SHEAR-WAVE SPLITTING IN A CRITICAL CRUST: II - COMPLIANT, CALCULABLE, CONTROLLABLE, FLUID-ROCK INTERACTIONS

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Abstract. This paper argues that the pervasive distributions of closely-spaced stress-aligned fluid-saturated microcracks in almost all rocks are a critical system close to fracture criticality and loss of shear strength. New evidence includes three examples in which observations and modelling directly imply non-linear interactive critical systems with some form of self-organised criticality (SOC). These are a direct calibration of anisotropic poro-elasticity (APE) by monitoring and modelling the response of a reservoir to a high-pressure injection. Monitoring and modelling velocity and attenuation dispersion in a rock physics laboratory. Monitoring the effect of the build-up of stress before earthquakes and volcanic eruptions, including the successful stress forecast of the time and magnitude of an $M_L=5$ ($M_S \approx 6$) earthquake in southwest Iceland.

These new results from three very different fields strongly suggest that the earth's crust is a critical interactive non-linear system with self-organised criticality (SOC). Some effects are subtle and easily ignored. Others are so common and familiar that we have developed one-off explanations in terms of conventional deterministic physics to describe their behaviour and occurrence. We suggest that the identification of the sub-critical physical processes is one reason for the success of APE-modelling.

Recognition of (crack) criticality leads to a new understanding of low-level (pre-fracturing) deformation that has massive implications for almost all dynamic processes in the crust. These include reservoir characterisation, hydrocarbon recovery, monitoring the progress of fluid-fluid fronts, and the build-up of stress before fracturing, faulting, and earthquakes, and the movement of magma before volcanic activity. The implications will be discussed and the arguments presented.

1 Introduction

Conventional geology and geophysics do not address four widespread phenomena:

(1) The nearly universal observation of stress-aligned seismic shear-wave splitting in almost all in situ rocks below some critical depth, usually between about 500 m and 1 km.

(2) The self-similar distributions widely associated with fluid-rock-stress interactions of cracks and microcracks in in situ rocks, including the well-known Gutenberg-Richter relationship between cumulative numbers and magnitudes of earthquakes. (We use self-similarity to refer to straight lines in log-log plots of frequency and dimension, sometimes referred to as fractal or power-law distributions.)

(3) The self-similarity of $1/f$-noise typically observed in well-log power spectra. We shall show that, although comparatively subtle and easily overlooked, these phenomena are per-
haps the three most widely available characteristic effects that strongly imply the near-criticality of microcrack distributions in in situ rocks (Crampin, 1997, 1998a, 1999a).

(4) A fourth effect, the occurrence of earthquakes (at levels of fracture criticality when shear strength is lost and faulting occurs) is well known. However, the issue of criticality is usually avoided, and earthquakes are typically described by particular one-off explanations in terms of conventional physics and geophysics.

A model for anisotropic poro-elasticity (APE), based on the near-criticality of fluid-saturated crack distributions in the Earth, has been developed. It matches a large range of phenomena involving cracks and stress in the crust. The APE model assumes that the fluid-saturated crack distributions in the Earth are a critical system (Zatsepin and Crampin, 1997). Critical systems are dynamic interactive non-linear systems that below criticality perturb locally, whereas when systems reach criticality, all members of the system influence all other members, usually over an extensive volume (Ma, 1976; Jensen, 1998). The transition temperature of equilibrium thermodynamics is the classical critical system, but critical systems are common in an enormous range of physical phenomena. This paper suggests that the stress-aligned fluid-saturated grain-boundary cracks and pores in most of the Earth's crust are another interactive non-linear critical system.

The non-linearity means that critical systems are typically sensitive to otherwise-negligible variations in initial conditions that can lead to order-of-magnitude differences as the system evolves (Bruce and Wallace, 1989). In the case of the Earth, the critical crust is highly compliant, and when it evolves to levels of fracture criticality, fracturing, faulting and earthquakes occur. If these various suppositions are correct, and there is now a large body of data supporting these ideas, there are massive implications affecting almost all low-level rock deformation, relevant particularly to levels of deformation before fracturing occurs (here referred to as pre-fracturing deformation). These include hydrocarbon recovery and reservoir characterisation (Crampin, 1999a, 1999b), the build-up of stress before fracturing, faulting and earthquakes occur (Crampin, 1999a; Crampin et al., 1999a), and much else besides (see Table 4, below).

The key effects that allow the approach to criticality to be monitored are that time delays and polarisations of seismic shear-wave splitting, that are controlled by crack geometry, can in many circumstances be measured with considerable accuracy. This means that second-order phenomena, the small differences in the arrival times of split shear waves, can be measured with first-order accuracy. In particular, anisotropy-induced shear-wave splitting directly monitors the pre-fracturing deformation of stress-aligned microcracks in the Earth's crust (Crampin and Zatsepin, 1997a). At the Eighth International Workshop on Seismic Anisotropy (8IWSA) at Boussens in 1998, it was suggested (Crampin, 1998a, hereafter referred to as Paper 1) that shear-wave splitting indicates that the distributions of fluid-saturated grain-boundary cracks and low-aspect ratio pores in almost all in situ rocks are in a meta-stable state close to fracture criticality. Such criticality has a profound effect on almost all aspects of fluid-rock interactions in the crust. Note that previous claims to criticality (Bak and Tang, 1989; Kagan, 1997; Leary, 1997; and others) are based on statistical distributions. The particular advance in Paper 1 was to identify the sub-critical physics of the critical crust as anisotropic poro-elasticity or APE.

Paper 1 suggested that the next step was to make practical applications of this new understanding. Definitive experiments in deep in situ rock are costly and difficult to arrange. This paper reports three of the most relevant studies supporting these ideas, and discusses tentative steps attempting to make practical use of the critical, calculable and ultimately controllable fluid-saturated microcracked rockmass. We shall briefly review our current understanding of the critical nature of in situ rock, report these new results and discuss the establishment of a stress-monitoring site and the practical implications of criticality for Earth Science.
2 Brief reviews

2.1 Shear-wave splitting

Stress-aligned shear-wave splitting (seismic birefringence), with azimuthal anisotropy, is observed with very similar characteristics in almost all in situ rocks in the Earth's crust (Crampin, 1994, 1996; Winterstein, 1996). There may be high values of velocity-anisotropy near the surface, in specifically heavily fractured beds, and in areas of high heat flow. However, below the critical depth (~500m to ~1km), there is a minimum shear-wave velocity-anisotropy of about 1.5% and a maximum in ostensibly intact rock of about 4.5%. The critical depth is the depth at which the increasing vertical stress equals the minimum horizontal stress. Below that depth the minimum stress is horizontal, so that cracks tend to be vertical. These values are independent of rock type (igneous, metamorphic, sedimentary), porosity, and geologic and tectonic environment (Crampin, 1994; Crampin et al., 1999a; Volti and Crampin, 2000). There are only a few well-understood exceptions, in which in situ rocks below the critical depth do not show stress-aligned shear-wave splitting (Crampin, 1994, 1999a).

The pervasive shear-wave splitting is caused by propagation through distributions of stress-aligned fluid-saturated grain-boundary cracks and low aspect ratio pores with crack densities between $\varepsilon = 0.015$ and $\varepsilon = 0.045$, where the percentage of shear-wave velocity anisotropy is approximately $\varepsilon \times 100$, when $Vp/Vs = 1.7$ (Crampin, 1993). Such distributions of stress-aligned microcracks, known as extensive-dilatancy anisotropy, or EDA, were first suggested by Crampin et al. (1984). We now recognise that such EDA-cracks are the small-scale limit of self-similar (fractal) distributions of cracks ranging over many orders of magnitude of frequency and dimensions (Paper 1; Crampin, 1997, 1999a, 1999b).

Note that such distributions of approximately parallel and approximately vertical cracks have hexagonal anisotropic symmetry (transverse isotropy) with a horizontal axis of symmetry, or a minor perturbation thereof (Crampin, 1981; Crampin and Zatsepin, 1997a). The exceptions, the only rock types that typically do not display such stress-aligned shear-wave splitting, are some carbonates, such as oolites and coccoliths, and most shales, clays and mudstones. Uncemented oolites and coccoliths have highly constrained microstructures without planar microcracks. Shales, clays and mudstones are typically composed of nearly horizontal platelets that frequently display strong shear-wave velocity anisotropy of several tens of percent with transversely isotropic symmetry about a vertical axis of cylindrical symmetry, but possess little or no azimuthal anisotropy. Shales, clays and mudstones also have strong chemical and electric potentials binding interstitial water to intergranular surfaces. Consequently, the rocks do not have compliant fluid-saturated grain-boundary cracks and low-aspect ratio pores that are free to take up stress-oriented alignments in other rocks (Crampin, 1994, 1999a).

Both observations and interpretation of percentages of shear-wave velocity anisotropy in terms of crack distributions suggest that, below the critical depth, the limit of crack density for aligned cracks at which shear strength is lost and fracturing is possible is between $\varepsilon = 0.045$ and $\varepsilon = 0.1$. This limit is known as fracture criticality (Crampin, 1994). Crampin and Zatsepin (1997a) show that fracture criticality is associated with the percolation threshold for distributions of stress-aligned fluid-saturated cracks at a crack density of $\varepsilon = 0.055$. This is within the $\varepsilon = 0.045$ to $\varepsilon = 0.1$ fracture criticality interval suggested by observations of stress-aligned shear-wave splitting (Crampin, 1994). Consequently, the nearly universally observed stress-aligned shear-wave splitting suggests that almost all the Earth's crust is pervaded by fluid-saturated crack distributions which are naturally close to fracture criticality and failure of shear strength.
2.2 Anisotropic poro-elasticity (APE)

The response of fluid-saturated EDA-cracks to changing conditions (the evolution of fluid-saturated microcracks) has now been modelled by anisotropic poro-elasticity, or APE (Zatsepin and Crampin, 1997; Crampin and Zatsepin, 1997a). The driving mechanism for such pre-fracturing deformation is fluid movement by flow or diffusion along pressure gradients between neighbouring grain-boundary cracks and low aspect ratio pores at different orientations to the stress field (Brodie and Rutter, 1985; Rutter and Brodie, 1991; Crampin and Zatsepin, 1997a). APE-modelling is tightly constrained, with almost no free parameters, yet it matches, or is compatible with, a large range of different phenomena relating to shear-wave splitting and crack distributions extending over more than eight orders of magnitude in linear dimensions (Crampin, 1997, 1999a). Table 1 lists a range of some 15 different phenomena (with tens of thousands of individual observations), which are in principle matched, sometimes very accurately, by APE-modelling.

APE is a mean-field theory (Jensen, 1998), and the underlying assumption is that the microcrack distribution is a critical system (Zatsepin and Crampin, 1997). Thus the near criticality of the crust is the underlying reason why APE-modelling is dimensionless yet matches, or is consistent with, the wide range of phenomena in Table 1 (Bruce and Wallace, 1989).

We have shown how cracks in ostensibly intact rock are close to the critical value of fracture criticality, \( \varepsilon \approx 0.055 \), when fracturing and other instabilities occur. A system held close to such a critical point is said to be in a state of self-organised criticality, or SOC (Bak et al., 1988; Jensen, 1998). When critical levels are reached in such a meta-stable SOC system, a critical event occurs, energy is released, and the system retreats to meta-stability again. An avalanche in a sand pile is the classical self-organised criticality event.

2.3 Self-similar distributions of cracks in the crust

A large range of distributions and properties, particularly those associated with cracks in the crust, possess self-similarity. Some of these phenomena are listed in Table 2. The list could be greatly extended. The phenomena are associated with cracks, earthquakes and volcanic eruptions. They range from the Gutenberg-Richter relationship (the classic example of SOC, Bak et al., 1988) to observed crack distributions in in situ rock and laboratory specimens (Heffer and Bevan, 1990), and sub-critical crack growth in the laboratory specimens (Atkinson, 1982).

The distribution of cracks in the crust - from microcracks in rock samples, fractures in outcrops, to photo-lineaments and fault lines on maps - is linear in dimensions for over eight orders of magnitude (Heffer and Bevan, 1990) and is probably the largest known range of self-similarity in the crust. This self-similar distribution of Heffer and Bevan is marginally above the line specified by the dimensionless fracture-criticality value from Figure 2 of Crampin (1999a). This is because fracture criticality is defined by open active cracks, whereas the line of Heffer and Bevan refers to all cracks; sealed, healed, and lines of weakness and open cracks. Thus the distributions of cracks in the crust are observed to be close to fracture criticality and hence possess SOC.

These self-similar distributions are extraordinary phenomena that cannot be easily explained by conventional physics or geophysics. The underlying reasons for such behaviour are not understood. The only real attempt at an explanation is the self-organised criticality mechanism proposed by Bak et al. (1988). The implications of such behaviour are also not fully understood, but one of the features is that because of the self-similarity, the behaviour at one scale is similar to that at any other scale. Thus the behaviour of the whole system may be determined by the behaviour at any particular scale. In particular, since the behaviour at the smallest scale
is the only place at which conventional physics is likely to apply, the behaviour of the whole critical system is determined by the physics at the smallest scale. The whole system of cracks, fractures, photo-lineaments and fault lines is controlled by the conventional physics of fluid-saturated stress-aligned EDA-cracks.

2.4 1/f-noise in well-logs

The 1/f decay, known as 1/f-noise, or flicker-noise, refers to straight lines in power spectra varying with frequency as approximately 1/f. Such flicker-noise is common in a large range of complex interactive systems. Its origin and cause are not understood. Although it has not been completely proven, Bak et al. (1987) showed that 1/f-noise and SOC were closely associated. It has recently been recognised (Leary, 1991; Leary and Abercrombie, 1994; Bean, 1996) that one of the most widespread examples of 1/f-noise in Earth structures is found in a wide variety of well-logs, where the 1/f-noise can be attributed to the distributions of fractures and microcracks in the crust, which in the previous section have been shown to have SOC.

Observations of 1/f-noise in well-logs are robust and are independent of geology and tectonics. The observations are generally consistent with the clustering of fractures in the rock column. However, the underlying cause of the self-similarity of 1/f-noise in rock fractures is not understood, so that the association with SOC seems pertinent.

In some ways, 1/f-noise is merely another variant of the self-similar distributions mentioned in the previous section. Its particular importance is that it is a directly measurable phenomenon that is observable in almost every well-log. It demonstrates that crack distributions in the Earth's crust have the same critical system behaviour as found in the many other distributions with 1/f-noise.

2.5 Rock criticality

The almost universal occurrence of fractal distributions, which are closely associated with critical systems, suggests that such systems may well be almost ubiquitous in a huge range of natural phenomena. There are three obvious, yet subtle, phenomena in the Earth's crust:

(1) The crack-induced shear-wave splitting seen in almost all rocks in the crust (and upper mantle), including the wide applicability of APE-modelling in Table 1.

(2) The self-similar distributions associated with faults, fractures, cracks, and microcracks, is shown in Table 2.

(3) The 1/f-noise ubiquitous in hundreds of examples of well-logs (Peter Leary, private communication).

These all indicate that the fluid-saturated EDA-cracks in the Earth's crust are, like many phenomena in the physical world, critical systems held close to (fracture) criticality.

The observation of similar percentages of shear-wave velocity anisotropy in almost all rocks, in which the splitting is aligned with the current stress field, and which changes as conditions change, implies that crack distributions in *in situ* rock are close to fracture criticality. Such SOC systems are held in marginally meta-stable states which, if they are perturbed, will naturally evolve back to a meta-stable state. It can be shown that in such critical systems, fractal statistics apply and there is no natural scale length (Bruce and Wallace, 1989; Turcotte, 1992b). The criticality of the system is the underlying reason why distributions of cracks are close to fracture criticality over many orders of magnitude in dimension (Heffer and Bevan, 1990; Crampin, 1999b).

The inherent SOC of fluid-saturated cracks within the Earth's crust has several remarkable properties. The microscale mechanism for deformation, fluid movement along pressure gradients around grain-boundary cracks and pores, is a recognisable physical process, that can be modelled, monitored and calculated by APE (Zatsepin and Crampin, 1997; Crampin and Zatsepin, 1997a). This physical real-
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ity leads to insights which are absent in many theoretical models of self-organised criticality popular in geophysics, such as cellular automata (Kadanoff et al., 1989; Rundle and Klein, 1993). The progress of rocks toward criticality and the proximity of fracturing within the (usually remote, usually inaccessible) interior of the solid can be (non-destructively) monitored by shear-wave splitting. Thus the stress-aligned shear-wave splitting that is almost universally observed at the surface of the Earth demonstrates the near-critical state of cracks in the Earth's crust.

Bruce and Wallace (1989) show how very different critical systems have remarkably similar statistical behaviour at criticality, despite widely differing sub-critical physics. This is known as critical-point universality and implies self-similar scaling. Much of the behaviour of such critical systems is controlled by the characteristic behaviour close to criticality rather than the classical physics, or geophysics, of the sub-critical matrix material.

Crampin (1999a) shows that despite the immense complexity and heterogeneity of the Earth's crust (and mantle), modelling with the highly-constrained mean field theory of APE matches the behaviour of distributions of fluid-saturated cracks, sometimes very accurately, over a range of phenomena, some 15 of which are listed in Table 1. This is exemplified by the narrow range of stress-aligned shear-wave velocity anisotropy of 1.5% to 4.5% observed in almost all intact in situ rocks worldwide (Crampin, 1994, 1996, 1999a; Winterstein, 1996). The reason for the extraordinary match of the nearly parameterless APE-modelling to numerous phenomena in a complex heterogeneous Earth is believed to be because the response of such critical media is controlled by the non-linear behaviour of the criticality. Criticality can be modelled by critical-point universality (Bruce and Wallace 1989) and mean field theory (Jensen, 1988) rather than by the linear physics of the sub-critical matrix material.

Note that the similarities in critical behaviour can be misleading. It is tempting to use simplistic models for complex Earth processes and make claims for relevance merely because they produce similar statistics and similar self-similarity. Much-quoted examples are the slider-block model of Burridge and Knopoff (1967) and the cellular automata of Kadanoff et al. (1989) and Rundle and Klein (1993). Models with SOC are widely available, but they reproduce only the statistics of SOC and are largely independent of the actual sub-critical physical process. Thus, the perceived similarity with some highly simplified Earth mechanism is arbitrary and largely irrelevant to a better understanding of Earth processes.

The physical manifestation of self-organised criticality and self-similar distributions in much of the Earth's crust and upper mantle is modelled by APE: the fluid-rock interactions of stress-aligned fluid-saturated grain-boundary cracks and pores (Crampin, 1997, 1999a). These are the small-scale interactions, with dimensions, or grain sizes typically of order 0.1mm to 1mm, of self-similar distributions of properties ranging over some eight orders of magnitude of dimensions (Item 6, Table 1). Although widespread, SOC is largely phenomenological and not wholly understood. Consequently, each new experimental result or new application is important for adding to our understanding of SOC in the Earth.

Note that APE may be considered as a stress-sensitive version of the poro-elasticity of Biot (1956). Biot treats wave propagation through isotropic porous media, in which the effects of stress on the rock matrix are ignored. Since truly triaxial stress is present throughout the Earth, resulting in stress-aligned microcracks and the nearly universal observation of stress-aligned shear-wave splitting, direct applications of the Biot model of isotropic poro-elasticity are limited. It is interesting that the equations of Biot require several parameters to be specified (properties of fluid, rock matrix and pore space), and yet still do not match many observations. By contrast, critical point universality means that mean-field APE-modelling is almost parameterless yet matches, sometimes with considerable accuracy, the wide range of phenomena in Table 1.
Figure 1: (a) Pre-injection waveforms of a multi-component nearly-vertical reflection survey near the centre of the Vacuum Field, New Mexico, carbonate reservoir (Davis et al., 1997). S1, S2, and P are record sections with mutually orthogonal polarisations, where the horizontals S1, and S2, have been rotated into the split shear-wave arrivals parallel and perpendicular to the direction of maximum horizontal stress, respectively. The left-hand five traces are observed waveforms at neighbouring recorders 17m apart, and the right-hand three traces are three synthetic seismograms modelled by APE to match the shear-wave arrivals. Top and bottom of injection zone for shear waves are marked by arrows with delay in ms. (b) Post-injection waveforms after a high-pressure CO$_2$-injection. Again, the left-hand traces are observations and right-hand traces are synthetic seismograms modelled by APE with structure from (a) and an injection pressure of 2500psi. (After Angerer et al., 2000a, 2000b.)
3 New applications

The main advances since Paper 1 at 8IWSA are a better understanding of SOC and APE, and the first direct applications of APE-modelling. These include a direct application to a hydrocarbon reservoir in which the response to a high-pressure fluid injection is calculated; a successful model of a laboratory dispersion experiment; and a successful stress forecast of an \( M=5 \) earthquake. In all three cases, the effects of changes have been directly or indirectly calculated by tightly constrained modelling with few parameters, so they may be considered as successful predictions of, in two cases, time-lapse observations. We briefly discuss these applications and report on applying these techniques to a projected stress-monitoring site (SMS) being developed in a fracture zone of the Mid-Atlantic Ridge in northern Iceland.

3.1 Modelling high-pressure CO\(_2\)-injection in a carbonate reservoir

Davis et al. (1997) report a time-lapse three-component reflection survey before and after a high-pressure CO\(_2\) injection in Vacuum Field, New Mexico, in Phase VI of the Reservoir Characterisation Project, Colorado School of Mines. Davis et al. found that variations in shear-wave splitting were the most diagnostic seismic parameter for identifying changes during the injection. Angerer (Angerer et al., 2000a, 2000b) reprocessed the data and constructed a model of aligned cracks with synthetic seismograms that accurately matched the observed shear-wave arrivals in the pre-injection seismograms (Figure 1a). Arrows mark the top and bottom of the target zone in which the injection took place. The initial pore-fluid pressure was about 1500psi and the injection pressure was about 2500psi with an overburden pressure of 4300psi. Angerer was able to model (in effect predict) the changes in shear-wave splitting post-injection seismograms. Angerer inserted the appropriate 2500psi injection pressure into an APE model of a cracked distribution based on the pre-injection seismograms and calculated synthetic seismograms for the post-injection records (Figure 1b). The match of modelled to observed arrivals is satisfactory. Note that the multiple arrivals in the observations are reverberations in the overburden, which Angerer did not attempt to model or calculate.

The synthetic seismograms were calculated with the ANISEIS Program of Taylor (2000). Angerer used a version of APE that allows for stress-induced modifications to microcrack geometry in the presence of large fractures with fixed polarisations. This modelling of the effects of the CO\(_2\) injection is the most accurate field test and calibration yet available for APE-modelling. It means that in this example the effects of the injection with a specified CO\(_2\) pore-fluid pressure could be predicted by APE.

Apart from the match of modelled to observed record sections, another feature is interesting. Before injection, in Figure 1a, \( S1 \) is parallel to the maximum horizontal stress, and the time delay between the top and bottom of the target zone is smaller for \( S1 \) than for \( S \). This shows that the \( S1 \) polarisation approximately parallel to the tectonic stress direction is the faster wave in the target zone. In contrast, after injection in Figure 1b, the order of the time delays between the top and bottom of the target zone for the same polarisations has been reversed. The time delay for \( S2 \) is now smaller than that for \( S1 \), showing that the \( S2 \) polarised wave is now faster than the \( S1 \) wave. This means that before injection, the polarisations of faster shear waves were parallel to the direction of maximum horizontal stress and the strike of the approximately vertical systems of cracks. After the high pore-fluid pressure injection, the faster split shear-wave polarisations had changed by 90° and were perpendicular to the direction of maximum horizontal stress, perpendicular to the presumed crack strike, and parallel to the direction of minimum horizontal stress. This switch of shear-wave polarisations in the presence of high pore-fluid pressures is predicted by APE (Crampin et al., 1996), see Table 1, Item 7.
An intuitive physical interpretation is that, in parallel distributions of cracks filled with fluid at low pore-fluid pressures, the crack face is a low-impedance interface and the faster split shear wave prefers to vibrate in the high-impedance direction parallel to the crack face. However, when pore-fluid pressure exceeds the differential horizontal stress, the crack face is a high-impedance interface and the faster, split shear wave vibrates normal to the crack face. Similar changes in shear-wave polarisations have been observed in an over-pressurised reservoir in the Caucasus (Crampin et al., 1996) and above earthquakes in a fault-zone where high pore-pressures are expected (Liu et al., 1997).

### 3.2 Modelling frequency dispersion in laboratory experiments

Several attempts have been made to match seismic velocity and attenuation measurements in field and laboratory experiments by invoking squirt flow (Dvorkin et al., 1995), the effects of pore geometry and inter-pore flow (Endres and Knight, 1997), and other phenomena. Although seismic velocities can be matched, there is typically significant frequency dispersion between field and laboratory measurements of attenuation. It seems likely that a combination of squirt flow and fluid-rock microstructure is the most likely source of the mismatch of velocities. This dispersion has not been satisfactorily modelled previously.

The initial APE model for the evolution of fluid-rock interactions was based on the behaviour of distributions of microcracks in low-porosity crystalline rocks (Zatsepin and Crampin, 1997; Crampin and Zatsepin, 1997a). This leads to non-dispersive mechanisms for seismic propagation, which appear to give good estimates of velocity anisotropy, even in high-porosity sedimentary rocks, but do not model appropriate attenuation. Chapman et al. (1998, 2000) developed an isotropic model of a random lattice with thin cracks or spherical pores at each vertex. As with all APE models, the driving mechanism for changes in crack behaviour is the fluid response to pressure gradients between neighbouring grain-boundary cracks and pores at different orientations to the direction of wave propagation.

The model demonstrates a fast and a slow $P$-wave in agreement with Biot (1956) and provides theoretical velocity and attenuation for both $P$-waves and shear waves (Chapman et al., 1998, 2000). The model has been calibrated in laboratory experiments using electronic transducers for sonic and resonant bar techniques for near seismic frequencies (Sothcott et al., 2000a, 2000b). Figure 2 shows theoretical variations of shear-wave velocity, $V_s$, and attenuation, $Q_s$, and laboratory data at four values of confining stress. Note that the curves are modelled. They are not least-square fits. The results are preliminary and sparse, but the agreement is good, particularly where small changes of curvature are matched both by theoretical curves and laboratory data. These changes in curvature occur where squirt flow begins to be effective and are a function of the crack density and the grain size. Although the model is isotropic and the observed measurements refer to the effects of confining stress and microscale fluid flow, the model is consistent with APE in that the mechanism for fluid flow is driven by pressure gradients in the crack and pore space. This is the most detailed match of APE-type modelling to laboratory measurements, although there have been several less-exacting tests in anisotropic and isotropic laboratory stress cells [Zatsepin et al. (1996), Crampin et al. (1997, 1999b)].

### 3.3 Successful stress forecast of time and magnitude of a M=5 earthquake

Since first observed by Peacock et al. (1998) and Crampin et al. (1990), variations in shear-wave splitting above small earthquakes have been recognised (with hindsight) before four earthquakes worldwide. That is whenever the severe constraints on the geometry of source earthquakes, recording network and neighbouring large (or larger) earthquakes have been satisfied (procedures reviewed by Crampin, 1999a). The breakthrough came when the
active seismicity of the onshore transform zone of the Mid-Atlantic Ridge in Southwest Iceland, and the recording and location procedures of the SIL network in Iceland (Stefánsson et al., 1993; Bödvarsson et al., 1999), satisfied these constraints. As a consequence, changes in shear-wave splitting have been routinely observed (with hindsight) since 1966 in a limited area of southwest Iceland where conditions were appropriate. This was funded by the European Commission in the PRELAB Projects.

Figure 3 shows the variations in time delays over four years at Station BJA in Southwest Iceland. The time delays are plotted in two solid angles: Band-1 is the (two-leafed solid angle of ray paths directions between ±15° to 45°) to the average plane of the crack distributions); and Band-2 (the solid angle between ±15° to the average plane of the cracks). Band-1 is sensitive to changes in crack aspect ratio, whereas Band-2 is sensitive principally to changes in crack density. If the directions of the principal axes of stress do not change, it can be shown that the immediate effect of increasing stress on the rock mass is to increase the aspect ratios of approximately parallel vertical cracks (Crampin and Zatsepin, 1997a). The effect of increasing aspect ratios is to increase the average time delays in Band-1 (Crampin et al., 1990; Crampin, 1999a). Increasing stress does not have a simple effect on crack densities. Some cracks close and some cracks open, depending on the crack orientations. Consequently, Band-2 shows no simple behaviour with increasing stress.

Before each larger earthquake at BJA and other stations in Iceland (Volti and Crampin, 2000), the average time delays between split shear waves are observed to increase in Band-1 of the shear-wave window, indicating increasing aspect ratios. The increase continues until fracture criticality is reached at a normalised time delay of between 11 and 14ms/km when an earthquake occurs. Cracks, like hydraulic fractures, open in directions normal-top the direction of least compressional stress, and Band-2 shows no recognisable patterns of behaviour.

Figure 2: Modelling observations of frequency and velocity dispersion in resonant bar and stress-cell experiments. Observations of P- and S-wave velocities in m/sec, and shear wave attenuation, Qs, for resonant bar (log frequency = -3.3 to -4.3) and transmission (log frequency = -5.5) for effective stresses of 40MPa and 20MPa (after Sothcott et al., 2000a, 2000b). The effective stresses are a pore-fluid pressure of 5MPa and a confining stresses of 45MPa and 25MPa, respectively. The velocity curves are modelled variations based on the APE crack distribution model (Zatsepin and Crampin, 1997) and a time scale parameter. (After Chapman et al., 1998, 2000.)
When levels of fracture criticality are reached and earthquakes occur, the time delays in Band-1 are observed to fall abruptly to approximately the original level before the increase began. In the limited range of earthquake magnitudes observed in Southwest Iceland during 1997 and 1998 ($M=3.5$ to $M=5.1$) earthquake magnitude can be assumed to be inversely proportional to the rate of increase of the time delays and directly proportional to the duration of the increase. In this limited range, the relationships may be assumed to be linear, so the rate of increase and duration can be correlated directly with the earthquake magnitude (Crampin et al., 1999a). The argument is that as stress increases in a heterogeneous earth and the stress accumulates over a small volume, the increase will be rapid but will last for only a short period of time, and the final earthquake will be small. However, if the increase is over a larger volume, the rate of increase will be slower over a longer period of time, and the final earthquake will be larger. Note that the largest distance in which changes in shear-wave splitting have been observed \textit{before earthquakes} in southwest Iceland is 43 km from an $M=5.1$ earthquake.

Figure 3: Shear wave splitting time delays for January 1, 1996 to December 31, 1999, at station BJA, in SW Iceland. The middle, and upper diagrams show the variation of time delays with time for ray paths in Band-1, and Band-2, which are the solid-angles $±15^\circ$ to $45^\circ$), and $±15^\circ$ to the average crack plane, respectively. The time delays in ms are normalised to a 1km path length. The vertical lines through the time delay points are (notional) error bars. The irregular lines are nine-point moving averages. The straight lines in Band-1 are least-square estimates beginning just before a minimum of the nine-point average and ending at a larger earthquake or an eruption. The arrows indicate the times of larger events with magnitudes and epicentral distances indicated. The lower diagram shows magnitudes and times of earthquakes greater than $M=2$ within 20km of the recording station. (After Volti and Crampin, 2000.)
(Crampin, 1999a; Crampin et al., 1999a). Studying stress-induced variations in shear-wave splitting is in its infancy, and there have been no opportunities yet for more detailed specifications.

In October 1998, an increase in time delays was recognised before a larger earthquake had occurred. An exchange of emails was initiated between the University of Edinburgh (EU) and the Icelandic Meteorological Office (IMO). These are listed in Table 1 of Crampin et al. (1999a). Preliminary forecasts were made on the 27th and 29th of October 1998, and the final forecast on the 10th of November was "that an event could occur any time between now (M≥5) and the end of February (M≥6)". A magnitude M=5 event occurred three days later. Figure 3 includes the variation of time delays between the split shear waves at station BJA in Southwest Iceland on which this forecast was based. The range of options in the forecast, the smaller-earlier to larger-later (SELL) window, is necessary because of the scatter of the data and errors in estimating both the rate of increase in time delays and the level of fracture criticality (Volti and Crampin, 2000). The large scatter in time delays in Figure 3 will be discussed below.

Note that information about the foreshocks before the forecast event (see Figure 3) were not yet on the PRENLAB website when the forecast was made. Note also that these variations in shear-wave splitting monitor the stress-dependent state of microcrack geometry between the source and the recorder, the stress-induced approach of fracture criticality, and the onset of fracturing. The variations do not directly monitor the increase of stress. They may indicate time and magnitude (Crampin, 1999a; Crampin et al., 1999a), as suggested above, but they do not give any direct information about the location. We call such estimates stress forecasts (Crampin, 1998b) to distinguish them from earthquake predictions, which usually refer to predicting the time, magnitude and location of impending large earthquakes. However, if the approach to fracture criticality is recognised, studies of other local phenomena may suggest the location, as happened before the forecast earthquake in Iceland (Crampin et al., 1999a).

3.4 Variations in shear-wave splitting during volcanic/ magmatic activity

Volcanism and movements of magma in the crust also causes of changing stress. Figure 3 shows the variations of time delays in Band-1 before earthquakes but also shows the variation before the Vatnajökull volcanic eruption at the end of September 1996 (Crampin et al., 1998; Volti and Crampin, 2000). Increases in Band-1 time delays were visible for three to five months before the Vatnajökull eruption at distances of about 240 km north (at GRI), 230 km (KRI) and 200 km (BJA), both west-Southwest, and 170 km Southwest (SAU). These are the greatest distances at which changes of shear-wave splitting (changes of stress) caused by specific events have been observed. At the time of the eruption, the shear-wave splitting did not indicate an abrupt decrease in stress (abrupt decrease in aspect ratios), as occurs at the time of earthquakes, but showed a gradual decrease in both Band-1 and Band-2 for about two-and-a-half years following the eruption (Figure 3).

This trend of about 2 ms/km per annum is visible at stations KRI, BJA and SAU. The variations in time delays before the earthquakes, as in Figure 3, are superimposed on this gradual trend following the eruption. There are not enough arrivals within the shear-wave window to specify the behaviour at GRI.

Vatnajökull was a fissure eruption. Our interpretation (Volti and Crampin, 2000) is that the eruption was part of a spreading cycle of the Mid-Atlantic Ridge, with an energy input from compressive stress that is much larger than any possible release by earthquake fracturing, which would be limited by shear strength. The attempt to inject magma through the crust is expected to be a fluid-fracture-type process, analogous to a conventional oil-company hydro-fracture, where the injection fluid is now magma. Such fracturing requires the crustal
rock to reach fracture criticality before the fracture can open (or slip). Consequently, just as before earthquakes, the crust showed an increase of stress-induced cracking until fracture criticality was reached, at which time the crust was able to fracture and the magma broke through in a fissure eruption.

The time delays of earthquakes during 1997 and 1998 in Band-1 in Figure 3 show regular behaviour superimposed on the gradual decrease following the Vatnajökull eruption. The corresponding time delays during 1999 are irregular, which we attribute to the interaction of the effects of stress changes before earthquakes and magmatic activity. There was volcanic/magmatic activity at Katla, a volcano about 110km east-Southeast of station BJA, that erupted in July 1999 and showed intermittent behaviour for almost the whole of the year. In addition Hekla, a volcano about 70km east-Northeast of BJA, had a minor eruption in March 2000.

Note that the effects of the $M=4.1$ earthquake immediately after Vatnajökull are not fully explained. There were several $M\geq4$ events near Vatnajökull at the time of the eruption. We suggest that the Vatnajökull event was so massive that $M=4$ events were just noise on the much-more-widespread effects of the magma injection before the eruption.

3.5 Significance of scatter in time delays above small earthquakes

A remarkable feature of Figure 3 is that the average variations of time delays before earthquakes, the nine-point moving averages, behave in a comparatively regular manner, with an apparent response to stress increases, despite the very large scatter of time delays about the mean. The $\pm80\%$ scatter appears to be too large to be caused by errors in location, identification or interpretation. It can be shown that shear-wave splitting is sensitive to minor variations in the stress field (Zatsepin and Crampin, 1997; Crampin and Zatsepin, 1997a). We are currently investigating whether the scatter can be caused by minor variations in the way cracks respond to changes in stress, and particularly whether the scatter is caused by changing dimensions of different-sized clusters of cracks as they coalesce and separate.

It is possible that the driving force modifying crack geometry, which is believed to be the source of the scatter, may well be Earth and ocean tides. Variations in both horizontal and vertical $P$-wave velocity of approximately 0.5% correlating with tides were observed in reflection and transmission experiments in the comparatively shallow crust by Tatham et al. (1993). Tatham et al. attribute these effects to the opening and closing of microcracks and pore throats. Since shear-wave splitting is more sensitive than $P$-waves to variations in microcrack geometry, it can be expected that tidal effects will be also visible in shear-wave splitting time delays. Water-level fluctuations (at shallow depths) in wells correlating with tides have also been observed, for example by Gupta et al. (2000) around the Koyna Dam in India, so tidal variations in shear-wave splitting may well be particularly common in near-surface rocks. Kümpel (1997) reviewed observations of variations of well levels with tides and barometric pressures. One of the first investigations of the SMSITES Project (next section) will be examining the short-term temporal stability of shear-wave splitting.

4 Development of a stress-monitoring site (SMS) in Northern Iceland

Stress forecasting of earthquakes, as reported in southwest Iceland (Crampin et al., 1999a; Volti and Crampin, 2000) and outlined above, using small earthquakes as a source of shear waves, is possible only when there is sufficiently persistent small-scale seismicity to provide adequate shear-wave signals for monitoring crack distributions within the rock mass. Continuous seismic activity as observed in Southwest Iceland is extremely rare. An alternative solution, using controlled-source observations, independent of small-scale seismicity, requires monitoring shear-wave splitting over the same solid
angle of directions that showed changes above small earthquakes. Crosshole seismic experiments are needed so that the ray paths are below the severe scattering and attenuation in the uppermost few hundred meters of the crust (Leary and Abercrombie, 1994; Leary 1995). Crosshole experiments using airguns in purpose-drilled, expensive, deviated wells were originally suggested by Crampin and Zatsepin (1997b) and Crampin (1998b). However, the recent commercial availability of the Downhole Orbital Vibrator (DOV) shear-wave borehole source (Cole, 1997), previously known as the Conoco Orbital Vibrator, now allows stress-monitoring sites (SMSs) to be developed using much cheaper and more commonly available vertical wells. The DOV has an eccentric cam that exerts a radial force on the borehole walls when it is swept in both clockwise and counter-clockwise directions. The radiated signals can be processed to simulate orthogonal point forces perpendicular to the borehole axis. The DOV has the great advantage in that it not only generates orthogonally polarised shear waves, there is also minimal tube wave generation. The wells for an SMS need to be in a particular three-well geometry with relation to the stress field, in order to sample shear waves along the ray paths in Band-1, which are sensitive to changes in aspect ratio and stress.

The European Commission is funding the development of an SMS in three vertical wells in a potential seismic gap in northern Iceland on the northern leg of the transform zone of the Mid-Atlantic Ridge underlying Iceland. The SMSITES Project (Crampin et al., 2000) makes use of three wells just north of the town of Húsavík adjacent to the Flatey-Húsavík Fault of the Tjörnes Fracture Zone of the Mid-Atlantic Ridge. The wells, one central 1.1 km deep and two shallower wells (Figure 4), were originally drilled for the local energy company, Orkuveita Húsavíkur, for extraction of geothermal heat. By good fortune, the wells happen to have nearly ideal geometry for monitoring changes of crack aspect ratio in crack-induced shear-wave splitting in Band-1.

The precision with which controlled-source direct-transmission seismic experiments can be measured and interpreted (as in the reflection profiles and VSPs of Li and Crampin, 1991a, 1991b, and Yardley and Crampin, 1993) suggests that stress-monitoring sites will lead to much more accurate and quantifiable observations than can ever be expected using earthquakes as source signals. This improved resolution, as well as monitoring changes indicative of increasing stress, is also likely to lead to a better understanding of several phenomena concerned with observations of and the stability of shear-wave splitting.

5 Implications of SOC for Earth science

Self-organised criticality (SOC) is still largely phenomenological, with a mathematical formalism and physical understanding that is only slowly emerging (Jensen, 1998). An enormous range of multi-component interactive systems are critical and possess SOC. These include the classic piles of sand and distributions of earthquakes of Bak et al. (1988) but also forest fires, magnetic flux in superconductors, water droplets on surfaces, economic systems, biological evolution, and a large range of interactive physical and non-physical systems which are driven by a slow driving force. In this sense, it would be surprising if the Earth, which is subject to the slow driving forces of moving tectonic plates and flexing by Earth and ocean tides, did not possess SOC. Note that the relaxation times of fluid-saturated cracks is rapid compared with the cycles of Earth tides (Zatsepin and Crampin, 1997).

Jensen (1998) shows that SOC behaviour must be expected in "slowly driven, interaction-dominated threshold systems". The essential ingredient is that a system slowly evolves from a marginally stable state of meta-stability toward a threshold (in the earth the threshold is the percolation threshold), and the critical state is fracture criticality and earthquake occurrence. Following the threshold, fracture or faulting occurs, and the system relaxes to another
meta-stable state. The slow drive is necessary in order for the intrinsic properties of the system to have sufficient time to control the dynamics (a continuous stream of sand on the sandpile would not have the discrete avalanches of SOC).

We suggest that the large variety of phenomena listed in Tables 1 and 2 suggests that crack distributions in at least the crust of the Earth are critical systems with SOC. This is not the first time that the critical nature of the Earth has been suggested (Bak and Tang, 1989; Kagan, 1992; Turcotte, 1992a; Leary, 1997; amongst many others). The new result is the recognition that the physics at the small-scale end of the self-similar distributions is the interaction of fluid-saturated grain-boundary cracks and pores as fluid is driven by pressure gradients between neighbouring cracks at different orientations to the stress-field. This local physics allows the behaviour to be calculated by APE.

5.1 The disadvantages of SOC

Table 3 lists some of the implications of the distribution of cracks in the crust being critical systems with SOC. They include several fundamental differences from conventional geophysics.

A critical system behaves nonlinearly. This means that properties may be extraordinarily complicated, and behave in ways that cannot be explained by classical or conventional physics (or geophysics), which is customarily assumed to be linear. In critical systems: fractal, self-similar, distributions are expected, particularly in anything to do with cracks (Table 2); power spectra decay as 1/f; properties may have Gaussian statistics (bell-shaped distributions) in specific rock volumes, but the average values fluctuate from with volume size and from volume to volume; properties (except at the minimum scale) tend to have no characteristic scale-length; there is the potential for systems to be extremely sensitive (deterministic chaos) to seemingly negligible variations in initial conditions; exceptionally long-range interactions may be expected; and there may be previously-inexplicable temporal variations, and other anomalies.

The most important of these is that there are spatial and temporal heterogeneities at all scale lengths and that Gaussian averages are only valid in particular limited circumstances. This means that any measurement of subsurface properties must be made at the time and place it is required. If high resolution is required, it may not be possible to extrapolate from place to place or from time to time. These various disadvantages in Table 3a, undermine, or place at risk, the detailed interpretation and conventional understanding and interpretation of a large variety of geophysical results, including conventional reservoir characterisation and hydrocarbon production (Crampin, 1999b).

This means that if any current geophysical technique proves useful, it may well be by-chance at the limit of its resolution as we try to extract more detailed information, or try to use it for more precise or detailed information. It also suggests that errors or inaccuracies displayed by current techniques may well be due to the inherent instabilities or inherent variations associated with SOC. These are unlikely to be resolved by conventional processes or processing. It seems likely that many techniques are at or near the limit of their resolution. Since the flow of fluid-fluid fronts through reservoir rock is controlled by the detailed geometry of microscale fluid-rock interactions, an understanding of the critical nature of the rockmass is essential for understanding the physics of hydrocarbon production.

5.2 The advantages of SOC

Table 3b lists possibly crucial advantages of SOC for geophysics. Quite apart from a more correct understanding of fluid-rock interactions, which has to be important in the long-term, there are three immediate advantages.

(1) Crack distributions can be monitored with shear-wave splitting: We have already described how observations of shear-wave split-
ting can be interpreted in terms of in situ distributions of grain-boundary cracks and pores.

(2) Changes in shear-wave splitting are controlled by the same parameters as control pre-fracturing deformation: This means that, in particular, time-lapse seismics can be interpreted directly in terms of the response of fluid-saturated cracks to changing conditions.

(3) The response of the rockmass to changing conditions can be calculated by APE: The reason this is possible in a heterogeneous complicated Earth is believed to be that APE is a mean field theory (Jensen, 1998) and has the critical point universality common to such critical systems (Bruce and Wallace, 1989).

These various features have massive practical implications for geophysics, some of which are listed in Table 4. More complete discussions of individual items can be found in Paper 1 and in Crampin (1999a, 1999b). We claim that the pre-fracturing deformation of a complicated heterogeneous Earth is beginning to be understood.

6 Implications of a critical crust with SOC

This paper suggests that the critical crack systems exist in much, perhaps most, of the heterogeneous complicated crust. Some of the practical implications for Earth Science are indicated in Table 4a. The increased understanding of how rock deforms is likely to have long-term benefits, and in particular to indicate profitable and unprofitable directions for future developments. Wholly successful Earth Science applications in the past have been in appropriate dimension and frequency windows within which resolution is adequate. These are likely to remain largely unchanged.

However, many existing Earth Science applications are not wholly successful. The two obviously non-optimal operations are hydrocarbon recovery and earthquake prediction.

6.1 Hydrocarbon recovery

Despite the astonishing amounts of oil reserves in the ground, and the time, thought, technology, and the huge amounts of money spent on recovery, it is seldom possible to extract even as much as 50% of known reserves, and it is frequently much less. Dry wells are still drilled. We suggest that the implications in Table 4b provide one explanation for the difficulty in producing all the reserves in any reservoir. Reservoirs are not the comparatively stable, uniform entities governed by conventional physical and geophysical processes that they were once thought to be. Table 4 suggests they are highly compliant in ways (the internal geometry of microcracks) that can be directly monitored only with shear-wave splitting. Since the permeability and directionality of fluid flow are largely controlled by the stress- and pressure-sensitive crack geometry, analysing shear-wave splitting is clearly of paramount importance for understanding and monitoring hydrocarbon production processes. It has been demonstrated that shear-wave splitting is the most diagnostic seismic parameter for monitoring the progress of fluid-fluid fronts in producing reservoirs (Davis et al., 1997; Pranter et al., 2000; Angerer et al., 2000a, 2000b).

There are two important conclusions:

A single-well configuration is essential for measuring reservoir properties and monitoring hydrocarbon recovery if high resolution is required. Reservoir characterisation, using low frequencies and long wavelengths and leading to low resolution, may be possible. The specific bad news in Table 3a for detailed conventional reservoir characterisation is that properties may vary from place to place and from time to time so that any average quantity may be unreliable (Table 4b). The near-surface attenuation and scattering mean that most surface-based observations cannot be expected to have sufficient resolution to monitor the detailed effects of fluid-rock interactions.
The only way to get accurate estimates of reservoir properties is by measuring the properties in the place (the reservoir) and at the time (during production) they are required. During hydrocarbon production, one way, possibly the only way, to get these properties is by a single-well imaging configuration (Crampin et al., 1993; Peveraro et al., 1994; Crampin, 1999b). Single well imaging is where a string of three-component geophones, inserted behind casing or behind tubulars in the producing well, records signals from an in-line source within the production zone, scattered from the internal structure within the reservoir. The optimum technique is time-lapse seismics: analysing the changes in scattering induced by movements of fluid-fluid fronts within the producing reservoir. Appropriate instrumentation for strings of receivers and borehole sources in a single-well configuration has only recently become available.

**Hydrocarbon production is likely to be most successful at slow production rates.** To take advantage of the good news in Table 3b, a crucial requirement is that any induced change must be sufficiently slow to leave ample time for natural stress-relaxation phenomena to occur. Calculable APE behaviour depends on SOC, and a requirement for SOC is that it is slowly driven (Jensen, 1998). Fast changes, which do not allow stress relaxation, would deliver the bad news in Table 3a without any mitigating advantages. This is the current situation. Fluid-fluid interactions are irregular and unpredictable, and surface-based seismics do not have sufficient resolution. There is real chaos, not even deterministic chaos. This suggests that producing reservoirs are likely to behave in more regular ways (and more likely to achieve their expected production targets), if production rates are sufficiently slow to allow stress relaxation as production proceeds.

### 6.2 Stress-forecasting not prediction of earthquakes and volcanoes

For more than a hundred years, an immense amount of money and thought has been expended on earthquake prediction without any really significant progress. The bad news shown in Table 3a specifically excludes the deterministic prediction of the time, place, and magnitude of future large earthquakes, (Geller, 1997; Leary, 1997; Kogan, 1997). The hypothesis behind the development of a stress-monitoring site (Crampin, 2000; Crampin et al., 2000), discussed above, is that a large or larger earthquake cannot occur without a significant build-up of stress within the Earth so that in situ stress-modified crack distributions approach fracture criticality. It is the approach to fracture criticality that can be monitored with shear-wave splitting, and this allows time and magnitude to be stress-forecast (Crampin et al., 1999a; Volti and Crampin, 2000). We have suggested that stress-monitoring sites (SMSs), where shear waves in cross-hole seismics are analysed over the same range of ray paths that show changes above small earthquakes, can be developed wherever the need for forewarning of earthquakes is required.

One difficulty is that there are two main sources of comparatively short-term stress changes in the crust: the build-up of shear-stress leading to earthquakes; and stresses changes caused by the movement of magma, leading to volcanic eruptions (both are physical manifestations of longer-term tectonic movements of the crust and mantle). It has not yet been established whether shear-wave splitting can distinguish between earthquakes and movements of magma. One possible difference has been observed. Whereas time delays in Band-2, ray paths ±15° to the crack plane, do not show any recognisable pattern of behaviour before earthquakes, time delays at several stations in Band-2 appeared to show a consistent increase before the Vatnajökull eruption in October 1996 and a consistent overall decrease for two to three years following the eruption (Figure 3). These differences, as with so much about SOC, are phenomenological and not yet understood.

### 6.3 Critical point universality

One of the principal motives in developing the ideas in this paper was the desire to understand the rea-
sons for the narrow range of shear-wave velocity anisotropy (and hence the narrow range of implied crack density) observed in all rocks, and why it is broadly independent of rock type (sedimentary, igneous or metamorphic), porosity, and geologic and tectonic history and environment (Crampin, 1994, 1999a). This universality appeared totally inexplicable when first observed. The narrow range in all rocks were either due to several extraordinary coincidences which were clearly untenable, or else it was a new phenomenon, inexplicable by conventional (that is, classical) physics and geophysics. This paper suggests that these features occur because the crust is a critical-system with self-organised criticality and critical point universality. The underlying stress-aligned fluid-saturated crack distributions appear to be a fundamental (universal) feature of almost all in situ rocks.

We repeat that the behaviour of both critical systems and particularly self-organised criticality is not yet wholly understood (Jensen, 1998). Such systems can be recognised by their properties, but their mathematical and physical formalism is not yet wholly identified. One of the observed features of critical systems is that they behave in characteristic ways (typified by self-similarity extending over wide ranges of frequency or dimension), irrespective of the different classical physics of the sub-critical behaviour. This is the critical-point universality of Bruce and Wallace (1989) and is presumably the reason for the success of APE-modelling in the narrow sub-critical range of crack densities and, coincidentally, a huge range of other phenomena (see Tables 1 and 2). This has important implications and applications for almost all aspects of Earth Science that involve any kind of deformation (see Tables 3 and 4): that is, almost all Earth Science. We have suggested some implications in Table 4, but the effects are so fundamental, and as yet so little understood, that readers may well be able to think of others.

There are two important features:

1) The necessary self-similarity of many distributions, often with 1/f-noise (see Table 2), implies temporal and spatial heterogeneities at all scale lengths. This means that Gaussian averages do not converge (except in particular circumstances) and that there is a limit to the resolution of any particular geological and geophysical measurement. Any satisfactory geophysical measurement is implied to be below the resolution limit, and any unsatisfactory measurement may well be attempting a higher resolution than is possible in the particular critical system. The scatter of time delays in shear-wave splitting measurements above small earthquakes, as in Figure 3, may be one example. Since the time delays between two orthogonally polarised shear waves can, in many circumstances, be read with great accuracy, time delays are second-order differential quantities that can be read with first-order accuracy. Thus the scatter in Figure 3 may well be intrinsic to critical-point universality and cannot be explained by conventional physics or geophysics. Consequently, one of the important investigations for the proposed stress-monitoring site is to examine the cause and properties of this scatter.

2) Another important feature of critical systems of crack distributions in the Earth, which may be unique, is that the proximity of the critical point (the level of fracture criticality) can be monitored in some detail within the deep interior of the critical solid by analysis of shear-wave splitting. It is possible that shear-wave studies of the cracked crust could provide useful information for a more general understanding of the behaviour of self-organised criticality and critical media.

7 Conclusions

We have presented what we consider convincing evidence that the fluid-saturated stress-aligned grain-boundary cracks and pores in almost all rocks of the earth's crust are critical interactive systems held close to the critical point of fracture criticality. This conclusion has profound implications for our
understanding of rock deformation. Rock is highly compliant, but the dominant seismic effect of any change in conditions is the temporal instability of shear-wave splitting. Shear-wave splitting has been observed to vary before fracturing over periods varying from hours before hydraulic fracturing to days and years, depending on the magnitude (and location) of earthquakes (see the review of Crampin, 1999a). These can be interpreted, modelled and calculated by anisotropic poro-elasticity (APE) as the effects of stress acting on the fluid-saturated grain-boundary cracks and pores present in most rocks in the crust. There are only a few well-understood exceptions.

The reason why this compliance has not been recognised earlier is that the principal tool used in seismology is interpreting P-waves, and liquid-saturated cracks are almost transparent in P-waves. Only the improvements in observations and understanding of shear-wave splitting, which is highly sensitive to microcrack geometry, have allowed this compliance to be recognised.

However, although the effects of rock compliance and criticality are limited seismically, there are massive effects elsewhere. It is the approach of fracture criticality, when crack distributions are so pervasive that shear strength is lost, that allows fracturing, faults, hydraulic fracturing and earthquakes to occur. Although not argued in this paper, the compliance is also the reason why thick tectonic plates can move over the varying curvature of the Earth's mantle. However, the important effect for this present audience of industrial geophysicists is that the movement of fluid-fluid fronts in hydrocarbon reservoirs is controlled by pressure gradients in porous rock. We suggest that every constriction and every pore throat tend to be aligned by stress and, although not yet proven, probably fluctuates with Earth and ocean tides and possibly even barometric pressures.

Critical interactive systems and self-organised criticality are pervasive models applicable to an enormous number of classes of phenomena in a wide range of disciplines. It would be astonishing if the Earth's crust were not such a system. We have demonstrated how this behaviour directly applies to earthquakes and oil-field injections. The behaviour of critical systems is still largely phenomenological and not fully understood mathematically or physically. It is perhaps amusing that it appears that one of the world's major industries, hydrocarbon production, which has major implications for the future of the world, probably depends, perhaps crucially, on the behaviour of critical interactive systems, which it does not understand and has previously not even recognised. We need a more detailed understanding of the behaviour of reservoirs, and this understanding can only be gained by seismic recording with a single-well configuration, with perhaps additional information from experiments such as the SMSITES Project.

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Table 1: Match of APE* modelling to observations (Crampin, 1999, updated).

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<td>12) Variations in SWTD for some 5 months before 30th Sept., 1996, Vatnajökull eruption, Iceland, observed at distances of: 230 km and 200 km WSW; 170 km SW; and 240 km, N.</td>
<td>[10]</td>
<td>£</td>
</tr>
<tr>
<td><strong>Variations of shear waves in laboratory experiments</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14)#Variations of (isotropic) shear wave velocities to changes in confining pressure and pore-fluid pressure for oil-, water-, and gas- (dry) saturations in stress cells of sandstone cores.</td>
<td>[13]</td>
<td>[13]</td>
</tr>
<tr>
<td>15)#Variations of velocity and attenuation from sonic (transducers) to seismic (resonant bar) frequencies.</td>
<td>[14]</td>
<td>[15]</td>
</tr>
</tbody>
</table>

*APE - anisotropic poro-elasticity; ‡SWVA – shear-wave velocity-amisotropy; £Effects compatible with APE; †SWTD – shear-wave time delays;

#Including recent examples;

References:
[1] Crampin (1994);
[2] Crampin and Zatsepin (1997a);
[3] Heffer and Bevan (1990);
[5] Crampin et al. (1996), Liu et al.(1997);
[6] Angerer et al. (2000a, 2000b);
[7] Crampin and Booth (1989);
[8] Booth et al. (1990), Crampin et al. (1990, 1991), Liu et al. (1997), Gao et al. (1997); Crampin et al. (1999a);
[9] Crampin et al. (1999a);
[10] Crampin et al. (1998), and Figure 3;
[11] King et al. (1994);
[12] Zatsepin and Crampin (1996);
[13] Crampin et al. (1997, 1999b);
[14] Sothcott et al. (2000a, 2000b);
Table 2: Self-similar (scale-invariant) distributions in crustal rocks.

<table>
<thead>
<tr>
<th>DISTRIBUTION</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Earthquakes worldwide:</strong></td>
<td></td>
</tr>
<tr>
<td>1) Cumulative number/ seismic moment or magnitude</td>
<td>[1]</td>
</tr>
<tr>
<td>a) shallow-depth &lt; 70 km</td>
<td></td>
</tr>
<tr>
<td>b) 70 km = intermediate depth = 280 km</td>
<td>[1]</td>
</tr>
<tr>
<td>c) deep &gt; 280 km</td>
<td>[1]</td>
</tr>
<tr>
<td>2) Cumulative number/ energy: all earthquakes</td>
<td>[2]</td>
</tr>
<tr>
<td><strong>Local earthquakes:</strong></td>
<td></td>
</tr>
<tr>
<td>3) Seismic moment/ corner frequency</td>
<td>[3]</td>
</tr>
<tr>
<td>4) Source radius/ seismic moment</td>
<td>[3]</td>
</tr>
<tr>
<td><strong>Microcracks, fractures, faults:</strong></td>
<td></td>
</tr>
<tr>
<td>5) Frequency/ crack spacing</td>
<td>[4]</td>
</tr>
<tr>
<td>6) Frequency/ aperture</td>
<td>[4]</td>
</tr>
<tr>
<td>7) Cumulative number/ crack length</td>
<td>[5]</td>
</tr>
<tr>
<td><strong>Roughness and wear on faulted surfaces:</strong></td>
<td></td>
</tr>
<tr>
<td>8) Wavelength/ power spectral density</td>
<td>[6]</td>
</tr>
<tr>
<td>9) Profile length/ root-mean-square roughness</td>
<td>[6]</td>
</tr>
<tr>
<td>10) Displacement/ thickness</td>
<td>[6]</td>
</tr>
<tr>
<td><strong>Volcanoes:</strong></td>
<td></td>
</tr>
<tr>
<td>11) Cumulative number/ fissure length</td>
<td>[7]</td>
</tr>
<tr>
<td>12) Cumulative number/ dike thickness</td>
<td>[7]</td>
</tr>
<tr>
<td>13) Cumulative number/ time between successive eruptions</td>
<td>[7]</td>
</tr>
<tr>
<td><strong>Distribution of properties in well-logs:</strong></td>
<td></td>
</tr>
<tr>
<td>14) Power spectra of sonic log (1/f-noise)</td>
<td>[8]</td>
</tr>
<tr>
<td>15) Power spectra of resistivity (1/f-noise)</td>
<td>[8]</td>
</tr>
<tr>
<td>16) Power spectra of gamma activity log (1/f-noise)</td>
<td>[8]</td>
</tr>
<tr>
<td><strong>Dynamic properties of cracks</strong></td>
<td></td>
</tr>
<tr>
<td>17) Crack growth velocity/ crack tip stress intensity in subcritical crack growth</td>
<td>[9]</td>
</tr>
</tbody>
</table>

Table 3: *Direct implications of distributions of cracks in the crust being critical systems with self-organised criticality*

<table>
<thead>
<tr>
<th>(a)</th>
<th><strong>The bad news</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>a.1</td>
<td>Spatial and temporal heterogeneities exist at all scale lengths.</td>
</tr>
<tr>
<td>a.2</td>
<td>Gaussian statistics (averages) are only appropriate in specific situations.</td>
</tr>
<tr>
<td>a.3</td>
<td>Inability to reliably extrapolate from place to place.</td>
</tr>
<tr>
<td>a.4</td>
<td>Inability to reliably extrapolate from time to time.</td>
</tr>
<tr>
<td>a.5</td>
<td>Hence the expectation that any measurement may degrade with time.</td>
</tr>
<tr>
<td>a.6</td>
<td>Possibility of long-range interactions between hydrocarbon reservoirs.</td>
</tr>
<tr>
<td>a.7</td>
<td>Possibility of long-range interactions between earthquakes in different regions.</td>
</tr>
<tr>
<td>a.8</td>
<td>Possibility of long-term interactions in hydrocarbon reservoirs.</td>
</tr>
<tr>
<td>a.9</td>
<td>Possibility of long-term interactions between earthquakes in the same region.</td>
</tr>
<tr>
<td>a.10</td>
<td>Behaviour of crustal may not correspond or be explicable by conventional geophysics.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(b)</th>
<th><strong>The good news when the rock mass is responding to slow changes</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>b.1</td>
<td>Current configuration of crack geometry within the deep interior of the reservoir or rockmass can be monitored with shear wave splitting.</td>
</tr>
<tr>
<td>b.2</td>
<td>Current configuration of cracks in reservoir or rocks can be evaluated by APE.</td>
</tr>
<tr>
<td>b.3</td>
<td>Response of reservoir or rockmass to known changes can be calculated by APE.</td>
</tr>
<tr>
<td>b.4</td>
<td>Response of reservoir or rockmass can be controlled by feedback by repeating b.1, b.2 and b.3, above.</td>
</tr>
</tbody>
</table>
Table 4: *Practical implications of critical crack systems with SOC for fluid-rock interactions within the earth’s crust.*

(a) **GENERAL IMPLICATIONS**

a.1 Fluid-saturated crack distributions are highly compliant and crack geometry responds to small changes of stress, pressure, and other conditions.

a.2 Since fluid-rock properties may vary with time, and vary from place to place with low-resolution averages, measured fluid-rock properties are only strictly valid at place and time they are measured. Hence, need for measurements with single-well configurations if accurate specifications are required.

a.3 Since fluid-rock interactions have a dominant effect on almost all physical and chemical behaviour with the crust and mantle, Item a.2, above applies to a huge range of geophysical phenomena, particularly those associated with any deformation, including almost all processes during hydrocarbon recovery.

a.4 Behaviour of stress-aligned fluid-saturated crack distributions appears to be remarkably uniform (within certain limits) even in very heterogeneous structures.

a.5 Pre-fracturing deformation of any given fluid-rock configuration can be monitored by observations of shear wave splitting.

a.6 Pre-fracturing deformation can be modelled by anisotropic poro-elasticity (APE).

a.7 Response of fluid-rock systems to known changes can be calculated by APE.

a.8 Response to calculated changes (a.6) can be monitored by shear wave splitting (a.4), and the response controlled by adjusting changes to optimised response.

(b) **SPECIFIC IMPLICATIONS**

1. **Implications for hydrocarbon exploration and production**

b.1 Reservoir properties may change from place to place.

b.2 Reservoir properties may change with time, even without production processes.

b.3 Relevant properties need to be measured at the place and time they are needed.

b.4 Response to known changes can be calculated (Angerer et al., 2000a, 2000b).

b.5 Response of reservoir can be controlled, in the sense of a.7, above.

b.6 Possibility of long-range and long-time correlations across reservoirs (Heffer et al., 1995).

b.7 There is a limit to the resolution of any measurement

(c) **Implications for geophysics**

c.1 Deterministic prediction of time, magnitude, and place of large earthquakes is likely to be impossible (Geller, 1997).

c.2 With sufficient source seismicity (Crampin et al., 1999a), or appropriate crosshole experiments, times and magnitudes of future large earthquakes can be stress-forecast.

c.3 In presence of sufficient source seismicity, times of future volcanic eruptions can be stress-forecast (Crampin et al., 1998).

c.4 There is possibility of long-range and long-time correlations between earthquakes.

(d) **Implications for rock physics**

d.1 Much of the behaviour in stress-cells in the rock-physics laboratory can be modelled and predicted by APE (Crampin et al., 1997, 1999b; Chapman et al., 1998, 2000).