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A decade of shear-wave splitting in the Earth's crust: what does it mean? what use can we make of it? and what should we do next?

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SUMMARY

It is 10 years since shear-wave splitting, thought to be diagnostic of some form of seismic anisotropy, was first positively identified in the Earth's crust. From the beginning it was argued that the splitting was probably associated with the presence of stress-aligned cracks (inclusions) in the crust, and that this would provide the opportunity for monitoring the *in situ* geometry of cracks and stress in a variety of different circumstances and in a variety of different applications. The early promise was not immediately realized, and the first 10 years were spent mainly in observing the phenomena in a variety of different situations. However, 1990 appeared to mark a turning point for anisotropy. Papers at the Fourth International Workshop on Seismic Anisotropy and elsewhere have announced major progress in understanding, interpreting, and particularly processing shear-wave splitting, with direct applications to hydrocarbon production, and a possible (but disputed) application to monitoring stress changes before earthquakes. However, there is still much that we do not understand about the phenomenon, and we are clearly only just beginning to appreciate the enormous information content of the shear wavetrain and its potential applications to science and engineering in the Earth's crust.

This paper briefly reviews the past 10 years, and speculates on how best we can exploit this new window of opportunity for exploring the internal structure of the crust. In particular, what causes the shear-wave splitting? what use can we make of the phenomenon? and what should we do next?

Key words: Earth's crust, seismic anisotropy, shear-wave splitting.

1 INTRODUCTION

Much of the Earth's crust appears to be effectively anisotropic to seismic waves so that, when appropriate equipment records appropriate signals, shear-wave splitting is almost universally observed, subject only to a few quite well-understood restrictions. Fig. 1 gives a schematic view of shear-wave splitting, where an approximately vertically propagating shear wave splits into two polarizations which propagate at different velocities and with different (fixed) polarizations. Identifying shear-wave splitting in the crust required two criteria to be met: digital three-component recordings made at high sampling rates so that the phenomena could be displayed; and sufficient understanding of the phenomena to be able to interpret what was observed. Appropriate technology for digital three-component recording only became readily available over the last 10 years or so, and the necessary insights into the behaviour of shear waves in anisotropic media were again made just over 10 years ago (Keith & Crampin 1977; Crampin 1978, 1981).

Following the suggestions in Crampin (1978), shear-wave splitting was first positively identified above small earthquakes by Crampin *et al.* (1980), and by Crampin, Evans & Üçer (1985) and Buchbinder (1985). Shear-wave splitting was also reported from a number of sedimentary basins (Alford 1986; Lynn & Thomsen 1986; Willis, Rethford & Bielandski 1986; Crampin *et al.* 1986a; and several others). Although much of the theoretical and computational developments were well established and the potential importance of shear-wave splitting had been identified some years before (Keith & Crampin 1977; Crampin 1978, 1981), widespread recognition of shear-wave splitting in the crust only became possible when three-component digital recording became available. Since 1986 there has been increasing interest both by earthquake and exploration seismologists in observations of shear-wave splitting in the crust, and sessions on seismic anisotropy

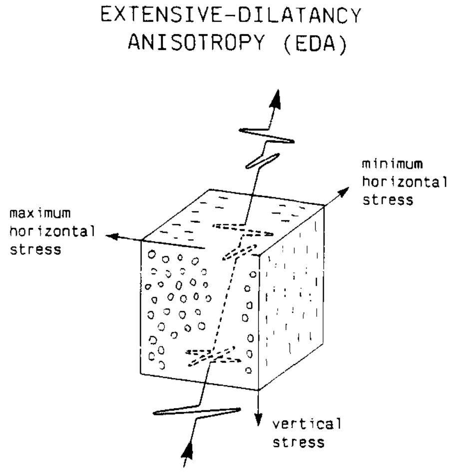

Figure 1. Schematic illustration of shear-wave splitting in the crust. A shear wave travelling along a ray path within about 35° of the vertical generally splits in two components with different arrival times and different, often nearly orthogonal, polarizations, where the polarization of the faster component is usually parallel, or sub-parallel, to the direction of maximum horizontal stress. In most cases, the splitting appears to be caused by the stress-aligned fluid-filled cracks, microcracks, and preferentially oriented pore space pervading most rocks in the uppermost 10 to 20 km of the crust. These distributions of aligned inclusions are known as extensive-dilatancy anisotropy, or EDA.

have become routine at a wide variety of meetings. This initial development culminated in 1990, when significant advances in observing, processing, interpreting, and applying shear-wave splitting were presented for the first time at the Fourth International Workshop on Seismic Anisotropy, 2–6 July, 1990, Edinburgh.

Despite the abundance of observations, there are many important questions still to be answered. It is still not clear exactly what causes shear-wave splitting in the crust. Although it is generally taken to be caused by aligned fluid-filled inclusions, we do not know how to distinguish whether the splitting is caused by large fractures, metres in diameter, say—small fractures or aligned pore-space a centimetre or less in dimensions—or micro-inclusions a few microns in diameter. The real difficulty is that the behaviour of shear waves and shear-wave splitting is essentially different from that of *P*-waves and carries different information from the *P*-wavetrain (Crampin 1981). This means that recording shear-wave splitting successfully requires specifically designed field experiments and very few wholly appropriate experiments have yet been devised. Most of the recording, processing, and to some extent the interpretative techniques, of the majority of shear-wave experiments up to now have been merely modifications of ideas developed over many years of using *P*-waves. These are almost certainly not optimal for shear waves.

The development of seismic anisotropy is now progressing too quickly to make an overall review easy, useful, or even possible, as any review is likely to be significantly out of date by the time it is published. This will be a somewhat biased account of one group's speculations about this exciting new opportunity for investigating internal properties of the rockmass which although important are inadequately understood. We believe that the most important developments, and certainly the most important applications are still in the future.

Some of the major questions still to be addressed are as follows.

(1) What causes the shear-wave splitting? Is the splitting the result of micro-inclusions, macro-cracks, large fractures, or some other source of effective anisotropy? How uniform is the anisotropy? To what depth does it extend? How does it vary?

(2) What use can we make of this new shear-wave technology which gives us, for the first time, access to the internal stress- and crack-structure of the *in situ* rockmass? Since stress and cracks are always important whenever we mine, drill, or excavate, or whenever we are interested in the detailed dynamics of the crust, there may be important applications. Can we yet identify them?

(3) What should we do next to increase our chances of exploiting these potentially important investigative techniques? Do we need new field experiments, new processing techniques, or new interpretative techniques?

Finally, it is claimed that this understanding of shear-wave propagation is a fundamental advance for seismology. In a further 10 years, how different is seismology going to be?

1.1 Commentary

(1) The behaviour of shear waves is basically different from the behaviour of *P*-waves and requires a new terminology to describe it. Crampin (1989) has suggested a consistent terminology to describe shear-wave phenomena, and this will be used throughout this review.

(2) Appendix A sets out some basic characteristics of shear waves and shear-wave splitting that are necessary to understand the behaviour of shear waves in the crust, and are a useful background for reading this paper.

(3) This paper principally refers to *azimuthal anisotropy*, where the behaviour of shear waves varies with azimuth and angle of incidence. This is fundamentally different from the *azimuthal isotropy* of what we shall refer to as matrix anisotropy, caused either by fine layering (PTL anisotropy) or aligned grains (lithologic anisotropy), both with a vertical axis of symmetry, so that shear waves split into strictly *SV*- and *SH*-wave polarizations.

Since Keith & Crampin (1977), computer programs, of varying degrees of sophistication, have been developed for calculating synthetic seismograms in anisotropic media. This is a separate development and will not be discussed here.

2 THE FIRST 10 YEARS

2.1 Observations of shear-wave splitting above earthquakes

From the outset, shear-wave splitting in the crust has been associated (not necessarily correctly) with aligned cracks. Crampin (1978) recognized that most rocks were likely to be cracked, that the cracks were likely to be aligned by the prevailing stress-field, and that shear-wave splitting (or birefringence) was probably the most diagnostic feature of wave propagation in such effectively anisotropic rock. A series of closely spaced three-component instruments designed to search for shear-wave splitting in stress-induced dilatancy were deployed over a swarm of small earthquakes near the North Anatolian Fault in Turkey, and the first positive identification of shear-wave splitting in the crust was made by Crampin *et al.* (1980). The recordings were analogue magnetic tapes (subsequently digitized), and the motion of the shear waves displayed in polarization diagrams (hodograms) showed behaviour similar to that of synthetic waves propagating through models of cracked rock (Crampin 1978). Progress was slow at first, and the next papers on observations of shear-wave splitting were in 1985, with a further seven papers about shear-wave splitting above small earthquakes in Turkey (introduced by Crampin *et al.* 1985), and a report of observations of shear-wave splitting in the Charlevoix seismic zone, Quebec (Buchbinder 1985).

Such shear-wave splitting has now been observed above earthquakes in a wide variety of geological and tectonic environments. Table 1 lists some of these observations. The most comprehensive examination of shear-wave splitting above small earthquakes has been in Japan, where splitting has been identified by Kaneshima and his colleagues in a wide variety of conditions in the four main islands (reviewed by Kaneshima 1990).

The major restriction on such observations is that, to obtain interpretable recordings of shear waves at the surface, the recording site needs to be within the shear-wave window. That is, shear waves need to have angles of incidence at the free surface less than the effective critical angle (Booth & Crampin 1985) of usually about 45° or 50° (see Appendix A2). This means that, to observe interpretable shear-wave splitting at the surface, in records of small earthquakes, the epicentral distance from recording sites must be no greater than the focal depth and preferably considerably less. Since many small earthquakes are shallow (between 5 and 15 km), comparatively closely spaced recording networks are required for the systematic observation of shear-wave splitting. Few networks have been sufficiently closely spaced to allow shear waves from earthquakes to be observed at more than a few isolated recording sites, and specially designed networks are required. The first and (as far as we are aware) the only networks specifically designed to record shear-wave splitting

Table 1. Observations of shear-wave splitting in the crust.

NATURAL EVENTS	
Above earthquakes in sedimentary rocks:	Booth *et al.* (1985); Buchbinder (1985); Crampin *et al.* (1980, 1985, 1986b); Du (1990); Kaneshima (1990); Kaneshima & Ando (1989); Young (1989).
Above earthquakes in igneous and metamorphic rocks:	Booth *et al.* (1985); Buchbinder (1990); Crampin *et al.* (1980, 1985, 1986b, 1990); Du (1990); Kaneshima (1990); Kaneshima *et al.* (1987, 1988b, 1989, 1990); Peacock *et al.* (1988); Saeki & Umeda (1988); Savage *et al.* (1989); Savage *et al.* (1990); Shih & Meyer (1990).
Mining induced rockbursts in mines:	Graham *et al.* (1991).
CONTROLLED SOURCE EXPERIMENTS	
Reflection profiles:	Alford (1986); Davis & Lewis (1990); Lewis (1989); Li & Crampin (1991b); Lynn & Thomsen (1986); Martin & Davis (1987); Mueller (1991); Squires *et al.* (1989); Willis *et al.* (1986).
Vertical seismic profiles:	Becker & Perelberg (1986); Becker *et al.* (1990); Bush & Crampin (1991); Cliet *et al.* (1991); Daley *et al.* (1988); Davis & Lewis (1990); Johnston (1986); Leary *et al.* (1987); Lefeuvre *et al.* (1989); Li & Crampin (1991b); Majer *et al.* (1988), but see Campden & Crampin (1990); Martin & Davis (1987); Naville (1986); Nicoletis *et al.* (1988); Peron (1990); Queen & Rizer (1990); Winterstein & Meadows (1990a,b,c,d); Yardley & Crampin (1990).
Crosshole surveys:	Li & Crampin (1991b); Liu *et al.* (1991).

were the three Turkish Dilatancy Projects on the North Anatolian Fault in 1979, 1980, and 1984 (Crampin *et al.* 1985; Evans *et al.* 1987).

Another difficulty with observations of shear-wave splitting above small earthquakes is that earthquakes usually occur in areas of complicated geology and tectonics. As a ray of shear waves passes from one rock type to another with different properties (possibly different matrix velocities, crack densities, crack aspect-ratios, and crack orientations), each split shear wave may split again. This frequently leads to observations of shear waves above earthquakes displaying multiple splitting. Since split shear waves necessarily adopt the polarizations of the structure within a few wavelengths of the recording site, the multiple splitting usually shows polarizations alternating between the two orientations of the near-site anisotropy. Since earthquakes have a wide range of source parameters, shear-wave splitting frequently displays wide variations of behaviour (Crampin & Booth 1985) and it is seldom that multiple shear-wave splitting can be correlated either between recording sites or between events. A particular difficulty of multiple splitting is estimating time delays between split shear waves. Time delays are an important measure of the degree (percentage) of shear-wave anisotropy, but multiple splitting frequently makes it difficult to obtain consistent readings.

Shear-wave splitting is believed to be caused by the stress-aligned fluid-filled inclusions present in most rocks. This is difficult to prove directly. However, because such inclusions would be the most compliant elements of the rockmass, appropriate changes to the conditions acting on the rockmass may be expected to modify the geometry of the inclusions, and hence modify the behaviour of shear waves passing through the rockmass. Thus, temporal changes in shear-wave splitting would strongly indicate fluid-filled inclusions.

Such temporal changes have been identified at Anza, before and after an $M = 6$ earthquake in California (Peacock *et al.* 1988; Crampin *et al.* 1990), and at Enola, before and after $M = 3$ earthquakes in Arkansas (Booth *et al.* 1990), and before and after hydraulic pumping in Cornwall (Crampin & Booth 1989). Note however, the discussion in Section 3, below. Crampin *et al.* (1990) were able to simulate the observed effects before earthquakes by increasing the aspect ratio of aligned cracks throughout the rockmass from $AR = 1/300$ to 1/100 over three years before the Californian ($M = 6$) event, and a return to the initial 1/300 at the time of the earthquake (or possibly shortly before, Booth *et al.* 1990).

Note that Aster, Shearer & Berger (1990) used an automatic algorithm on the same dataset as Peacock *et al.* (1988) and Crampin *et al.* (1990) and did not find the same variations with time. However, Crampin *et al.* (1991) were able to demonstrate that the comparatively simple algorithm of Aster *et al.* (1990) was clearly not appropriate for estimating shear-wave splitting above earthquakes (see discussion in Appendix B1.3). Ray paths from earthquakes and earthquake mechanisms are frequently complex producing multiple splitting and complicated waveforms. As a result, automated algorithms to measure shear-wave splitting above small earthquakes are seldom successful.

The anelastic 'bowing' of samples in the laboratory under strong uniaxial stress, suggests that a smaller increase of stress acting on the distributions of fluid-filled inclusions already pervading the *in situ* rockmass might also result in a similar increase in aspect ratio as the stress is increased, and a corresponding decrease as the stress is relaxed.

2.2 Observations of shear-wave splitting in controlled-source experiments

The phenomenon of stress-aligned fluid-filled inclusions was recognized as being pervasive in most rocks, and shear-wave splitting in exploration seismics was anticipated (Crampin 1983; 1984a). In 1986, this was confirmed when several oil companies reported that they had identified shear-wave splitting in a number of sedimentary basins. Stimulated by Alford's (1986) identification of shear-wave splitting in reflection surveys, two sessions at the 1986 Annual SEG convention in Houston discussed observations of shear-wave splitting in reflection surveys and vertical seismic profiles (VSPs) in hydrocarbon reservoirs. There were papers from Amoco (Alford 1986; Lynn & Thomsen 1986; Willis *et al.* 1986), Arco (Corrigan, Justice & Neitzel 1986), Compagnie Générale de Géophysique (Naville 1986), Chevron (Frasier & Winterstein 1986), and Exxon (Becker & Perelberg 1986; Johnston 1986)—note that Becker & Perelberg later withdrew their claim for the exceptionally strong (25 per cent) differential shear-wave anisotropy they initially reported. The year 1986 also saw the first tentative steps at matching synthetic to recorded seismograms of shear-wave splitting in multi-offset VSPs in the Paris Basin by Crampin *et al.* (1986a).

An important innovation was the use of two shear-wave source orientations, which when recorded on two horizontal geophone components leads to *four-component seismic surveys*. These were first used in the field by Robertson & Corrigan (1983) demonstrating azimuthal isotropy in shales. The vector combination of two source orientations allowed Alford (1986) to rotate source and geophone polarizations synchronously until they coincided with the fixed polarizations of the anisotropy. This rotation, known as the Alford rotation, was important for the initial introduction of shear-wave splitting to exploration seismologists. The addition of a vertical *P*-wave source and vertical geophones leads to full *nine-component surveys,* which combine conventional *P*-wave data acquisition with the new shear-wave technology.

2.2.1 *Reflection surveys*

Following the pioneering work by Alford (1986), Lynn & Thomsen (1986), and Willis *et al.* (1986), and others, there has been comparatively little work with shear-wave reflection surveys in anisotropic substrates. The Reservoir Characterization Project, Colorado School of Mines reported a comprehensive 3-D shear-wave reflection survey in Silo Field, Wyoming in which shear-wave polarizations were correlated with fracture orientations (Martin & Davis 1987; Lewis 1989). Squires, Kim & Kim (1989) interpreted a reflection profile in the Lost Hills Oil Field, Kern County, California, in terms of 90° changes in shear-wave orientation (crack orientation) in some blocks within the rockmass.

At least part of the reason for the small number of reported three-component shear-wave reflection surveys has been the realization that there are at least three, possibly severe, problems with surface to surface shear-wave reflection surveys. They are all the result of the recorded polarizations being those of the structure surrounding within a wavelength or two of the recording site.

(1) If the polarizations of the shear waves vary throughout the rockmass, the observed polarizations are those of the near-surface structure, not those of the deeper zone of interest.

(2) The changes brought about by shear waves interacting both with the free surface (Booth & Crampin 1985) and with internal interfaces (Liu & Crampin 1990) disturb surface to surface reflection surveys much more severely than they disturb VSPs where only the source is at the surface (Yardley & Crampin 1991).

(3) Fluid-filled inclusions, like hydraulic fractures, tend to open and remain open perpendicular to the direction of minimum compressional stress. Since this minimum will be vertical near the surface, but horizontal at depths where the vertical stress exceeds the minimum horizontal stress, there are likely to be orientation anomalies near the surface (Crampin 1990a). At the very near-surface, there are also likely to be weathering effects which may lead to multi-planar vertical cracks and joints in surface outcrops, but except for those subparallel to the direction of horizontal compression, these probably do not remain open below the weathered zone.

These various anomalies mean that the polarizations of shear waves seen on surface recordings may not be the polarizations at depth in the zones of interest. This suggests that shear-wave reflection surveys will be useful only in particular circumstances, specifically, where the near-surface structure is particularly simple, and particularly where crack orientations are relatively uniform throughout the rockmass. Certainly, stress directions may change locally in areas of tectonic disturbance (near faults for example), or between beds or strata of differing elastic properties, but at present there is too little information about stress orientations at depth to recognize how serious a problem this is going to be for shear-wave reflection surveys.

2.2.2 *VSPs*

Since shear-wave polarizations tend to be determined by the anisotropic structure close to the recorder, analysis of VSPs at geophone levels near to a zone of interest is clearly more informative for investigating shear-wave splitting in the zone of interest than surface to surface reflections. Shear-wave splitting is commonly seen in three-component VSPs (Crampin 1984a, 1987a), and it is comparatively easy to measure the polarizations and time delays in VSP seismograms. Consequently, most of the important developments have been in VSP recording and analysis.

Two developments have been particularly significant.

Anisotropy may be difficult to interpret intuitively, and clearly the most complete confirmation that an interpretation is correct is that the particle displacements of the recorded motion can be matched by fullwave synthetic seismograms. Analysis of a multi-offset VSP in the Paris Basin by matching synthetic and observed polarization diagrams has been particularly informative (Bush 1990; Bush & Crampin 1987, 1991; Crampin *et al.* 1986a). The data showed non-parallel shear-wave polarizations at different azimuths and offsets, and polarizations dominated by parallel cracks and fractures were clearly not sufficient. In a comprehensive examination, Bush (1990) demonstrated that the anomalous behaviour could be the result of the plausible combination of matrix anisotropy (transverse isotropy, or azimuthal isotropy, with a vertical axis of symmetry commonly found in sedimentary basins) and crack anisotropy. The patterns of particle motion of fullwave synthetic seismograms were a good match of the details of the observed patterns at five of the offsets (Bush & Crampin 1991) confirming for the first time the orthorhombic symmetry of, at least some, sedimentary basins.

The second important development has been the layer stripping technique of Winterstein & Meadows (1990a, b, c, d), at a range of VSPs in California, including a comprehensive multi-offset VSP in the Lost Hills Field. Vectorially combining shear-wave polarizations from level to level down geophone strings, allows the variation in time delay and polarization to be estimated as they vary with depth. However, there are some severe limitations (see discussion in Appendix B2.4).

2.2.3 *Crosshole surveys (CHSs)*

Cracks at depth in the crust usually appear to be aligned parallel and vertical (Crampin 1990a). This means that for nearly vertically propagating shear waves, the faster split shear wave is polarized approximately parallel to the strike of the cracks (subject to the complications of combinations of matrix and crack anisotropy, see Section 2.2.2, above). This is a very informative, directly interpretable phenomenon. Shear waves along more nearly horizontal ray paths in CHSs do not display such distinctive phenomena (Liu, Crampin & Booth 1989) and there may be no characteristic behaviour that can be immediately interpreted in terms of crack alignments unless the azimuth of the (usually vertical) plane sampled by the CHS has a particular geometrical relationship with the aligned cracks.

It has been shown both theoretically [from the calculation of dispersion curves and synthetic seismograms (Lou & Crampin 1991)] and observationally (Liu, Crampin & Queen 1991) that when there is continuity of interfaces between the wells, the energy from a suitable source at a suitable depth may propagate as modes of guided waves tied to one or more interfaces. Sometimes these waves may be more appropriately called channel waves, interface waves, or Stoneley waves, but in a very wide set of circumstances there will be some mode, or modes, propagating at most depths in most layered structures. These will frequently be inhomogeneous so that energy leaks into the regions above and below the guiding structure.

In an isotropic structure there are two families of modes with Rayleigh- and Love-type motion, combining *P*- and *SV*-wave particle motion, and *SH*-wave particle motion, respectively. In anisotropic structures, one family of generalized mode guided waves will propagate with elliptical motion in three dimensions, combining particle motion in the sagittal plane (*P*- and *SV*-waves, or Rayleigh wave) and transverse-horizontal motion (*SH*-wave, or Love wave) (Crampin 1975). This 3-D particle motion is very sensitive to the details of the anisotropy and structure along the wavepath. Liu *et al.* (1991) show that guided waves tied to a shallow relatively high-velocity limestone layer at the Conoco Borehole Test Facility, Oklahoma, display generalized three-component motion that is compatible with the orientations of joints and fractures on neighbouring surface outcrops.

2.2.4 *Reverse VSPs*

Reverse vertical seismic profiles, where the source is downwell and is recorded by surface geophones, is subject to many of the disadvantages of surface to surface reflection surveys (see Section 2.2.1, above), but in appropriate circumstances can provide useful information about crack alignments (Liu *et al.* 1991).

3 WHAT CAUSES SHEAR-WAVE SPLITTING?

Shear-wave splitting, where an incident shear wave splits into two phases with polarizations that are not parallel to *SV*- and *SH*-waves, is diagnostic of some form of effective azimuthal anisotropy along the ray path (Keith & Crampin 1977; Crampin 1981). Five possible sources of such seismic anisotropy in the rockmass have been suggested (Crampin, Chesnokov & Hipkin 1984b; Crampin 1987a):

(1) aligned crystals;
(2) direct stress-induced anisotropy;
(3) lithologic anisotropy (for example aligned grains);
(4) structural anisotropy (for example fine layering); and
(5) stress-aligned crack-induced anisotropy.

Each of these phenomena could in certain circumstances cause shear-wave splitting locally, but only stress-aligned vertical fluid-filled cracks are likely to cause comparatively uniform splitting oriented parallel or sub-parallel to the present-day directions of maximum horizontal stress throughout at least the uppermost 10 to 20 km of the crust. The arguments for crack-induced anisotropy have been repeated in several places (Crampin 1987a; Crampin *et al.* 1984b; Kaneshima & Ando 1989), but it is probably worth restating the principal arguments for fluid-filled cracks as the cause of the widely observed shear-wave splitting.

3.1 Arguments for fluid-filled inclusions

(1) Shear-wave splitting is seen along ray paths in almost all geologic materials: ranging from poorly consolidated sediments (Crampin *et al.*, 1986b) and sedimentary basins (Willis *et al.* 1986), to granite batholiths (Roberts & Crampin 1986; Kaneshima, Ando & Crampin 1987), and including a wide range of different structures of various degrees of complexity (Crampin 1987a; Peacock *et al.* 1988). Since the differential shear-wave velocity anisotropy (Crampin 1989) is usually similar (between 0.5 and 5 per cent) it is tempting, although not necessarily correct, to seek a common cause. Stress-aligned fluid-filled inclusions are the only source of anisotropy that has been suggested that is common to all rocks (Crampin *et al.* 1984b; Kaneshima 1990).

(2) The polarizations of the leading (faster) split shear wave, within the shear-wave window at the surface, are usually observed to be parallel or sub-parallel to the direction of maximum horizontal stress. There is frequently a scatter of ±15°, but these sub-parallel polarizations are observed even in areas of great structural complication such as the North Anatolian Fault (Booth *et al.* 1985). The only class of anisotropic symmetry that displays parallel polarizations over a ±45° or ±50° solid angle of directions is hexagonal symmetry with a horizontal axis of symmetry. Such hexagonal symmetry is a severe constraint that immediately restricts possible sources of anisotropy. Parallel vertical cracks have such symmetry, whereas the vast majority of rock-forming crystals do not (although partially aligned distributions of crystals may have hexagonal symmetry). Note that the anisotropic symmetry of sedimentary basins may be orthorhombic as a result of combinations of matrix anisotropy and crack anisotropy (Wild & Crampin 1991), which leads to variations in the polarizations of non-vertically propagating shear waves observed by Bush & Crampin (1991).

(3) The success of the match of synthetic with observed polarization diagrams in the Paris Basin data set (Bush & Crampin 1991), based on a combination of matrix and crack anisotropy, places quite tight constraints on the possible source of the anisotropy, although the interpretation is not mathematically unique. In general, the pattern of shear waveforms in polarization diagrams is very similar to those of synthetic seismograms calculated through parallel vertical cracks (Crampin & Booth 1985).

(4) The use of shear-wave splitting to identify fractures and fracture alignments in the Austin Chalk in Texas, which were later confirmed by horizonal drilling (Mueller 1991).

(5) Correlating the amount of hydrocarbon production with the percentage of differential shear-wave velocity anisotropy in oil fields with variable production in Wyoming (Lewis 1989; Davis & Lewis 1990) and Russia (Brodov *et al.* 1991; Cliet *et al.* 1991).

(6) Changes of shear-wave splitting with time would be confirmation of fluid-filled cracks as the cause of shear-wave splitting (Crampin 1978), as none of the other possible causes (Crampin *et al.* 1984b) is likely to vary with time. Temporal changes in shear-wave splitting have been claimed after hydraulic pumping in granite (Crampin & Booth 1989), and before and after earthquakes (Crampin *et al.* 1990; Booth *et al.* 1990). Although these last two claims have been disputed (and defended, see discussion in Section 2.1, above), they are consistent and plausible.

3.2 Difficulty of examination *in situ*

There are at least 20 phenomena affecting the behaviour of inclusions in the crust (Crampin 1987a), which are all directly or indirectly dependent on stress. This means that whenever we directly access *in situ* rocks by drilling or mining, the rock is at least partially de-stressed and a new stress anomaly imposed, so that the inclusions in any sample or viewed by any borehole instrumentation are not in their *in situ* condition. Since the time constants for these 20 phenomena range over at least six orders of magnitude, from the instantaneous elastic reponse to very long periods of time for some tectonic processes, it is clear that the geometry of the *in situ* inclusions cannot be restored merely by returning the stress-field to its (assumed) *in situ* state. Similarly, the inclusions have a continuous spectrum of dimensions ranging, again, over six orders of magnitude, from microns in igneous and metamorphic rocks to metres in fractured rock. This means that directly recognizing *in situ* crack distributions, and particularly crack alignments, in core samples and well-logs is not possible. Careful examination of core samples allow some deductions to be made (Blenkinsop 1990), but the interpretation is not straightforward.

3.3 Indirect and circumstantial evidence

Denied direct examination of the *in situ* inclusions, we are confined to indirect and circumstantial evidence for cracks in crustal rocks. There is considerable indirect and circumstantial evidence that the shear-wave splitting in the crust is caused by propagation through the fluid-filled cracks, microcracks, and pore-space known to be present in most sedimentary, igneous, and metamorphic rocks in the crust (Fyfe, Price & Thompson 1978; Crampin *et al.* 1984a; Crampin 1987a). Such fluid-filled inclusions are the most compliant elements of the rockmass and will become aligned in the prevailing stress-field and effectively anisotropic to seismic waves (Crampin *et al.* 1984a; Crampin 1985a; Crampin & Atkinson 1985).

3.4 Extensive-dilatancy anisotropy

These distributions of aligned inclusions are known as *extensive-dilatancy anisotropy* or *EDA* (Crampin 1987a). Since many of the effects of these inclusions, despite the possible wide range of physical shapes and dimensions, can be simulated by distributions of flat penny-shaped cracks, it is convenient to refer to the individual inclusions as *EDA cracks* (Crampin 1991b).

Note that when first identified, the phenomenon of EDA was though to refer only to stress-induced microcracks in earthquake preparation zones (Crampin *et al.* 1984a). As further observations subsequently demonstrated, shear-wave anisotropy exists in most rocks and is caused by a wide range of aligned inclusions of various dimensions and physical shapes, including the irregular but nevertheless marginally aligned pore space in sedimentary rocks. Such inclusions are stress-aligned but not necessarily directly stress-induced. Since the shear-wave splitting in this wide range of igneous, metamorphic, and sedimentary rocks, has remarkably similar properties in terms of shear-wave orientations and degree of effective anisotropy, it is convenient to retain the same name, EDA, but extend the meaning to include all types of inclusions (Crampin 1987a).

These initial investigations of shear waves in cracked rock were stimulated by the recognition, both experimentally in the laboratory (Nur & Simmons 1969) and theoretically (Crampin 1978, 1984b; Hudson 1981, 1982), that aligned cracks could cause shear-wave splitting. Initially such aligned cracks were expected to be present only in the strong stress field immediately in the vicinity of potential fault planes (Crampin *et al.* 1980). It soon became apparent, however, that shear-wave splitting occurred very widely in most crustal rocks, and it was suggested that aligned fluid-filled cracks were present in most rocks (Crampin 1984a, 1985a; Crampin & Atkinson 1985).

The various theoretical formulations for aligned cracks, discussed in Appendix C, have played an important part in the development of seismic anisotropy. However, until recently it was not possible to calibrate these theoretical formulations against real distributions of cracks, either in the laboratory or in the field, and the strongest argument for the validity of the formulations was the general consistency of the results with observations in the field (Crampin *et al.* 1985; Crampin 1987a), particularly in the matching of observed polarization diagrams of multi-offset Paris Basin VSPs (Bush & Crampin 1987, 1991). Recently, Rathore *et al.* (1991) made the first successful attempt to propagate waves through an artificial sample containing known distributions of parallel cracks with known parameters. This is an important advance. The results have not yet been critically examined, but in general appear to agree with theoretical formulations.

Despite the general consistency of the interpretation of shear-wave splitting in terms of extensive-dilatancy anisotropy, our understanding of the behaviour of shear waves is by no means complete. Appendix D lists a number of anomalies in shear-wave propagation that have not yet been convincingly explained. It is expected that any explanations are not going to seriously disturb the interpretation in the text of this paper. However, it is our experience that understanding such seeming anomalies usually contributes significantly to our understanding of the whole phenomenon of shear-wave splitting in the crust. Consequently, such anomalies could well indicate important areas for research.

4 WHAT USE CAN WE MAKE OF THIS SHEAR-WAVE TECHNOLOGY?

It has been suggested (Crampin 1985b) that the shear wavetrain typically contains three or four times the information carried by the *P*-wavetrain. Shear waves carry a different type of information from *P*-waves, contained in waveforms rather than arrival times, and these require different recording techniques from those used conventionally for *P*-waves. In particular, the multiplicity of source to geophone ray paths, required to analyse *P*-wave arrival times, is not needed to obtain information from shear waves. In principle, a few ray paths, possibly even a single ray path if the signal-to-noise ratio is appropriate, and possibly multiple source orientations, could supply information about crack and stress alignments.

The various attributes offer a new window of opportunity for examining the stress- and crack-structure *in situ*. What use can we make of this opening? The following list of suggestions is not in order of importance.

4.1 Understanding the geometry of fluid-filled inclusions

4.1.1 Identifying the geometry of the cracked rockmass

A study of the anisotropic symmetry should give some estimate of the alignments of the cracks. Assuming nearly vertical parallel cracks, as often appears to be the case, crack density and crack-strike can be estimated from nearly vertically propagating shear waves.

Once below the near-surface weathered zone and the near-surface stress anomalies (Crampin 1990a), it can be assumed that the pore-fluid in EDA cracks is usually liquid water or hydrocarbon, or some high-pressure, high-temperature, possibly heavily mineralized fluid phase. With these assumptions, the only other feature of the geometry of EDA cracks that can be reliably determined, at present, is the aspect ratio. If the temporal changes in the behaviour of shear-wave splitting at Anza (Peacock *et al.* 1988; Crampin *et al.* 1990) and Enola (Booth *et al.* 1990) are to be believed, then it is likely that the aspect ratio of EDA cracks in hard rock is small (flat cracks, with aspect ratios less than 0.01, say). In sedimentary rocks it is likely that the effective aspect ratio (the averaged effects of distributions of very irregular intergranular pore-space) is relatively large (Crampin 1991b), and indeed Kaneshima & Ando (1989), in an examination of shear-wave splitting in the Shikoku area of Japan where the surface rocks are sedimentary, suggest aspect ratios greater than 0.01. Note, however, that the structure is complex in this area, Kaneshima & Ando use events down to the subducting slab, and the interpretation has to make several assumptions that may not be wholly justified.

Almost no other features can be estimated at present. In particular, observations of velocity anisotropy carry very little information about the dimensions of the fluid-filled inclusions. This is because the likely dimensions of the inclusions, ranging from possibly a few microns in igneous and metamorphic rocks, through sub-millimetre inclusions in sedimentary rocks, to a few metres in fractured reservoirs, are so much smaller than the wavelengths of most shear waves observed in the crust, which are from several tens of metres in reflection experiments to several kilometres in teleseismic shear waves, that the effects are those of the long-wavelength limit. Multi-offset, multi-azimuth, three-component shear-wave vertical seismic profiles (VSPs) seem the best way to examine the geometry of cracks with shear waves. Crosshole surveys, although in principle having higher frequencies and consequently higher resolution, are less satisfactory than VSPs for examining the geometry of near-vertical cracks unless there happen to be a multiplicity of azimuthal cross-sections as from horizontal drilling (Liu *et al.* 1989).

4.1.2 Variation of shear-wave splitting with depth

There is conflicting information about the depth to which shear-wave splitting can be observed. Shear-wave splitting above earthquakes sometimes displays significant time delays and consistent near-parallel polarizations, even in complicated areas, which suggest that the effects are deep seated (Crampin *et al.* 1985; Crampin 1987a). Two pieces of direct evidence suggest splitting throughout the whole thickness of the crust. Gerhard Graham (private communication) found time delays of up to 1 s for regional events recorded at the TDP networks in Turkey, where splitting in the top half of the crust yields a maximum time delay of 0.17 s (Booth *et al.* 1985). Similarly, Yegorkina *et al.* (1977) find time delays of up to 1.2 s between shear waves from regional events in Armenia. These last observations were taken from analogue records and the data quality is low. Nevertheless, both these sets of observations suggest that in some areas, significant shear-wave splitting can occur in the lower half of the crust. In contrast, Kaneshima & Ando (1989) found evidence from earthquake seismograms to suggest that the largest contribution to splitting occurs in the top half of the crust, although thinner near-surface layers of stronger anisotropy could not be excluded. VSP observations frequently display splitting at several kilometres depth. Sometimes the anisotropy is greater near the surface (Bush & Crampin 1991; Winterstein & Meadows 1990c, d), but this is not always the case as the reflection profiles of Alford (1986) indicate. It is suggested that, just as there are areas where the lower crust displays high *P*-wave reflectivity, there are areas where the shear waves display significant splitting and other areas where they do not.

4.1.3 Understanding the near-surface crack- and stress-orientations

The polarizations of split shear waves suggest that fluid-filled inclusions within the rockmass are aligned perpendicular to the direction of minimum compressional stress just like hydraulic fractures (Crampin 1987a). Since the minimum compressional stress is typically vertical at the surface and horizontal at depth it is likely that shear-wave splitting may display a variety of behaviour near the free surface. Analysing shear-wave splitting, by shallow (<1000 m) multi-offset multi-azimuth VSPs for example, offers a technique for investigating the near-surface stress and inclusion orientations. Quite apart from the importance of this for many engineering, building, and near-surface investigations, it is also important for calibrating shear-wave surface-to-surface reflection surveys. This is because the polarizations of recorded shear waves are those within a cycle or two of the geophone, and any surface recording is likely to be dominated by the near-surface crack- and stress-geometry. Thus, unless the near-surface behaviour is understood, it may be difficult to extract the anisotropic parameters appropriate to the deeper structure.

4.2 Applications to hydrocarbon production and other industrial applications

4.2.1 Locating sub-surface fractures

Analysing shear-wave splitting in VSPs and reflection profiles may allow the orientation, and possibly the crack density, of sub-surface fractures to be estimated. Mueller (1991) identifies the location and orientation of vertical fractures in the Austin Chalk of Texas by analysing two shear-wave reflection profiles shot over the same ground with shear-wave sources oriented parallel and orthogonal to the fractures. Both position and orientation were confirmed by horizontal drilling.

4.2.2 Correlating production with amount of fracturing

Correlation of hydrocarbon production with the amount of observed shear-wave splitting has been possible in two areas. In a contoured map of the degree of shear-wave splitting seen in the Silo Field, Wyoming, the rate of production at a range of production wells approximately correlated with the high points in the anisotropy map (Lewis 1989; Davis & Lewis 1990). The map of anisotropy was obtained by a 3-D nine-component reflection survey. Similarly Cliet *et al.* (1991) and Brodov *et al.* (1991) were able to correlate the rates of hydrocarbon production with amount of shear-wave splitting in VSPs in two wells in the Romashkino reservoir, Tatarskaya, USSR. Estimates were also made for a further well which had not yet begun production. However, this excellent quantitative correlation depended on a number of physical assumptions and measurements of cores which are not necessarily universally valid.

4.2.3 Estimating the orientation of maximum compressional stress

The polarizations of the leading (faster) split shear-wave travelling along nearly vertical ray paths are parallel to the strike of vertical cracks (Crampin 1978, 1981; Crampin *et al.* 1985; Alford 1986), which are expected to be aligned perpendicular to the direction of minimum compressional stress. This means that the polarizations of a single shear-wave arrival along a nearly vertical ray path can give an estimate of the horizontal direction of maximum stress. Direct correlations of shear-wave polarization directions have not been reported widely in exploration literature (Bush & Crampin 1991 is an example), but it is commonly reported for shear waves above earthquakes (Crampin & Evans 1986; Crampin 1987b).

4.2.4 Estimating orientations of hydraulic fractures

The importance of the previous application is that observations of a few shear waves (not a full scale shear-wave VSP) recorded at an appropriate depth could give an estimate of the directions of the principal axes of stress, and could thus predict the orientations of any hydraulic fractures. This could provide important information for optimal design of patterns of injection and recovery wells for hydrocarbon production in sedimentary reservoirs. This also could give information for the development of hot-dry-rock geothermal reservoirs, but note that in hard rock such as granite, hydraulic pumping may open joints and fractures which may be at a small angle to the stress directions (Crampin & Booth 1989).

4.2.5 PTL and EDA anisotropy and singularities

Sedimentary basins frequently contain matrix anisotropy with a vertical axis of cylindrical symmetry caused by fine layering or aligned grains. [Theoretical formulations exist for obtaining the elastic constants of structures made up of periodic thin layers (Postma 1955) abbreviated to PTL, and for convenience we shall refer to such transverse isotropy of the matrix as PTL anisotropy, although it is recognized that the cause of the anisotropy may be various.] Such PTL anisotropy is recognized in exploration by horizontal *P*-wave velocities being greater, sometimes substantially greater, than vertical velocities. This possibly strong (up to 30 per cent) transverse isotropy with a vertical axis of symmetry of the PTL anisotropy combines with the weaker (usually less than 5 per cent) transverse isotropy with a horizontal axis of symmetry of the EDA anisotropy to yield a rock with orthorhombic symmetry. Such combinations of PTL and EDA anisotropy were first observed in the Paris Basin (Brush & Crampin 1991) and are probably common in sedimentary basins.

Such orthorhomic symmetry contains cones of ray path directions called shear-wave singularities, where the two phase velocity surfaces touch (Crampin & Yedlin 1981). The behaviour of shear waves in these cones is disturbed from the regular shear-wave splitting observed in other directions, and may vary rapidly for small changes in ray path direction (Crampin 1991a). In general, the smaller the ratio of EDA to PTL anisotropy the closer the cone of disturbed shear-wave propagation is to the vertical direction (Wild & Crampin 1991). Since this ratio is probably small for most sedimentary basins, directions of disturbed shear-wave propagation for near-vertical ray paths must be expected. Unless these directions of disturbed propagation are correctly identified as anomalies associated with possibly uniform anisotropy, they could be mistakenly interpreted as the effect of some structural irregularity or discontinuity. By contrast, if the phenomena are correctly identified, the directions of the singularities place quite close constraints on the ratio of EDA to PTL anisotropy. Since these two values are typically obtained from different data (PTL anisotropy from normal moveout corrections to *P*-wave velocities, and EDA anisotropy from observations of shear-wave splitting), an independent ratio would be an important confirmatory quantity which could be important for understanding the phenomena. (Also see the discussion of singularities in Appendix A4).

4.3 More speculative applications

The previous five applications are confirmed in the sense that test cases have provided direct evidence that the application works. The following two applications have not, to our knowledge, been confirmed, but would appear to be at least promising from *P*-wave observations of EOR, and what is known of the properties of seals and abnormally pressurized compartments.

4.3.1 Monitoring hydrocarbon production procedures such as enhanced oil recovery (EOR)

Hydrocarbon production alters the properties of the fluids in the inclusions within the rockmass, and observations of changes in *P*-wave response during fire or steam floods in heavy oils have been identified from reflection surveys (de Buyl 1989; Robertson 1989) and crosshole tomography (Justice *et al.* 1989). Since shear waves contain considerably more information than *P*-waves about the internal structure of the rockmass (Crampin 1985), it is likely that shear waves are more sensitive than *P*-waves to the changes during EOR, so that analysis of shear-wave propagation could be used to monitor production and EOR processes. There are two possibilities: because shear waves are very sensitive to the geometry of fluid-filled inclusions and the properties of the pore-fluids, in ways which probably no other technique can match, it may be possible to recognize unspecified changes to the rockmass by changes in the behaviour of shear-wave splitting. However, there is also the possibility that, in some circumstances, the actual, possibly 3-D, change to the fluid-filled inclusions might be identified. Since many processes at depth in hydrocarbon reservoirs are poorly understood, and are likely to be prospect specific, shear-wave analysis could provide important additional information for reservoir production and engineering.

4.3.2 Identifying seals and abnormally pressurized compartments

At present, there is believed to be no *P*-wave signature to seals or to abnormally pressurized compartments. However, Powley (1989) in his pioneering recognition of the geometrical relationships between seals and compartments, also recognizes that seals are subject to repeated cycles of hydraulic fracturing and sealing, and that abnormally pressurized compartments are pervaded by small open intergranular fractures, usually less than an inch long. Both these phenomena are likely to cause subtle changes in the crack-induced anisotropy of the rock, and consequently in the behaviour of shear-wave splitting. Sensitive techniques for identifying the parameters of shear-wave splitting are currently being developed (see Section 5.4, below) which may well allow the small changes in crack parameters in seals and pressurized compartments to be identified.

4.3.3 Monitoring stress changes before earthquakes (also see Sections 2.1 and 4.1, and Appendix B1)

The shear-wave splitting widely observed in most rocks appears to be caused by the stress-aligned fluid-filled inclusions (EDA cracks) pervading most rocks. Such fluid-filled inclusions would be the most compliant elements of the rockmass, and modifications of the geometry of these inclusions would be the most direct effect of changes of stress and strain on the rockmass, and changes in crack geometry would be expected to modify the behaviour of shear-wave splitting (Crampin 1978). Such changes in splitting are believed to have been observed before and after both a medium sized (Peacock *et al.* 1988; Crampin *et al.* 1990) and a small earthquake (Booth *et al.* 1990). The effects can be plausibly simulated by changes in aspect ratio of the EDA cracks, with possibly some minor modifications to the crack density (see Section 2.1). Many of the other precursors that are sporadically observed before earthquakes can be explained in terms of less direct effects of the stress-induced modifications of EDA cracks.

These changes in shear-wave splitting are, at present, the only known way that changes in stress and strain can be identified within the interior of the rockmass. There is much that is not understood about the causes of shear-wave splitting, the behaviour of EDA cracks, and the stress and strain within the *in situ* rockmass. Shear waves carry a great deal of 3-D information about the internal crack- and stress-geometry of the rockmass, and being able to monitor *in situ* changes in crack- and stress-geometry by analysing shear waves could be an important step towards earthquake prediction (Crampin 1987b).

4.3.4 Monitoring stress-changes before rockbursts in mines

Shear-wave splitting is observed in 200 to 500 Hz shear waves from rockbursts recorded subsurface in South African Gold Mines (G. Graham, private communication). The shear-wave splitting in general has characteristics very similar to those seen for 5 to 30 Hz elsewhere. Since in some circumstances shear waves from rockbursts can be observed over a very wide range of azimuths and incidence angles, these high-frequency signals may provide important information about the phenomenon of crack-related shear-wave splitting, as well as the possibility of monitoring changes before rockbursts. Another important advantage of studying rockbursts is that the source can be exhumed after the event, which could lead to a better understanding of the physical phenomenon.

4.3.5 Monitoring hazardous waste depositories

Shear waves are very sensitive to cracks and crack-alignments, and monitoring the geometry of EDA cracks would allow the directions of any post-depository cracking or leakage to be predicted. Perhaps more importantly, monitoring shear waves along ray paths, from repeated shear-wave sources to borehole geophones, bracketing the depository would be a very sensitive indicator of any change in the rockmass surrounding the depository.

4.3.5 Other possible applications

Shear waves are very sensitive to the internal structure of the rock through which they propagate. Consequently, analysing shear waves could be important for monitoring any situation where the rockmass is likely to suffer deformation or disturbance. Such applications could be monitoring: the disposal of waste fluids by injection into mines; solution mining of salt, potash, copper, sulphur, uranium, etc.; slope stability of mine debris and talus; and ground stability of buildings, tunnels, dams; etc. The advantages of shear waves are that they monitor new properties of the rockmass *in situ*. These may be important in their own right, but the overall importance is that analysing shear waves gives us a new, sensitive, technique for examining the internal structure of the rockmass, and consequently, a new technique for examining changes, particularly temporal changes, in phenomena about which we have very little information.

5 WHAT SHOULD WE DO NEXT?

The previous section identified a range of applications. We have just begun to develop techniques for exploiting the new information that shear waves can give us. Because shear waves carry so much information, a few shear waves along critical ray paths can provide critical information without the multitude of source-to-geophone ray paths required for most *P*-wave experiments. In this section we suggest a number of possible developments that would aid the progress of shear-wave technology in the future.

5.1 Differential shear-wave attenuation

The most important attribute of shear-wave splitting that has not yet been exploited is differential shear-wave attenuation. Usually attenuation is difficult to measure in the Earth, but some estimate of the differential shear-wave attenuation can be obtained comparatively easily from the relative amplitudes of the two split shear-waves which have travelled along the same ray path from the same source.

Note that there is a reciprocal relationship between velocity anisotropy and attenuation anisotropy. In directions where the velocity is relatively high, the attenuation is relatively low, and in directions where the velocity is low the attenuation is high (Crampin 1981). This is one of the reasons why the leading split shear wave is such a stable phenomenon: it is less attenuated than the slower split shear wave.

5.2 Inversion

Anisotropic parameters are almost always expensive to compute directly. This makes procedures which use database, look-up table, techniques particularly attractive (Doyle *et al.* 1985), particularly as more sophisticated versions allow comprehensive statistics to be computed (MacBeth, 1991a, b). There are two parameters of shear-wave splitting that offer possibilities for inversion, the polarizations of the leading split shear wave, and the time delay between the two split shear waves. Together, these are a powerful combination, because they each contain largely independent information, that when inverted should give similar results. Initially inverting data from VSPs seems most simple, but extensions to reflection surveys and other configurations are possible. MacBeth (1991a, b) is developing techniques for inverting the polarizations of shear waves from VSPs in a multi-layered structure and comparing the polarizations with those at appropriate azimuths and incident angles in a large database (currently about 50 000 structures). Shear-wave polarizations are particularly stable and robust (Crampin 1981), and the technique looks promising even when inverting only for polarizations. Additional inverting for time delays is likely to be particularly powerful.

5.3 Neural networks for pattern recognition

Identifying and estimating the parameters of shear-wave splitting is relatively simple in exploration type record sections, where a known source is observed over a range of ray paths at an array of closely spaced geophones, and many reasonably successful techniques have been devised (see Appendix B2).

The situation is quite different when estimating parameters of anisotropy from earthquake sources, where the source location, source mechanism, and source radiation pattern are unknown; the splitting has to be interpreted along individual ray paths and frequently in areas of topographic irregularities. Even the interaction of noise-free synthetic seismograms with a plane free-surface can lead to patterns of behaviour (Crampin & Booth 1985) that would be difficult to recognize with deterministic algorithms (see Appendix B1). In these circumstances, probably the best way to tackle automatic analysis of shear-wave splitting is by some form of pattern recognition within the framework of a neural network (Colin MacBeth, private communication); for geophysical applications of neural networks, see Raiche (1991).

5.4 Processing shear waves with the Shear-Wave Analysis Package (SWAP)

At present, preferred procedures have not been finally selected, and many techniques are currently being investigated for analysing and processing shear-wave splitting. It may well be that different procedures are optimal for different structural and anisotropic configurations. In these circumstances, it is useful to process any given data set with a variety of techniques. The oil-company consortium supported Edinburgh Anisotropy Project has developed a Shear-Wave Analysis Package, SWAP (Wild 1991) for processing shear-wave data sets which currently contains over 15 different techniques for estimating the polarization of the leading split shear wave and the time delay between the split shear waves, and which includes all known published and some unpublished procedures. SWAP is proving invaluable for the rapid assessment of shear-wave splitting in a variety of different circumstances. Using SWAP, Yardley & Crampin (1990) were able to match observed with synthetic seismograms for the Lost Hills four-component VSP very easily.

5.5 Vector tomography

One of the important advantages of seismic anisotropy is that there are a number of almost independent attribute variations (velocities, polarizations, shear-wave time delays, etc.) that should support and confirm each other if the anisotropic interpretation is correct. Thus, information from the entire vector wavefield will provide a more accurate and reliable image of the internal structure of reservoir rocks than has previously been available from scalar or anisotropic P-wave velocity tomography. Integrating the results of full waveform crosswell imaging for a monitory survey with well-log information would provide the opportunity to investigate physical parameters of importance for reservoir engineering.

5.6 Aquisition geometry

The amount of information about the anisotropy in any *in situ* layer that can be obtained from a series of observations of shear-wave splitting is dependent on the range of azimuths and angles of incidence sampled by the ray paths in relation to the symmetry and alignment of the anisotropy. MacBeth & Wild (private communication) have developed a procedure for assessing the amount of information in given multi-offset VSPs in a multi-layered structure with a given anisotropic structure of a given orientation. This procedure is designed to optimize the geometry of field experiments so that the maximum information can be obtained for the minimum field deployment.

5.7 Instrumental developments

The small amount of information carried by the P-wavetrain (principally the arrival time) should be contrasted with the wealth of, often directly interpretable, geophysical information carried by shear waves. An example is that multiple source-to-geophone ray paths are usually required to extract structural information from P-waves, whereas the anisotropic information in shear waves is usually contained in the 3-D behaviour of the waveforms, which in principle can be obtained from a small number of three-component recordings. This difference in quality and kind of information suggests that different recording configurations are desirable.

A small number of three-component observations of shear waves recorded subsurface can give directly interpretable information about the internal crack- and stress-structure of the rockmass. Such information could be particularly important for monitoring hydrocarbon production processes including EOR or for monitoring any situation where the rockmass is expected to be deformed in any way. Consequently, a small number of three-component geophones installed subsurface recording a repeated shear-wave source, preferably at two orientations, would provide data that would be very sensitive to any changes occurring in the rockmass. The shear-wave source would be excited as frequently, or as infrequently, as was appropriate. There are several instrumental developments that would be desirable.

(1) Three-component geophones built into the well casing would be useful for monitoring hydrocarbon extraction processes.

(2) Records of shear waves from earthquakes are usually recorded at the free-surface and are subject to the restrictions of the shear-wave interactions with a free-surface (Booth & Crampin 1985). Recordings of shear waves subsurface are free of such restrictions as long as the recordings are made at sufficient depths so that reflections from the surface do not contaminate the recordings of the direct shear-wave arrival. The necessary depths should be large enough so that the time delay before the reflection from the free-surface arrives is significantly larger than any possible time delay between the two split shear-wave arrivals. Past experience suggests that it is essential to leave the well open so that instruments can be replaced or updated, and this would be particularly necessary if any long-term monitoring were required (for example, at hazardous-waste disposal sites).

(3) Development of a suitable shear-wave source capable of operating at two or more orientations from prepared sites on the surface. The source would need to be comparatively simple, stable, comparatively inexpensive, and a simple procedure for azimuthal rotation on a fixed base-plate would be desirable. Note that signals from impulsive sources are easier to interpret directly than frequency sweeps from vibrating sources. A number of possible instruments have been developed using sliding weightdrops, and horizontal pistons.

(4) Development of a shear-wave source for operation downwell. This should be capable of generating signals with orthogonal polarizations, and should be capable of operating at a range of dominant frequencies. Again, a number of possible instruments are being developed.

6 CONCLUSIONS

It has been claimed that the progress in understanding shear-wave propagation is the most fundamental advance in seismology for some decades. Shear waves can provide information about the internal crack- and stress-structure of the *in situ* rockmass that is probably not available in any other way. Cracks and stress are often crucially important, and yet at present we have very little understanding or knowledge of cracks or stress in the *in situ* rockmass below a few metres of the free surface. Witness the arguments in the literature about strong versus weak stress, stress reversals, changes in stress orientation, relationships between vertical and horizontal stresses, amongst others (see for example, Crampin 1990a). It is likely that at least some of the inexplicable features of shear-wave splitting in Appendix D are the result of our lack of understanding of the internal structure of the rockmass. It is likely that a fuller understanding of shear-wave splitting, which can examine the undisturbed *in situ* rockmass, is going to improve our understanding of the stress-field in the undisturbed rockmass.

If shear-wave splitting is so important, how is it going to affect seismology? We speculate on the seismological activities in 10 years time.

(1) Shear waves are going to give us a much better understanding of the crack- and stress-geometry of the rockmass, particularly the stability of the internal structure with respect to man-made and natural disturbances to the geological structure.

(2) The expected internal structure of particular rock-types will have been classified with respect to the external and internal conditions acting on the rockmass, and many questions as to the relative cause, degree, and influence of anisotropy will be resolved.

(3) There will be some very detailed interpretations, but in most examples, the geological structure will be too complex to interpret in great detail. Nevertheless temporal changes in the behaviour of shear-wave splitting (particularly changes in differential shear-wave attentuation) will place much tighter constraints on possible interpretation.

(4) Such temporal changes will be valued for monitoring changes during hydrocarbon production processes, including enhanced oil recovery.

(5) Similarly, temporal changes will be valued for monitoring stability of large or particularly sensitive civil engineering constructions: buildings, tunnels, dams, etc.

(6) Hazardous waste depositories will be monitored by networks of subsurface geophones with repeated sources so that a web of source to geophone ray paths encloses the depository.

(7) The value of monitoring the stability of the rockmass in the above items will ensure that three-component seismometers/geophones will be commonly installed in wellbores, either included as a standard inclusion in well casings, or at the bottom of the well (TD), possibly with prepared sites for repeated source excitations. One could envisage legislation that mandated installation of three-component recorders at the bottom of all wells before they were abandoned.

(8) There will be instrumental developments of three-component geophones, and shear-wave sources, both for surface and particularly borehole installations.

(9) There are likely to be computer algorithms and installations for on-line on-site identification and estimation of shear-wave splitting.

The interesting question is what have we missed out?

When shear-wave technology is so fundamentally different from the previous *P*-wave seismology, there could be major applications that have not yet been identified. It will be an interesting future for shear-wave seismology.

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APPENDIX A: SOME CHARACTERISTICS OF SHEAR WAVES AND SHEAR-WAVE SPLITTING

A1 Non-orthogonality of shear-wave polarizations in anisotropic solids

The polarizations (particle motions) of the three plane body waves propagating in the same direction of phase propagation in an anisotropic solid are (strictly) mutually orthogonal (Crampin 1981). (The three waves are a quasi P-wave, qP, and two quasi shear waves, the faster, $qS1$, and the slower $qS2$.) However, except in particular symmetry directions, the propagation of energy at the group velocity has a component parallel to the surface of constant phase. This means that, *in general, the polarizations of the three body waves travelling along the same ray path direction are not orthogonal,* so that the particle motion of the qP-wave is not longitudinal, and the particle motion of the $qS1$- and $qS2$-waves are not perpendicular to the ray path (Crampin 1981). Also, if the anisotropy is sufficiently strong to produce cusps in the shear-wave group-velocity surfaces (the wave surface), there may be more than two quasi-shear waves travelling along some ray path directions. Note that P-wave group-velocity surfaces in anisotropic solids do not have cusps (Crampin 1981). The deviation of the polarizations of the two split shear waves from orthogonality may be several times greater (in degrees) than the maximum differential shear-wave velocity anisotropy (in per cent) in any anisotropic material. This makes the behaviour of shear waves travelling along ray paths with a curved wavefront from a point source very different from the behaviour of plane waves, and plane wave interpretations must be treated with caution.

The non-orthogonality is most severe for surface observations. Crampin & Booth (1985) display polarization diagrams at the surface of a half-space for synthetic seismograms, generated by a linear source polarization, propagating through vertical parallel cracks at a range of azimuths and incidence angles. The horizontal projections of orthogonally polarized shear waves are only orthogonal for strictly vertical ray paths, and there are a wide range of non-orthogonal split shear waves.

A2 Behaviour of shear waves at the free surface: the shear-wave window

The shear-wave window beneath a recording site is defined by the critical angle arcsin (V_S/V_P). This critical angle is the point at which the apparent velocity of the incident shear-wave along the surface equals the horizontal velocity of the P-wave. For angles of incidence within the window with incidence less than the critical angle, the behaviour of shear waves at the surface is similar to that of the incident wave (Evans 1984; Booth & Crampin 1985; see also Crampin *et al.* 1985). For angles of incidence greater than this critical angle (outside the shear-wave window), shear waves have such severe interactions with the free surface that almost all similarities with the incoming waveform are irretrievably lost (Booth & Crampin 1985). The only exception is when the incident wave is a purely SH-wave in an isotropic layer, when there is always total reflection without change of waveform. There is even a precursory phenomenon for shear-wave arrivals outside the window (an S-to-P conversion), which may on some occasions dominate the record (Crampin 1990b), so that in some circumstances even the arrival time of the main shear-wave arrival may be difficult to identify.

The critical angle defining the shear-wave window is just over 35° in a half-space with a Poisson's ratio of 0.25. However, ray curvature due to low-velocity surface layers frequently allows the effective window to be enlarged to angles of incidence of 45° or 50°. The relationships are considerably more complicated for incidence at the free surface from an anisotropic substrate, but the general principles still apply. (Note that shear-wave window is also sometimes used as the area on the surface above an earthquake focus defined by the same critical angle of incidence).

A3 Shear-wave windows at an internal interface

Just as there is a shear-wave window at the free surface, there are several shear-wave windows at internal interfaces. These are defined by the critical angles arcsin (V_{S_1}/V_{P_2}), arcsin (V_{S_1}/V_{P_1}), and arcsin (V_{S_1}/V_{S_2}) for a low (1) to high (2) velocity interface, and arcsin (V_{S_2}/V_{P_2}), and arcsin (V_{S_2}/V_{P_1}) for a high (2) to low (1) velocity interface (Liu & Crampin 1990). Within the innermost window the properties of the incident shear wave are essentially preserved. Beyond each window the effects get progressively more complicated with the excitation of inhomogeneous interface waves which disturb the behaviour near the interface by, generally small, changes in phase and orientation of the shear waves.

However, in anisotropic structures where the polarizations of the shear waves are controlled by the anisotropic symmetry, even outside the innermost window the effects of the internal windows are likely to be negligible (Liu & Crampin 1990).

A4 Shear-wave singularities

The two shear-wave phase velocity sheets necessarily intersect (analytically they are continuous) in three types of singularity: kiss-, line-, and point-singularities (see Crampin & Yedlin 1981; Crampin 1989). Although there are no particular complications in phase-velocity propagation, such singularities can produce severe anomalies to rays of shear waves travelling at the group velocity (Crampin 1991a).

Shear-wave singularities were once thought to be rarely encountered (Crampin & Yedlin 1981), but analysis of multi-offset VSPs in the Paris Basin (Bush & Crampin 1987, 1991) has shown that combinations of fine-layer or matrix anisotropy (PTL anisotropy) and EDA crack anisotropy in sedimentary basins possess orthorhombic symmetry where shear-wave point singularities may occur quite close to vertical directions (Wild & Crampin 1991). In such circumstances, shear waves travelling along nearly vertical ray paths could display anomalies in behaviour caused by point singularities in a wholly uniform material, which unless correctly identified would be attributed to structural irregularities.

Propagation near point singularities is complicated by the interaction of phase and group velocities. As the direction of a ray path crosses from one side of a point singularity, the polarizations of the two split shear waves may change orientation by up to 90°, while still displaying a non-zero delay. This can cause considerable complications in the shear-wave particle displacements which could easily be misinterpreted (Crampin 1991a).

A5 Shear-wave polarizations

The polarizations of shear waves in the isotropic crust may vary widely. Earthquake fault mechanisms radiate a wide range of shear-wave polarizations, which should persist to the recorder in isotropic structures, and in shear-wave reflection profiles the vector polarization of the reflected phase may vary by up to 180° for varying angles of incidence on the reflector (Liu, Crampin & Yardley 1990). This means that consistency of shear-wave polarizations alone may often be an indication of seismic anisotropy.

APPENDIX B: PROCESSING AND INTERPRETING SHEAR-WAVE SPLITTING

The behaviour of shear-wave splitting depends critically on: the frequency, polarization, polarity, amplitude and phase spectra of the incident wave; the orthogonality of and delay between split shear waves; the multiplicity of the splitting; signal-to-noise level, abruptness of onset, and other characteristics of the signal; the orientation, amplitude and phase frequency response; sampling rate, and other characteristics of the recording instruments; the location, distance, orientation, wave-type, frequency content, coupling, and other characteristics of the source; and the direction of the ray path through the anisotropic symmetry, degree of velocity anisotropy, differential shear-wave attentuation anisotropy, and homogeneity and other characteristics of the ray path and the rockmass. These parameters are not all wholly independent, but clearly, in some circumstances the detailed behaviour of shear-wave splitting can be complicated. Several means of identifying and processing shear-wave splitting have been and are being developed.

There are two classes of problem, which probably require different techniques to process and evaluate as follows.

Evaluating shear-wave splitting above earthquakes, where details of the source and ray path are poorly known, and where observations are confined to single widely spaced stations. In addition, earthquakes usually occur in areas of complex geology and complex surface topography, so that the behaviour of shear-wave splitting above small earthquakes is usually very complicated. Even synthetic noise-free shear-wave splitting within the shear-wave window at the free surface produces a very wide range of patterns of behaviour which vary markedly with azimuth, offset, and source orientation (Crampin & Booth 1985).

The other class of problem, evaluating shear-wave splitting in controlled source experiments by exploration techniques, is a much more favourable situation. The source and ray path are usually much better known, and geophones and sources are more closely spaced and controlled so that gradual variations of shear-wave splitting can be traced over small changes in direction and small changes in distance.

B1 Evaluating shear-wave splitting above earthquakes

B1.1 Polarization diagrams

Shear-wave splitting was first recognized in seismograms recorded above small earthquakes (Crampin *et al.* 1980, 1985) by visual examination of plots of mutually perpendicular cross-sections of the particle motion, known as polarization diagrams. Almost all initial shear-wave arrivals were observed to be linear, followed, after a delay of usually a few hundredths of a second, by abrupt changes in direction into elliptical motion, or further linear motion at different polarizations if the time delays were great enough to separate the split shear-wave arrivals. Much of the continuing analysis of shear-wave splitting from earthquake records has also been by evaluating polarization diagrams. Such diagrams were first used to identify the effects of anisotropy in polarization anomalies of surface waves by Crampin & King (1977).

Plotted as three mutually perpendicular cross-sections of the wave motion for successive time intervals along three-component time series, polarization diagrams display details of anisotropic behaviour in, we would argue, an easily interpretable form. It is useful for the observer to have some experience in interpreting polarization diagrams, but Chen, Booth & Crampin (1987) have listed a simple sequence for identification that does lead to consistent interpretations by inexperienced observers. Doubts, however, have been cast on interpretations of shear-wave splitting based on such visual analyses (Aster, Shearer & Berger 1990, 1991). The principal objections are the lack of objectivity and the time taken by such visual examinations.

These are real disadvantages, however, polarization diagrams of shear waves from earthquakes may be extremely complicated and, as yet, no wholly digital algorithm to analyse shear-wave splitting from earthquakes has yet been devised. Certainly, the comparatively simple algorithm of Aster *et al.* (1990) fails to identify time delays between split shear waves correctly (Crampin *et al.* 1991).

More objective techniques are needed and digital algorithms to read shear-wave splitting in earthquake data are currently being developed by BGS (MacBeth & Crampin 1991a, b; and others) based on the developments of the Edinburgh Anisotropy Project for analysing the controlled source experiments (see Section B2). Nevertheless, the human eye can often recognize 2-D patterns even in the presence of considerable disturbance, and we suggest that polarization diagrams still have an important role in analysing shear-wave splitting from earthquakes, if only as calibration checks on other techniques.

B1.2 Rotation of seismometer axes

An apparently simple way to recognize shear-wave splitting is to rotate the two (orthogonal) horizontal axes of digitally recorded shear waves by a trial and error procedure until the two arrivals are most clearly separated. This usually means obtaining the orientation that most nearly linearizes the first split shear-wave arrival by a trial and error technique. This has been used to identify shear-wave splitting in the upper mantle from teleseismic arrivals by Ando, Ishikawa & Wada (1980), who by rotating axes showed two signals with very similar waveforms arriving at different times on the different component axes. Earlier, Crampin & King (1977) rotated seismometer axes to display the 3-D anisotropic coupling of the particle motion in the wavetrains of higher mode seismic surface waves propagating across Eurasia. Such rotation to separate the high-frequency shear-wave splitting above earthquakes in the crust, although occasionally employed to display splitting (Aster *et al.* 1990; Crampin *et al.* 1991), has not been used routinely to separate split shear waves above small earthquakes.

One difficulty with this technique for examining shear-wave splitting above small earthquakes, is that the split shear waves are seldom strictly orthogonally polarized and consequently seldom display similar waveforms on the rotated axes (see Appendix A1). This means that it is difficult to judge when the optimum rotation has been achieved, particularly in the presence of the *P*-wave coda.

B1.3 Digital techniques

Shih, Meyer & Schneider (1989) developed an automated technique for estimating the polarization of the leading split shear-wave arrival. They determined the linearity by maximizing the ratio of the sum of the particle displacement projected onto two orthogonal axes as the axes rotate. (Confusingly, for a phenomenon concerned with cracks, the ratio of the sums is called the aspect ratio.) In many cases, the estimates are reasonable, but the results are very sensitive to the pre-specified shear-wave arrival times, the duration of time intervals, and the signal-to-noise ratios.

Aster *et al.* (1990) developed a variation of the technique of Shih *et al.* (1989) by estimating the linearity from the eigenfunctions of an orientation matrix. Again the estimates are sensitive to the pre-specified parameters, and although it appears to give consistent polarizations, the time delays between the split shear waves may be severely in error. See the discussion in Crampin *et al.* (1991) and the reply (Aster *et al.* 1991).

It is clear from the complications of the synthetic motion in Crampin & Booth (1985) that deterministic algorithms are not going to be wholly satisfactory for estimating the parameters of shear-wave splitting above earthquakes (see Section 5.3, above).

B2 Evaluating shear-wave splitting in controlled source experiments: processing

Estimating parameters of shear-wave splitting in controlled source experiments where differential information can be analysed from an (effective) array of geophones, at the surface in reflection surveys, or downwell in VSPs, is a much more advantageous situation, particularly if there are records from more than one source polarization. This was immediately recognized (Alford 1986; Naville 1986), and a number of techniques have now been developed. Some of these techniques will be briefly described here.

B2.1 Synchronous rotation of source and geophone axes

A controlled source experiment, in which two approximately orthogonal shear-wave source polarities are recorded by two orthogonal horizontal geophone axes (a four-component seismic experiment), allows any source orientation to be simulated by vector combinations of the two recorded traces. Synchronous (simultaneous) rotation of both source and geophone axes seeks to find the orientations that maximize the energy when the source polarizations are parallel to a rotated geophone axis, and consequently minimize the energy on the orthogonal geophone axis. These are the diagonal and cross terms, respectively, in the matrix of rotated seismograms. The first observations of shear-wave splitting in reflection surveys were recognized by such synchronous rotations (Alford 1986; Willis *et al.* 1986). The technique is currently widely used to recognize and display shear-wave splitting in reflection surveys and VSPs (Winterstein & Meadows 1990a, b, c, d; and elsewhere), and has become known as the 'Alford technique'.

Two assumptions are implicit in this technique. First, the polarizations of the two recorded split shear waves need to be orthogonal, and this is not necessarily the case (see Appendix A1). Second, the orientations of the split shear waves need to be consistent throughout the whole of the ray path, and again this is not always the case. The critical decision, usually the minimization of the energy of the energy in the cross terms of the rotated matrix, is difficult to judge in anything except the classic example of vertically propagating orthogonal split shear waves in a uniform structure (MacBeth & Yardley 1991). Various approximations can be devised to allow for changes of polarization direction (Winterstein & Meadows 1990a, b, c, d), but these usually require subjective or empirical judgements of the best orientation. MacBeth & Yardley (1991) have critically examined the effects of neglecting the assumptions of uniform crack-strike in reflection and VSP data. Changes of crack-strike may produce anomalous measurements which cannot be resolved by this technique.

Zeng & MacBeth (private communication) have developed an analytical version of the synchronous rotation, that selects optimal rotations by algebraic operation on three-component seismograms recorded level by level down the VSP. This gives similar results to the numerical rotation. It is deterministic and rapid, but cannot resolve changes of crack-strike.

B2.2 Independent rotation of source and geophones axes

A more sensitive technique than the synchronous rotation in Section B2.1 is a development of the independent rotation of Igel & Crampin (1990) adapted into a form suitable for exploration (MacBeth & Crampin 1991c). The axes of source and geophone are numerically rotated independently to produce a matrix of correlations, which allows the behaviour of the shear waves to be examined, free of the constraints of orthogonality and uniform polarizations. The optimum polarizations and time delays can be selected by visual inspection or numerically. Again, changes of crack-strike may not be resolved by this technique, and again Zeng & MacBeth (private communication) have developed an analytic version, which is deterministic and rapid.

B2.3 Linear transform techniques

Li & Crampin (1991c) have developed a technique that separates four-component seismic data into the faster and slower shear-wave components by four linear transforms. This allows various attributes of anisotropy to be directly measured. The technique is not constrained by orthogonality of the split shear waves, and for zero-offset VSPs does not require downwell geophone orientations, but changes of crack orientation with depth may not be resolved. The technique is again determinisitic and rapid.

B2.4 Layer stripping

An alternative method for extracting the parameters of shear-wave splitting from VSP seismograms is the layer stripping technique developed by Winterstein & Meadows (1990a, b, c, d). They interactively combine the vector polarizations of the two split shear waves from level to level down the geophone string, successively restoring the source polarization at each level. This allows estimates of the polarizations and time delays between the different levels. This technique appears to give consistent results, and is a considerable advance on the Alford rotation, but it does make several fundamental assumptions. It assumes orthogonality of the split shear waves, and the absence of differential attenuation, so is strictly applicable only to vertical ray paths, in a structure where there are vertical planes of symmetry. If these are not justified, the results could be systematically biased. Nevertheless, despite these restrictions, the technique appears to give reliable and consistent estimations for nearly zero-offset VSPs.

B2.5 Propagator matrices

Naville (1986), and later Nicoletis and her colleagues (Nicoletis, Cliet & Lefuevre 1988; Lefuevre, Cliet & Nicoletis 1989), developed a propagator technique for estimating changes in polarization, time delay, and attenuation from level to level downwell. This technique produces azimuthal variations of properties for each level. Although of considerable sensitivity, it is subject to constraints of orthogonality, and there does not yet seem a technique for condensing the data into a more manageable format.

B2.6 Propagator matrices and vector decomposition

Esmersoy (1990) has used a local vector wavefield decomposition and propagator matrices to resolve interfering reverberations in a layered model. The technique appears very effective for plane horizontal layers and zero-offset VSPs, but is again constrained by orthogonality.

MacBeth & Zeng (private communication) have developed algebraic expressions: for propagator matrices to simulate the changes between two three-component geophone levels for two orthogonal source orientations; and between three geophone levels for a single source orientation.

B3 Evaluating shear-wave splitting in controlled source experiments: interpretation

Complex component analysis

Li & Crampin (1991a, b) have developed a technique where the horizontal plane at the geophone is treated as a complex plane, which allows instantaneous attributes of amplitude and shear-wave polarization to be determined from each source polarization. Li & Crampin plot these attributes as record sections of instantaneous amplitude overlain by colour plots of the instantaneous polarization of the leading split shear waves, allowing the colour and length of the initial shear-wave arrival to be immediately identified from the record section display. Although values of the parameters can be listed, the great utility of these displays is that they immediately identify the shear-wave polarizations and time delays of the split shear waves, particularly if there are four-component records so that the common polarizations can be immediately recognized (Li & Crampin 1991b). It is suggested that these plots, for the first time, allow the routine analysis of shear-wave splitting.

APPENDIX C: THEORETICAL FORMULATIONS FOR ALIGNED CRACKS

Hudson, using the Eshelby (1957) expression for the strain field due to an ellipsoidal inclusion, has set out, and is setting out in a series of papers, a comprehensive and consistent theoretical foundation for calculating wave propagation through aligned ellipsoidal cracks in an isotropic matrix (Hudson 1981, 1982; also see Crampin 1984b). Hudson's algebraic formulations are currently restricted to crack densities, $CD = Na^3/v$, less than about 0.1 (Crampin 1984b), and aspect ratios $AR = d/a$, less than about 0.3 (Douma 1988), where N is the number of cracks of radius a, and half-thickness d in volume v. Nishizawa (1982), in a less convenient integral formulation, used the Eshelby technique to calculate elastic response for cracks with arbitrary aspect ratio, but again with similar limitations of crack density.

Hudson (1986, 1990) has extended his formulations to include distributions of cracks with more than one crack orientation and distributions of cracks in anisotropic matrix rocks. Hudson does this by including the second-order interactions of the perturbations from isotropy (the effective crack-to-crack interactions). [Note that the Schoenberg & Muir (1989) group formulation for combining different anisotropies, although attractive in concept and simplicity, does not take account of the second-order interactions, and Hudson & Crampin (1991) demonstrate that the group formulation is valid only for combined differential shear-wave anisotropies of probably less than 5 per cent]. Peacock & Hudson (1990) further extend the formulations to take account of aligned cracks where there is a distribution of cracks about a given orientation.

In a separate development, Thomsen, in an abstract in *EOS* (Thomsen 1986), has adapted the formulations of Hoenig (1979) for parallel cracks to include non-aligned pore-space (equant porosity). To our knowledge, these formulations have not been fully published, and it is not clear if the effects differ from those of Crampin (1991b) for rocks containing distributions of both parallel cracks and randomly aligned pore space.

APPENDIX D: SOME UNEXPLAINED FEATURES OF SHEAR-WAVE SPLITTING

Although much of the behaviour of shear-wave splitting above earthquakes is believed to be, at least partially, understood, there are several features that we do not yet understand. We suggest such features are important. Unexplained features may convey new information that may help in more fully understanding shear-wave splitting. Some of these unexplained features are listed below.

(1) Shear-wave splitting has been identified in a very wide range of rock types, and it is remarkable that although the physical geometry and dimensions of fluid-filled inclusions in sedimentary, metamorphic, and igneous rocks are very different, the general features of shear-wave splitting are remarkably similar in many different rock types. The principal exception is the combination of matrix and crack anisotropy believed to be common in sedimentary basins (Bush & Crampin 1991; Wild & Crampin 1991). In many sedimentary rocks the micro-inclusions are irregular pore-space of usually high porosity, probably with a mixture of narrow throats between more open pore-space. In igneous and metamorphic rocks, the micro-inclusions are narrow cracks of small aspect ratio interspersed with more spherical inclusions of large aspect ratio (Crampin 1991b). In all types of rock there may be larger fractures which again will only remain open when aligned approximately normal to the minimum compressional stress, and will also contribute to the shear-wave splitting. There are two unexplained features:

(a) Both EDA-cracks (Bush & Crampin 1991) and macro-fractures (Mueller 1991) may contribute to shear-wave splitting, but the mixture of micro- and macro-inclusions is not understood. It presumably differs for different rock types, and yet the final effect on the shear-wave splitting is remarkably consistent for different rock types.

(b) Despite the clearly very different physical configuration of inclusions in sedimentary, igneous, and metamorphic rocks, and the clearly very different distributions of large fractures, the degree of differential shear-wave anisotropy is generally within comparatively narrow limits (0.5 to 5 per cent), and has similar effects on shear waves. It is remarkable that this should be the case for rocks with such widely ranging porosities, strengths, and elastic constants, and must be a reflection of an underlying relationship between fluids, stress, and mineral constituents.

(2) Although the differential shear-wave velocity anisotropy is usually between 0.5 and 5 per cent, occasionally much larger values can be found, such as the 15 to 30 per cent at one station from earthquakes in the Long Valley Caldera reported by Savage *et al.* (1990). The reason for these occasional exceptional values is not understood. [Note that there are no obvious theoretical limits to the amount of anisotropy that can exist. In extreme (theoretical) examples, the classification into *P*-waves and shear waves breaks down, and waves can be found which vary smoothly with direction from *P*-wave polarizations in some directions to shear-wave particle motion in others (Hudson & Crampin 1991).]

(3) A specific study has not been made, to our knowledge, but the degree of differential shear-wave anisotropy does not appear to have any obvious correlation with rock type (sedimentary, metamorphic, or igneous), or geological conditions. The amount of anisotropy does appear to correlate with the amount of hydrocarbon production where the anisotropy is believed to be due to large-scale fracturing (Lewis 1989; Mueller 1991; Cliet *et al.* 1991).

(4) Observations of the waveforms of shear-waves on *vertical* components at the surface can seldom be correlated directly with *horizontal* components, in arrival time, amplitude, or phase (Crampin *et al.* 1991). Probably related to the interaction with irregular topography, and *P*-to-*S* conversions, and reverberations in low-velocity near-surface layers, the exact behaviour is not understood, and might very well vary with different near-surface layering.

(5) In most cases, the polarizations of the faster split shear wave are parallel or subparallel to the direction of maximum horizontal stress (or probably more correctly, perpendicular to the *minimum* horizontal stress), but they usually display a scatter of ±10° to ±20° for arrivals both at single stations and between different stations in any seismic network. Occasional orthogonal polarizations are expected when a source excites only the slower split shear wave (Crampin *et al.* 1986b). Similarly, sites near slate, which has a dominating fabric anisotropy (Christensen 1965, 1966), typically display pronounced scatter (Peacock 1985). A major source of scatter is the interaction with irregular surface and subsurface topography, and since earthquakes are frequently manifestations of the forces that build mountains, earthquakes are usually located beneath irregular topography. Sometimes, such anomalies in

shear-wave polarizations can be directly attributed to the effect of a steep slope (Booth *et al.* 1985; Evans *et al.* 1987), a hilltop site (Peacock *et al.* 1988), or stress anomalies near accommodation zones in rift valleys (Young 1989; and possibly Kaneshima, Ito & Sugihara 1989). However, there is commonly a large apparently systematic difference between the shear-wave polarization and the regional stress field that cannot be easily explained by stress-aligned cracks.

(6) Shear-wave splitting is sometimes, but not always, greater in the immediate near-surface layering. It has often been suggested that fluid-filled cracks will be closed at depth under large lithostatic pressure. However, isolated fluid-filled inclusions without drainage paths, abnormally pressurized components in hydrocarbon reservoirs, and the presence of heavily mineralized water at all depths in the Kola Deep Well (Kozlovsky 1982), indicate that fluids are present at all depths in at least the uppermost 10 to 20 km of the crust. We are only beginning to investigate variations in differential shear-wave velocity anisotropy, and the degree of anisotropy is expected to contain information about the geologic, hydraulic, and tectonic history of the rockmass.

(7) There have been several examples where the delay between split shear waves appears to decrease with depth in VSPs (Lewis 1989; Winterstein & Meadows 1990a, c; Yardley & Crampin 1990) and reflection surveys (Squires *et al.* 1989). In a structure with uniform anisotropy, the delay between the split shear waves would be expected to be cumulative, and increase with increasing depth. This decrease has been interpreted as caused by the orientation of the fluid-filled inclusions changing by up to 90°, so that what was once a positive delay is exactly reversed (Squires *et al.* 1989; Winterstein & Meadows 1989a, c). Although variations of stress directions and crack orientations may be expected, changes of up to 90° seem unlikely, and the exact mechanism is not understood.