlates with rates of hydrocarbon pro- duction in Wyoming (Lewis, 1989; Lewis et al., 1991), Tatarskaya (Brodov et al., 1991; Cliet et al., 1991) and Texas (Li et al., 1993; Yardley and Crampin, 1993):

There have been several oil fields where the percentages of shear-wave anisotropy correlate with the rates of produc- tion in fields where the production varies between wells. Lewis (1989) and Lewis et al. (1991) were the first to docu- ment in western literature the correlation of oil production with seismic anisotropy in a fractured reservoir. In their anal- ysis of three-dimensional three-component reflection surveys in the Silo Field, Wyoming, contoured maps of percentages of shear-wave splitting correlate with rates of hydrocarbon production. Wells with high productivity are in areas with high shear-wave anisotropy, with the implication that the shear-wave splitting indicates fracture-related hydrocarbon recovery.

Similarly, Cliet et al. (1991) correlate the percentages of shear-wave splitting noted on two VSPs in the Romashkino oil field, Tatarskaya, Russia with hydrocarbon production rates. (A third well with the largest percentage of anisotropy had not yet gone into production.) Estimating the properties from the cores of reservoir rock, Brodov et al. (199 1) were able to correlate the rates of production almost exactly with reservoir properties derived from the analysis of cracks within cores examined in the laboratory. If the splitting and production rates correlate with the properties measured in cores, it implies that the shear wave splitting and the hydro- carbon production depends on small-scale cracks within the rock mass as well as, or in addition to, large fractures.

Li et al. (1993) analyzed three three-component shear- wave reflection profiles also above the Austin Chalk in Texas. One was in an area without many producing wells, another was on the edge of a producing field, and a third was in the middle of a producing field. The shear-wave anisotropies correlated with the distribution of horizontal production wells where the larger anisotropy is associated with a greater density of wells. (The profiles were shot by Amoco to evaluate the relationship between anisotropy and production in the Austin Chalk.) Yardley and Crampin (1993) also find that the shear-wave anisotropy above the Austin Chalk, noted in VSPs, correlates approximately with production at three sites in Texas. An interesting observation of Li et al. (1993) is that to a large extent the relative levels of anisotropy which correlate with production in the Austin Chalk several thousand metres below the surface are established in the near-surface layers and the level of anisotropy is largely preserved throughout the rock column above the Austin Chalk (Li et al., 1993).

7) Direct observations of EDA cracks (Powley, 1990; Queen and Rizer, 1990; Mueller, 1991, 1992; Holmes et al., 1993):

There are perhaps four studies that have a direct bearing on the nature of EDA cracks. Three show that EDA cracks are small-scale features and one shows that they can be large-scale fractures aligned parallel to the small-scale features. Queen and Rizer (1990) in an integrated examination of shear-wave splitting in an azimuthal VSP to a depth of 853 m at the Conoco Borehole Test Facility, Oklahoma, correlated shear-wave polarizations and azimuthal traveltimes with core fractures, borehole televiewer images and outcrop fracture patterns. All observations are internally consistent and the polarizations of the shear waves are generally subparallel to the aligned vertical microcrack structure.

Powley (1990), in an extensive interpretation of large numbers of drilling records and well logs from around the world, demonstrated that most reservoirs in sedimentary basins are in abnormally pressurized compartments beneath horizontal seals. The pressurized compartments are pervaded by cracks (EDA cracks) a few centimetres in diameter (Powley, 1990) which would be expected to be aligned normal to the direction of minimum compression. Their origin is not established but they are probably created by thermal expansion of the fluid as the basin sinks.

Mueller (199 1, 1992) recognized differential amplitudes between split shear waves reflected from the Austin Chalk in Texas and interpreted dimming of the amplitudes of the second split shear wave as indicating fractured zones in the Chalk. Horizontal drilling located fractures indicated by the dimming of the split shear waves. This application is important commercially as the Austin Chalk has high porosity but low permeability except along fractures. Consequently, wells may be highly productive if fractured zones are penetrated, particularly by horizontal drilling orthogonal to the fractures, but may be dry or have low productivity if no fractured zones are encountered.

Potentially, the most direct evidence for EDA microcracks in in-situ igneous rock will come from the Mine-by experiment in Manitoba, Canada, where the effects of excavating a tunnel are investigated for the feasibility of nuclear waste disposal in a granite batholith in the Canadian Shield. The rock mass was chosen for homogeneity and absence of fractures. Holmes et al. (1993), in a preliminary study, observe shear-wave splitting in 4 kHz signals from shear-wave sources sampling a 40 x 40 x 40 m^3 volume of intact rock at a depth of 420 m where the largest natural fracture is expected to be no greater than, at most, a few centimetres in diameter. The polarizations and time delays indicate 1 to 4% differential shear-wave anisotropy compatible with small stress-aligned horizontal EDA cracks and there is some indication that the EDA cracks are horizontal. The Mine-by experiment is in the depth range where the direction of minimum stress is still rotating from vertical to horizontal as the overburden increases (Crampin, 1990).

Table 2. Summary of arguments for EDA.

1) Shear-wave splitting diagnostic of some form of azimuthal anisotropy is seen in most rocks and fluid-filled microcracks and inclusions are common in most rocks (Fyfe et al., 1978; Shepherd, 1990);
2) Polarizations of leading split shear waves within the shear-wave window at each recording site are typically subparallel to the direction of maximum horizontal compressional stress. This can only be caused by hexagonal anisotropic symmetry with a horizontal symmetry axis, or a very similar structure, and parallel vertical fluid-filled cracks are the only common source of such symmetry orientations in the crust (Crampin and Lovell, 1991);
3) Shear-wave splitting has similar percentages of differential shear-wave anisotropy in most rocks (Crampin and Lovell, 1991), and the limited range of observed anisotropy (1% to 5%) is probably due to the limited cracking that can occur in an intact rock mass before fragmentation occurs;
4) Particle motion of synthetic seismograms propagating through theoretical simulations of cracked rock can match observed particle motion with considerable accuracy (Bush and Crampin, 1991; Slater et al., 1993; Yardley and Crampin, 1993);
5) Temporal changes in the behaviour of shear-wave splitting are believed to have been observed before and after earthquakes (Booth et al., 1990; Crampin et al., 1990; and possibly Liu et al., 1993b) and before and after hydraulic pumping (Crampin and Booth, 1989);
6) Differential shear-wave anisotropy, indicating aligned cracks, correlates with rates of hydrocarbon production in Wyoming (Lewis, 1989; Lewis et al., 1991), Tatarskaya (Brodov et al., 1991; Cliet et al., 1991) and Texas (Li et al., 1993; Yardley and Crampin, 1993);
7) Direct observations of EDA cracks (Powley, 1990; Queen and Rizer, 1990; Mueller, 1991, 1992; Holmes et al., 1993).

ARGUMENTS AGAINST EDA

Although other sources of effective seismic azimuthal anisotropy are clearly possible locally, only one (Liischen et al., 1991) has been proven (see below). EDA cracks are expected to be aligned normal to the direction of minimum compressional stress. Stress in the crust is difficult to estimate reliably, even at the comparatively shallow depths (say' 5 km) that can be reached by drilling (Cuisiat and Haimson, 1992), and at such shallow depths the direction of minimum stress is expected to rotate with increasing overburden from, typically, vertical at the surface to horizontal at depth (Crampin, 1990). Consequently, orientations of shear wave polarizations which vary from site to site locally may well indicate variations of stress directions rather than variations of the cause of the effective anisotropy. It would be a remarkable coincidence if the rather tight constraints imposed by stress-aligned vertical microcracks of hexagonal symmetry with an axis of symmetry within a few degrees of the horizontal were also common to other causes of seismic anisotropy in the crust. If the cause of the anisotropy varied, it might be expected that where the polarizations varied the degree of anisotropy would also vary by more than 1 to 4% usually observed and anisotropy would sometimes be absent. Such features are not usually observed. Polarization directions sometimes vary at different recording sites but the time delays usually display very similar scatter.

There have been several studies where shear-wave splitting in the crust has been claimed to be due to crystal or fabric alignments, or unknown phenomena, rather than aligned cracks. Three typical cases will be briefly discussed.

1) Shear-wave splitting at one station (KNW) of the Anza seismic network is interpreted in terms of a palaeostrain alignment of fabric and/or microcracks with no dependence on the current stress field (Aster and Shearer, 1992):

Aster and Shearer (1992) analyze fault-lane mechanisms beneath the Anza seismic network and conclude that the direction of principal compression of the fault-plane mechanisms (the f-axis) is north-south (note that the principal axes of fault-plane mechanisms may be significantly different from the principal axes of stress in the rock mass). This is the data set in which Peacock et al. (1988) and Crampin et al. (1990) found temporal changes in shear-wave splitting (discussed above). Aster and Shearer agree with Peacock et al. and Crampin et al. that the average north-south orientations of shear polarizations at most of the Anza stations are probably due to aligned cracks (EDA cracks) but claim that the polarizations at KNW (N40°W) are consistent with the palaeostrain alignment of bedrock minerals.

The arguments of Aster and Shearer (1992) and Aster et al. (1991) with respect to KNW are not conclusive (Crampin et al., 1991). The principal axes of the fault-plane mechanism do not uniquely define the principal axes of stress within the surrounding rock mass. The technique for extracting principal axes of stress from focal mechanisms by seeking common compressional or tensional segments of the focal sphere (Doyle et al., 1985) appears to identify reliable axes of stress within the rock mass (Crampin and Booth, 1985; Crampin et al., 1986a). Applied to 20 of the 22 mechanisms in figure 4 of Aster and Shearer (1992) with epicentres within 3 km of KNW, the common compressional segments are compatible with shear wave polarizations of N40°W, and there must clearly be some kind of stress anomaly near KNW to induce the most active cluster of small earthquakes within the Anza network. I have no explanation for the two Incompatible events, 880329 and 881125, although the earlier event is poorly constrained, and the 3-km region around KNW is an arbitrary choice. Cracks oriented at about N40°W are displayed in the photograph of rock fabric at the surface near KNW in figure 6 of Aster and Shearer (1992). Aster and Shearer suggest these orientations are due to palaeostress, not current stress directions. This may be the case for the weathered zone near the surface, but this palaeoalignment is unlikely to extend to the 20-km focal depths of the deepest earthquakes beneath KNW where temperatures are large enough for crack fabric to be reoriented by the current stress field.

2) P-wave velocity anisotropy in a complicated terrain is interpreted in terms of aligned fabric (Brocher and Christensen, 1990):

Brocher and Christensen (1990) interpret f-wave reflection and refraction profiles (Brocher et al., 1989) following a winding path through the Chugach Mountains, Alaska, including a 90" change of direction, as due to fabric anisotropy caused by heavily foliated schists. They suggest that foliated rocks are likely to be a common cause of the anisotropy widely observed in the crust.

Both these ideas can be criticized (Crampin, 1991c). Common-shot gathers for the shot near the junction of the orthogonal profiles show arrival times differing by 30% to 50%. Geological maps in Brocher et al. (1989) and Brocher and Christensen (1990) of the Valdez Group show considerable complexity including the implication that older rocks, with higher velocity, lie below one of the orthogonal lines. Consequently, Crampin (199 lc) suggested that the variations of P-wave velocity are more likely to be due to unrecognized discontinuities than substantial velocity anisotropy. Foliations can only produce the observed parallel shear-wave polarizations if they are constrained to be within a few degrees of the vertical and have hexagonal symmetry. The foliations in the Valdez Group have an average dip of about 60" in figure lb of Brocher and Christensen (t990) and would not lead to the parallel shear-wave polarizations within most of the shear- wave window typically observed elsewhere (Crampin and Lovell, 1991). Thus, foliated structure is unlikely to cause the typical parallel polarizations of shear-wave splitting, either in the Chugach terrain, or elsewhere.

In their reply to Crampin's (199 1 c) comment, Brocher and Christensen (1991) claim, on the basis of a very simplified geological map, that the area is not complicated. This despite the evidence of the shot gathers in Brocher et al. (1989) which all show substantial asymmetry. They repeat the assertion that cracks are closed at high lithostatic (they say hydrostatic) pressures, ignoring the evidence of substantial fluids at abnormal pressures (greater than hydrostatic) at great depths in the crust beneath seals in both sedimentary rocks (Powley, 1990) and metamorphic rocks (Fyfe et al., 1978; Kozlovsky, 1984) and in fluid-filled inclusions in almost all rocks at all depths (Shepherd, 1990).

One of the difficulties in claiming foliations as the source of shear-wave splitting seen throughout most rocks is that the orientations of the foliations are usually determined by palaeostress, but to cause the observed shear-wave splitting

As fractures are important for extraction in many, perhaps most, hydrocarbon reservoirs, it is tempting to interpret all shear-wave splitting in terms of large-scale fractures in the rock mass. Consequently, it is the implicit assumption of Alford (1986), Lewis et al. (1991), Squires et al. (1989) and others in exploration geophysics, that the splitting is caused by (large) fractures. Unquestionably, aligned fractures in fractured reservoirs may cause pronounced shear-wave splitting, as demonstrated by Mueller (1991, 1992). However, shear-wave splitting is also seen throughout the record sections of Alford (1986), Squires et al. (1989), Mueller (1991, 1992), Li et al. (1993) and many others. The presence of numerous hydrocarbon and hydrological seals throughout the rock mass makes it unlikely that large fractures extend throughout all the rock mass, and the presence of smaller fluid-filled EDA cracks of Powley (1990) and Holmes et al. (1993) must be invoked. Queen and Rizer (1990) found evidence for both large fractures and much smaller EDA cracks. However, it is likely that the dimensions of fluid-filled EDA cracks vary substantially with rock type. Powley (1990) observes cracks in sedimentary basins a few tens of millimetres wide, whereas Holmes et al. (1993) see shear-wave splitting for 4 kHz shear waves in intact in-situ granite where the largest cracks are no greater than a few centimetres in diameter.

Shear-wave splitting is seen over a wide range of scales. Table 3 shows estimates of shear-wave splitting by papers in this conference proceedings that yielded 1 to 4% shear-wave anisotropy in a wide range of materials for over three orders of magnitude of frequency and path length for EDA crack dimensions varying from a few microns to a few metres. With the exceptions of Liu et al. (1993a) and Graham and Crampin (1993), these observations show similar properties at all scales. Liu et al. (1993a), in shallow (< 40 m) reverse VSPs in limestone with pronounced jointing where it is likely that the limit on crack density before fragmentation occurs is exceeded, report shear wave anisotropy of about 10% as well as pronounced anisotropic attenuation. Graham and Crampin (1993) report shear-wave splitting from regional earthquakes that suggest substantial differential shear wave anisotropy of 10% averaged over the whole thickness of the crust where the anisotropy is concentrated in the lower crust.

Table 3. Scales over which 1 – 4% shear-wave anisotropy has been observed.

Frequency (Hz)	Path length (m and km)	Rock type	Reference
4200	8-60 m	granite at 420 m	Holmes et al. (1993)
20	15-40 m	near-surface*	Liu et al. (1993b)
6	1-2 km	sedimentary basins	Slater et al. (1993)
6	1-2 km	sedimentary basins	Yardley and Crampin (1993)
0	1-3 km	sedimentary basins	Li et al. (1993)
5-10	4-40 km	mixed geology above earthquakes	Booth et al. (1993)
3-10	5-15 km	mixed geology above earthquakes	Rowlands et al. (1993)
0	5-12 km	mixed geology above earthquakes	Liu et al. (1993c)
1	30 km	whole crust*	Graham and Crampin (1993)

*Differential shear-wave anisotropy of about 10%.

Orientations of EDA Cracks

It is expected that EDA cracks, like hydraulic fractures, are aligned perpendicular to the direction of minimum compressional stress. At the surface, the minimum stress direction is typically vertical but the direction of this minimum rotates as the overburden increases with depth. Eventually the vertical stress exceeds the minimum horizontal stress and below that depth it is expected, and shear-wave splitting appears to confirm, that the statistical average of EDA cracks will be typically vertical, striking parallel to the maximum horizontal compressional stress (Crampin, 1990).

Such uniform orientations of stress and EDA cracks will persist throughout at least the top brittle half of the crust in stable regions such as sedimentary basins. This has been demonstrated in several studies of shear-wave polarizations above the Austin Chalk in Texas (Alford, 1986; Mueller, 1991, 1992; Li et al., 1993; Yardley and Crampin, 1993). Note that multiplanar distributions of parallel vertical cracks yield polarizations and time delays which in many cases are indistinguishable from those of monophanar parallel vertical cracks with the average alignment of the multiplanar distributions (Liu et al., 1993a). This means that distributions of multiplanar crack orientations could cause a ±10° to ±20° scatter in polarization directions, which may well be one of the reasons for the scatter in observed shear-wave polarizations above small earthquakes. Bedding and topography can cause large stress changes in comparatively undisturbed areas, including reorienting stress by as much as 45" (Warpinski and Teufel, 1991). In tectonically disturbed areas much larger variations may be expected.

One of the phenomena that are not wholly understood at present is that it is very common in shear-wave VSP experiments and reflection surveys for relatively large time delays between the split shear waves to be set up in the top few tens to hundreds of metres which then persist, or sometimes decrease, as waves propagate through underlying structures (Lewis, 1989; Li and Crampin, 1991; Winterstein and Meadows, 1991a; Slater et al., 1993; Yardley and Crampin, 1993). Sometimes the increase and decrease of time delays appears to alternate with depth (Squires et al., 1989). There are several possible explanations. Rotations of 90" of the axes of principal stress are expected near-surface as the overburden increases with depth (Crampin, 1990). The direction of minimum stress, which is thought to control the orientation of fluid-filled EDA cracks, might also alternate with the intermediate stress in areas where brittle beds carry horizontal stresses so that interleaved softer rocks respond to a different stress regime. Both these are directly stress-induced phenomena. However, changes of 90" in shear-wave polarizations may also occur in uniform media when the directions of raypaths straddle directions of shear-wave singularities, as raypaths vary in combinations of matrix anisotropy (caused by bedding or lithology) and crack-induced anisotropies. Such combinations are thought to be common in sedimentary sequences (Crampin, 1991a; Wild and Crampin, 1991) and may provide an explanation for the changes of 90" in shear-wave polarizations in uniform anisotropic structures that do not require geological complications.

The strong near-surface anisotropy, such as that observed by Crampin et al. (1980b) and Liu et al. (1993b) where shear wave radiation patterns may vary substantially over comparatively short distances, with different radiation patterns and different preferred shear-wave polarizations and time delays is known as Natural Directivity, ND (Puzirev et al., 1985). ND can be a function of weathering, joints and fractures, stress relaxation, soil compaction and other phenomena which can substantially vary over metres. This was demonstrated for soil compaction by Puzirev et al. (1985). Such ND may affect the interpretation of source functions for all surface shear-wave sources in reflection profiles and VSP offsets and the cause of anomalies in the walkaway VSPs of Slater et al. (1993) can probably be ascribed to such effects. It is tempting to dismiss such phenomena as shear-wave statics in the same way as P-wave statics has been dismissed as an awkward necessity. It is suggested that since the behaviour of shear-wave waveforms is often the key to interpreting shear waves, the sometimes pronounced ND anisotropy must be understood if shear-wave recorders and sources are going to be used at the surface.

DEPTH RANGE OF EDA CRACKS

Observations of shear-wave splitting record the polarizations and the time delays established in the medium within a few wavelengths of the receiver. There is no direct information about the location or extent of the anisotropy along the raypaths. The most direct information about the extent of the anisotropy is the time delay between the split shear waves, which should increase with distance through the anisotropy. However, there are two principal difficulties. Time delays are difficult to estimate from seismograms (Chen et al., 1987) because the arrival of the second split shear wave marking the end of the time delay always arrives on a record disturbed by the faster split shear wave and the second split shear wave is likely to be modified by more severe attenuation than the faster shear-wave arrival (Crampin, 198 1). The second difficulty is that time delays through an anisotropic medium necessarily vary with direction so that it must be expected that time delays vary from the maximum value through zero where the faster polarization changes by sign to a negative value for directions within a few tens of degrees of each other. These difficulties make estimates of depth range of anisotropy difficult except for direct estimates in VSPs.

1) Upper crust:

Shear-wave splitting is seen above small earthquakes and acoustic events whenever there are suitable three-component digital networks within the shear-wave window of the events (Crampin and Lovell, 1991). Such events may range in depth from 400 m (Holmes et al., 1993) through 1.5 km (Roberts and Crampin, 1986) to 22 km (Peacock et al., 1988). In general, each set of data displays similar polarizations with respect to stress orientations and similar time delays (when normalized to distance) even in quite complicated tectonic regions such as near the North Anatolian Fault (Booth et al., 1985). There is no proven technique for estimating the level at which the anisotropy occurs but the consistency of the shear-wave characteristics usually suggests a well-distributed region of low-level anisotropy, rather than a shallow near-surface layer of much stronger anisotropy, although this is difficult to exclude.

Shear-wave splitting is also seen in VSPs and reflection surveys down to several kilometres in sedimentary basins (Alford, 1986; Bush and Crampin, 1991; Mueller, 1991, 1992; Li et al., 1993; Yardley and Crampin, 1993; amongst many others) and areas of tectonic disturbance (Squires et al., 1989; Yardley and Crampin, 1990; Winterstein and Meadows, 199 la, b). High near-surface anisotropy, ND, is frequently observed both in reflection surveys (Li et al., 1993) and VSPs (Slater et al., 1993; Yardley and Crampin, 1993) and often is associated with a decrease in anisotropy at depth.

One important factor which should be taken into account is that the behaviour of fluids, such as water, changes substantially with increasing temperature and pressure. Generally, the fluid velocity increases with increasing pressure at any given (high) temperature (Burnham et al., 1969). However, at temperatures near 400°C, the acoustic velocity of water initially decreases from about 1.5 km/s at surface pressures to about 0.5 km/s at about 100 MPa, before increasing with increasing pressure. This anomaly apart, the increase of fluid velocity with increasing pressure means that the seismic effects of increasing aspect ratio by increasing pressure are accentuated by the corresponding decrease in pore-fluid velocity (Crampin et al., 1990; Crampin et al., 1991d).

2) Lower crust:

Correlations of seismic velocities and electrical resistivity suggest that fluid-filled openings in the rock mass exist below the brittle/ductile transition, possibly throughout much of the lower crust (Marquis and Hyndman, 199 1, 1992). Both velocities and resistivities in the lower crust are generally lower in Phanerozoic areas of sedimentary accretion than in Precambrian areas of Archaean rocks, implying higher porosity (Marquis and Hyndman, 1992). In the ductile zone of the lower crust, it is expected that textural equilibrium (pore equilibrium) applies to rock grains, minimizing the solid-fluid surface energy (von Bargen and Waff, 1986). This makes the value of the dihedral angle at fluid/solid interfaces crucial for retaining fluids within the rock mass. Fluids with dihedral angles greater than 60°, such as carbon dioxide and methane, are thought to be retained within the rock mass as isolated pores at the corners of crystal grains. Fluids with dihedral angles less than 60°, such as water and brine, will percolate freely through the rock mass (von

Bargen and Waff, 1986). This suggests that carbon dioxide is likely to be retained in openings throughout the lower crust whereas water and brine may be dispersed, unless contained by impermeable seals. [Note, however, that the dihedral angles of fluids at high temperatures and pressures (supercritical fluids) are not well-known, and if they are modified substantially different conclusions might be drawn.]

This suggests that there may be two types of lower crust: the Phanerozoic containing higher densities and the Precambrian containing lower densities of cracks and inclusions, In the absence of seals, the Phanerozoic areas would be pervaded by cracks and inclusions possibly containing carbon dioxide. It is well-known from P-wave reflection surveys that there are two types of lower crust, those pervaded by P-wave reflectors (of unknown provenance) and those that are transparent to ***P-waves.*** There are a few published examples of the presence or absence of shear-wave splitting in the lower crust. Gledhill (1991) finds anisotropy ranging from 20 to 30 km in the possibly Phanerozoic crust beneath the Wellington Peninsula, New Zealand. Graham and Crampin (1993) analyzing shear-wave splitting from regional events in Turkey find shear-wave splitting which may be interpreted as indicating substantial shear-wave splitting (over 10%) in the Phanerozoic lower crust in western Turkey, which was accreted from the subduction of the Tethyan Sea.

CONCLUSIONS

Shear-wave splitting with similar properties displaying azimuthal variations is widely observed along almost all raypaths in the upper half of the crust through almost all types of rock. Although anisotropy caused by crystal or fabric alignment cannot be excluded in specific localities, the constraint implied by near-parallel alignments of shear-wave polarizations, indicating approximately hexagonal symmetry with symmetry axes nearly parallel to the current direction of the maximum horizontal stress, places severe restrictions on possible causes of the shear-wave splitting. The similarities suggest a common cause, and the only common source of such hexagonal symmetry present in almost all rocks is stress-aligned fluid-filled EDA cracks. This paper reviews a large body of evidence supporting the hypothesis of extensive-dilatancy anisotropy, that is the shear-wave splitting is caused by distributions of stress-aligned cracks, microcracks and preferentially oriented pore space throughout most rocks in at least the uppermost half of the crust. There is some evidence of similar splitting implying similar symmetry systems in Phanerozoic areas of the lower crust.

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