SHEAR-WAVE SPLITTING IN A CRITICAL CRUST: THE NEXT STEP

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BIRÉFRINGENCE DES ONDES TRANSVERSALES DANS LES CROÛTES CRITIQUES : LA PROCHAINE ÉTAPE

On pourrait avancer que l'anisotropie dans la biréfringence des ondes transversales n'a pas répondu à ses promesses initiales, à savoir ouvrir une nouvelle voie dans la compréhension des phénomènes de fissures et de contraintes dans la croûte terrestre. Dans cet article sont présentés deux développements révélés récemment, qui paraissent raviver ces premiers espoirs et apportent des opportunités nouvelles pour le contrôle, la modélisation et même la prévision des déformations (avant fracture) dans les roches microfracturées et saturées de fluides.

Ainsi, un modèle de poroélasticité (APE) développé récemment concerne l'évolution sous contraintes des roches microfracturées et saturées en fluide et reproduit une large gamme de phénomènes, qui seraient autrement inexpliqués ou dissociés, et semble être une bonne approximation au premier ordre de l'évolution des roches microfracturées et saturées en fluide. Puisque les paramètres qui contrôlent à petite échelle la déformation (avant fracture) contrôlent aussi la biréfringence des ondes transversales, il apparaît que l'évolution des roches microfracturées et saturées peut être aussi directement contrôlée par cette biréfringence et que la réponse à des changements futurs peut être prédite par l'APE.

Le bon usage de la modélisation de l'APE et des observations de la biréfringence des ondes transversales implique que la plupart des roches soient proches d'un stade de fracturation critique associé à une percolation limite, situation où la résistance aux contraintes transversales disparaît et où les fractures transversales peuvent se propager. Ceci corrobore une autre hypothèse concernant la mise en situation critique spontanée des roches *in situ.* La conséquence de cette identification est que la physique à petite échelle, qui contrôle l'ensemble du phénomène, peut maintenant être associée aux contraintes générées par les fluides baignant les fissures intergranulaires. Ceci a probablement l'avantage unique, parmi les systèmes critiques, de donner la possibilité de contrôler en chaque point les détails des déformations avant fracture et l'approche du seuil critique (dans ce cas l'approche d'une fracturation), au moyen d'observations adéquates de la biréfringence des ondes transversales.

Cet article passe en revue ces développements et commente leurs conséquences et leurs applications, en particulier les conséquences sur la mise en situation critique des roches spontanément. L'étape suivante sera d'exploiter ces techniques pour modéliser, contrôler et prédire les effets de changements de conditions sur la déformation de la masse rocheuse.

SHEAR-WAVE SPLITTING IN A CRITICAL CRUST: THE NEXT STEP

Arguably, shear-wave splitting displaying azimuthal anisotropy has not lived up to its initial promise of opening a new window for

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understanding cracks and stress in the crust. This paper reviews two recent related developments which appear to renew these initial hopes and provide new opportunities for monitoring, modelling, and even predicting, the (pre-fracturing) deformation of fluid-saturated microcracked rock.

A recently developed model of anisotropic poro-elasticity (APE) for the stress-induced evolution of fluid-saturated microcracked rock matches a wide range of otherwise inexplicable or dissociated phenomena and appears to be a good first-order approximation to the evolution of fluid-saturated microcracked rock. Since the parameters that control small-scale (pre-fracturing) deformation also control shear-wave splitting, it appears that the evolution of fluid-saturated microcracked rock can be directly monitored by shear-wave splitting, and the response to future changes predicted by APE.

The success of APE-modelling and observations of shear-wave splitting imply that almost all rock is close to a state of fracture criticality associated with the percolation threshold, when shear-strength is lost and through-going fractures can propagate. This confirms other evidence for the self-organized criticality of in situ rock. The significance of this identification is that the small-scale physics that controls the whole phenomena can now be identified as the stress-induced manipulation of fluids around intergranular microcracks. This has the possibly unique advantage amongst critical systems that details of the pre-fracturing deformation and the approach to the criticality threshold (in this case the proximity to fracturing) can be monitored at each locality by appropriate observations of shear-wave splitting.

This paper reviews the these developments and discusses their implications and applications, particularly the implications of self-organized criticality. The next step is to employ these techniques to model, monitor, and predict the effects of changing conditions on the deformation of the rockmass.

DIVISIÓN POR ONDA DE CIZALLAMIENTO EN UNA CORTEZA CRÍTIC : EL PRÓXIMO PASO

Puede discutirse que la división por onda de cizallamiento con anisotropía azimutal no ha cumplido sus promesas iniciales: abrir una nueva vía para la comprensión de las grietas y de las tensiones de compresión que actúan en la corteza. Este artículo revisa dos líneas de desarrollo recientes, relacionadas entre sí, que parecen renovar esta esperanza inicial y que proporcionan nuevas oportunidades para monitorear, modelizar e incluso predecir la deformación (previa a la fractura) de rocas con microgrietas saturadas de fluidos.

Un modelo recientemente desarrollado de poro-elasticidad anisotrópica (APE) para la evolución inducida por la tensión de compresión en rocas con microgrietas saturadas de fluidos hace coincidir una amplia variedad de fenómenos que de otra manera resultan inexplicables o disociados y parece representar una buena aproximación de primer orden para estudiar la evolución de la roca con microgrietas saturada de fluidos. Dado que los parámetros que controlan la deformación en pequeña escala (previa a la fractura) también controlan la división por onda de cizallamiento, pareciera que la evolución de la roca con microgrietas saturada de fluido puede ser monitoreada directamente a través de la división por onda de cizallamiento, y que la respuesta a cambios futuros podría ser predicha por APE.

El éxito de la modelización APE y las observaciones de división por onda de cizallamiento implican que casi toda la roca se encuentra cercana a un estado de fractura críticamente asociado con el umbral de percolación, cuando la resistencia al cizallamiento se ha perdido y las fracturas traspasantes pueden propagarse. Esto aporta una evidencia adicional a la criticalidad auto-organizada en la roca in situ. La importancia de esta identificación es que la física en pequeña escala que controla el conjunto de los fenómenos puede ser ahora identificada como la manipulación de fluidos inducida por la tensión de compresión en torno a microgrietas intergranulares. Esto tiene la ventaja, quizás única entre los sistemas críticos, que los detalles de la deformación previa a la fractura y el enfoque del umbral crítico (en este caso, la proximidad de la fracturación) pueden ser controlados en cada localidad mediante observaciones apropiadas de la división por onda de cizallamiento.

Este artículo revisa estas líneas de desarrollo y discute su implicación y aplicación, en particular las implicaciones de la criticalidad auto-organizada. El próximo paso es el empleo de estas técnicas para modelizar, controlar y predecir los efectos de condiciones cambiantes sobre la deformación de las masas rocosas.

INTRODUCTION

Since stress-aligned shear-wave splitting was first positively identified in the shear-wave window above small earthquakes (Crampin *et al.*, 1980), azimuthally-aligned shear-wave splitting has now been observed *with very similar properties,* whenever suitable three-component recordings of shear-waves have been recorded for ray paths below 1 km in almost all types of igneous, metamorphic, and sedimentary rocks in a wide variety of geologic and tectonic regimes (reviewed by Crampin, 1994). This followed the earlier recognition (Crampin, 1978) that distributions of aligned cracks would be seismically anisotropic and cause (long-wavelength) shear-wave splitting. Such shear-wave splitting has now been reported in well over a hundred different locations. There are only a few well-understood exceptions where such azimuthal anisotropy is not observed in appropriate conditions, see Section 1.1, below. As a consequence, shear-wave splitting with azimuthal anisotropy is now an accepted property of crustal rocks, as increasingly frequent reports in geophysical journals testify.

The underlying cause of the splitting is more controversial. Shear-wave splitting in igneous and metamorphic rocks above small earthquakes was originally sought, found, and positively identified in the Turkish Dilatancy Projects (Crampin *et al.*, 1980, 1985) in the expectation that it was caused by distributions of stress-aligned fluid-saturated intergranular microcracks now referred to as *extensive-dilatancy anisotropy,* or EDA (Crampin *et al.*, 1984). The seismic response to EDA-cracks was later analytically formulated in a series of papers by Hudson following Hudson (1981). However, the existence of strong crystalline anisotropy in many minerals in the crust has led many geophysicists to suggest that shear-wave splitting in the crust is also caused by mineral anisotropy (see for example Babushka and Caro, 1992). This paper attempts to resolve this controversy by summarising the evidence for a model of *anisotropic poro-elasticity,* or APE (Zatsepin and Crampin, 1995, 1997), for the evolution of stressed fluid-saturated microcracked rock. This model also shows that observations of shear-wave splitting are directly tied to implications of criticality for a compliant critical crust sensitive to minor changes of conditions.

Since shear-wave splitting in industrial seismic exploration reflection and VSP surveys was first recognized (Crampin, 1985; Crampin *et al.*, 1986a; Alford, 1986), shear-wave splitting in sedimentary rocks has usually been assumed to be caused by stress-aligned cracks and low aspect-ratio pores, although the dimensions of the cracks is in question. Mueller (1991) and many reports from the Reservoir Characterization Project, *Colorado School of Mines* (reviewed by Davis, 1995) suggest that pronounced shear-wave splitting is caused by large aligned-cracks. There are other papers (Li *et al.*, 1993) and the recent observation of temporal changes in splitting during hydrocarbon production (Davis *et al.*, 1997) and other phenomena that suggest that the splitting is microcrack induced. It is convenient to use the term EDA-cracks to cover aligned low aspect-ratio pores as well as aligned microcracks.

Note that the term “shear-wave splitting” in this review refers to splitting showing azimuthal variations (azimuthal *anisotropy*) where shear-wave splitting is not in general parallel to *SH*- and *SV*-wave. Splitting into strictly *SH*- and *SV*-waves (azimuthal *isotropy*, or TIV-anisotropy) is characteristic of fine sedimentary layering and the lithology of aligned platelets in shales and clays (Crampin, 1986). Although such transverse isotropy may lead to substantial *P*-wave and shear-wave velocity anisotropy (causing problems for industrial seismic processing), its causes and behaviour are comparatively well understood and such splitting does not provide much additional information about the Earth. In contrast, this review suggests that shear-wave splitting with azimuthal anisotropy is monitoring the deformation of the crust before fracturing occurs, and is providing new information with important implications and applications. The terminology for anisotropy used in this paper is that of Crampin (1989).

1 OBSERVATIONS OF SHEAR-WAVE SPLITTING

1.1 Observations

Crampin (1994) reviewed all reported examples of shear-waves along ray paths in the crust that were recorded usually at the surface by digital three-component instruments with adequate digital sampling rates (typically at least a 100 samples per second). Crampin found 23 reports of shear-wave splitting in igneous and metamorphic rocks principally in the shear-wave window above small earthquakes, and 23 reports from seismic exploration reflection surveys and vertical seismic profiles in sedimentary rocks. In all cases, the polarizations of the leading (faster) split shear-wave were within ± 15° the presumed direction of the horizontal compressional stress where this was known.

High shear-wave velocity anisotropy was found in the uppermost 1 km of the crust, in specific heavily-fractured beds, and in areas of high heat flow. However, independent of rock-type or tectonics, the reviewed reports showed a minimum shear-wave velocity anisotropy of about 1.5% and a maximum of about 4.5% in ostensibly-intact rock below about 1 km in almost all rocks. (The only rocks which did not show such azimuthally varying shear-wave splitting are rocks without free-fluid inclusions such as shales, clays, and mudstones, where fluids are tied to grain boundaries by chemical and electrical potentials, and some carbonates with constrained microstructures such as oolites). At the suggestion of a referee (Leon Thomsen), I specifically list in Table 1 the criteria for classify ranges of azimuthally-varying shear-wave splitting as found by Crampin (1994). Leon Thomsen also points out that shales, clays, mudstones, and oolitic carbonates, which do not show azimuthal anisotropy, form a large proportion of the sedimentary crust. It is interesting that it is the economic and academic interest in the remaining rocks that has presumably stimulated the large number of observations of shear-wave splitting in sedimentary structures.

Note that in many circumstances shear-wave splitting can be estimated with great accuracy by rotating seismograms into preferred orientations (viewing rotated records at fast paper-speeds and high gain, for example). Such measurements are robust. A 10% error in estimating time-delays, or a 10% error in estimating path length, for example, are each equivalent to a 10% error in estimated velocity anisotropy. Since shear-wave velocity anisotropies are typically less than 5%, this means that many measurements of shear-wave splitting have remarkable relative accuracy and justifies specifying anisotropy to one place of decimals, and is also one of the reasons for the stability of many of the analyses of shear-wave splitting.

Many further observations of shear-wave splitting in the crust have been reported since 1994. In particular, in 1996, Don L. Winterstein of *Chevron*, released over the *Internet* (*Anisotropists Digest*, 147, 6th Feb., 1996) reports of 38 further observations of shear-wave splitting mostly in VSPs in sedimentary sequences. These new observations could be classified within the same range of values (1.5% to 4.5% in intact rock) and with the same exceptions as those of Crampin (1994) in Table 1 (*Anisotropists Digests*, 149 and 150).

(Note that Winterstein reports are from highly-selected structures. Over 65% are from different levels (mostly above 1 km) in only three wells, one of which is on an anticline with beds dipping by up to 45°).

TABLE 1

Criteria for classifying shear-wave velocity anisotropy with azimuthal variations (SWVA) based on review of field observations by Crampin (1994)

Crampin (1994) in a review of observations of digitally recorded shear-waves found the following:

- SWVA was observed to be up to or greater than 5% for observations above 1 km. (This depth was interpreted as being the level at which the vertical stress exceeds the minimum horizontal stress. Above this level stress relaxation can lead to very strong anisotropy)[1].
- SWVA was observed to be up to or greater than 5% in zones specifically identified as being heavily fractured or having high heat flow. (These identifications were only made when authors reported such phenomena)[2].
- SWVA observed in shales, clays, and mudstones*, and in oolitic carbonates, was usually negligible (~ 0%). Note that shales, clays, and mudstones may have up to 30% shear-wave velocity anisotropy in transverse isotropy with a vertical symmetry axis, where shear-waves split into strictly SH- and SV-polarizations[3].
- SWVA in otherwise unspecified rock below 1 km was observed to have a minimum of 1.5% and a maximum of 4.5%. This unspecified rock was assumed to be unfractured (intact) rock, which seems to be supported by APE-modelling which replaces the 1.5% to 4.5% range with 1% to 5.5%[4].

* also clastics —see *Anisotropists Digests*, 149 and 150 deduced from Don Winterstein's observations of shear-wave splitting (*Anisotropists Digest*, 147). To my knowledge, there were no previous observations of shear-waves in clastics.

(1) The above criteria were observed to be independent of rock-type (igneous, metamorphic, and sedimentary), tectonic history, and porosity (Crampin, 1994).

(2) The observed range of SWVA lead Crampin (1994) to suggest a fracture criticality limit to SWVA in intact rock in the range 4.5 < % < 10 SWVA. (APE-modelling suggests this limit can be associated with the percolation threshold at about 5.5% SWVA (Crampin and Zatsepin, 1997)).

(3) Anisotropic symmetry shows characteristic variations over angles of incidence and azimuth. Consequently, any range of observation, unless having a particularly comprehensive coverage, may only yield lower bounds to the upper limit of anisotropy, and upper bounds to the lower limit of anisotropy.

(4) Shales, clays, and mudstones typically have TIV-anisotropy with shear-wave velocity anisotropy (with *SV*- and *SH*-polarizations) of up to 30% or more. Clearly, any dip to the structure may lead to this TIV-anisotropy causing azimuthal variations and SWVA.

1.2 The Causes of Shear-Wave Splitting

The observed parallel polarizations within the shear-wave window identify transverse isotropy (hexagonal symmetry) with a horizontal axis of symmetry (or a minor perturbation thereof) as the anisotropic symmetry system causing the splitting (Crampin, 1993a). This is because no other symmetry system has parallel shear-wave polarizations over a sufficiently wide solid-angle of directions (± 35° to ± 45°) to reproduce the observations (Crampin, 1981). However, hexagonal symmetry with such orientation is rare amongst crustal constituents, the only common source of such oriented symmetry is fluid-filled cracks which are aligned like hydraulic fractures perpendicular to the direction of minimum compressional stress. Since below about 1 km the minimum stress is typically horizontal, microcracks like hydraulic fractures will tend to be aligned vertically, striking parallel to the direction of maximum horizontal stress. The observed shear-wave splitting is parallel to the strike of the cracks and parallel to the horizontal stress. Observations of azimuthal shear-wave splitting in particular localities may have other explanations, particularly in igneous and metamorphic rocks, although few have been identified wholly satisfactorily. However, since there are distributions of fluid-saturated microcracks in most crystalline rocks (Kranz, 1983) and distributions of low aspect-ratio pores (pore-throats) in porous sedimentary rocks, stress-aligned fluid-saturated intergranular microcracks (EDA-cracks) are the only likely source of the nearly-universally observed shear-wave splitting (Crampin, 1993a).

A further source of azimuthal shear-wave splitting is dipping TIV-anisotropy. Since the TIV-anisotropy of shales and clays may be strong (up to 30% or greater), comparatively small dips to strata can result in significant azimuthal anisotropy (Crampin and McGonigle, 1981). Such dip-induced azimuthal anisotropy is almost certainly present in some of Winterstein's data in *Anisotropists Digest*, 147.

1.3 Interpretation in Terms of Microcracks

The seismic properties of uniform crack distributions of parallel cracks can be specified by a crack density $\varepsilon = Na^3/v$, where N is the number of cracks of radius a in volume v (Hudson, 1981). Since for this formulation of crack density, the percentage of shear-wave velocity anisotropy is approximately equal to $\varepsilon \times 100$ when Poisson's ratio is 0.25 (Crampin, 1993b), the range of observed percentage of shear-wave velocity anisotropy can be specified in terms of crack densities. Figure 1 shows cartoons of uniform crack distributions which have the observed values of shear-wave splitting. The cartoons suggest a level of crack density in the range $0.045 \leq \varepsilon \leq 0.1$ known as *fracture criticality* separating intact from heavily fractured rock (Crampin, 1994).

1.4 Justifiable Approximations

There are three approximations in the above interpretation of shear-wave splitting in terms of distributions of intergranular microcracks which require justification.

Uniform distributions of equally-sized cracks: since most rocks have a limited range of grain size, intergranular microcracks are also likely to display a limited range of dimensions in comparatively uniform distributions.

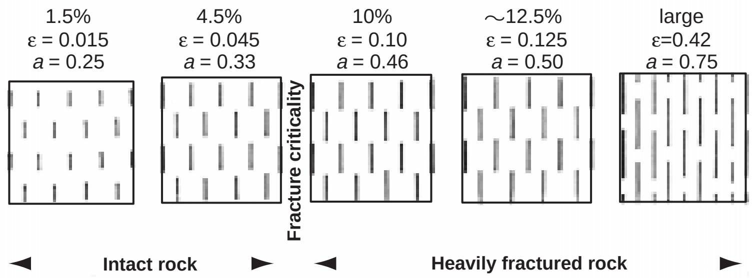

Figure 1

Schematic illustration of observed percentages of shear-wave velocity-anisotropy interpreted as uniform distributions of equal-sized parallel penny-shaped cracks with the same percentage anisotropy, where ε is crack density (approximately equal to a hundredth of the percentage anisotropy), N is number of cracks of radius a in volume v. The fracture criticality limit in intact rock is about $\varepsilon \approx 0.055$. Note Figure 1 is dimensionless (After Crampin, 1994).

Penny-shaped cracks: since grain-boundary cracks will have a restricted range of crack topography, penny-shaped cracks are likely to be a reasonable average shape, particularly as the shape of flat cracks has only second-order effects on seismic properties.

Parallel alignments: wholly parallel crack alignments lead to the observed parallel shear-wave polarizations. However, Liu *et al.* (1993) have shown that two sets of parallel cracks, and by implication any combination of nearly-parallel crack distributions, has effects very similar to those of the average parallel crack distribution.

The overall stability of observations of shear-wave polarizations and time-delays in remarkably heterogeneous structures suggests that shear-wave splitting is not sensitive to interfaces or velocity structures but is sensitive to average regional-stress induced microcrack alignments. This suggests that the effects of average microcrack properties on shear-wave splitting are an effective representation of real crack distributions in the crust.

1.5 Remarkable Properties

Figure 1 is not meant to imply that EDA-cracks are in uniform distributions of wholly parallel flat penny-shaped cracks. It merely indicates densities of cracks of aligned cracks that would yield the observed velocity anisotropies. Nevertheless, the cartoons in Figure 1 suggest some remarkable properties of intergranular microcracks in ostensibly intact rock below about 1 km in the crust.

- There is a minimum crack density of $\varepsilon \approx 0.015$;
- There is a maximum crack density of $\varepsilon \approx 0.045$;
- This suggests a very narrow range of crack density in intact rock, with a factor less than two (1.86) between the average crack radius in the minimum observed anisotropy with crack density $\varepsilon \approx 0.015$, and that of heavily fractured rocks near the surface with $\varepsilon \approx 0.1$;
- There is a level of crack density, fracture criticality, in the range $0.045 \leq \varepsilon \leq 0.1$, separating intact from heavily fractured rock;
- The observations (Crampin, 1994) suggest that the behaviour in Items 1 to 4, above, is largely independent of rock-type, porosity, geology, and tectonic history.

The implications of these cartoons are that almost all rocks in the Earth's crust are geometrically close fracture criticality, that is close to a critical state where fracturing is likely if conditions change appropriately (the weakness of rock under tension may be deduced from Fig. 1). The five properties listed above are based on simple empirical inferences drawn from observations of shear-wave splitting in at least the uppermost 15 km of the crust below a depth of about 1 km. In order to obtain some physical insight into the behaviour of stressed fluid-saturated EDA-cracks in the crust, Zatsepin and Crampin (1995, 1997) and Crampin and Zatsepin (1995, 1997a) have developed a model of *anisotropic poro-elasticity* or *APE* for the stress-induced evolution of fluid-saturated microcracked rock in the crust.

2 ANISOTROPIC PORO-ELASTICITY, APE

There are fluid-saturated microcracks and (low aspect-ratio) pores in almost all rocks. These *"cracks"* are necessarily the most compliant elements of the rockmass, so that microcrack geometry responds almost immediately to changes in stress and pressure. The suggested mechanism for pre-fracturing deformation of fluid-saturated microcracks is fluid migration (by flow or diffusion) along pressure gradients between neighbouring intergranular microcracks at different orientations to the stress field (Zatsepin and Crampin, 1995, 1997). This mechanism was suggested previously by Brodie and Rutter (1985) and Rutter and Brodie (1991), but its significance could be confirmed only when its association with shear-wave splitting was recognized. Note that for small changes the response of the rock matrix is essentially elastic and the initial response to changing conditions is expected to be rapid (Zatsepin and Crampin, 1997).

Figure 2 is a schematic (but geometrically correct) illustration of microcrack evolution with 6% porosity from an initially random distribution of (vertical) intergranular microcracks under increasing differential horizontal stress (Crampin and Zatsepin, 1995). (Differential stresses s_V, s_H, and s_h are $s_V = \sigma_V - \sigma_h$, $s_H = \sigma_H - \sigma_h$, and $s_h = 0$, where σ_V, σ_H, and σ_h are the principal axes of vertical- and maximum and minimum horizontal-stresses, respectively, and below about 1 km $\sigma_V > \sigma_H > \sigma_h$). Hexagons are elastically isotropic, with transverse isotropy about a vertical symmetry axis

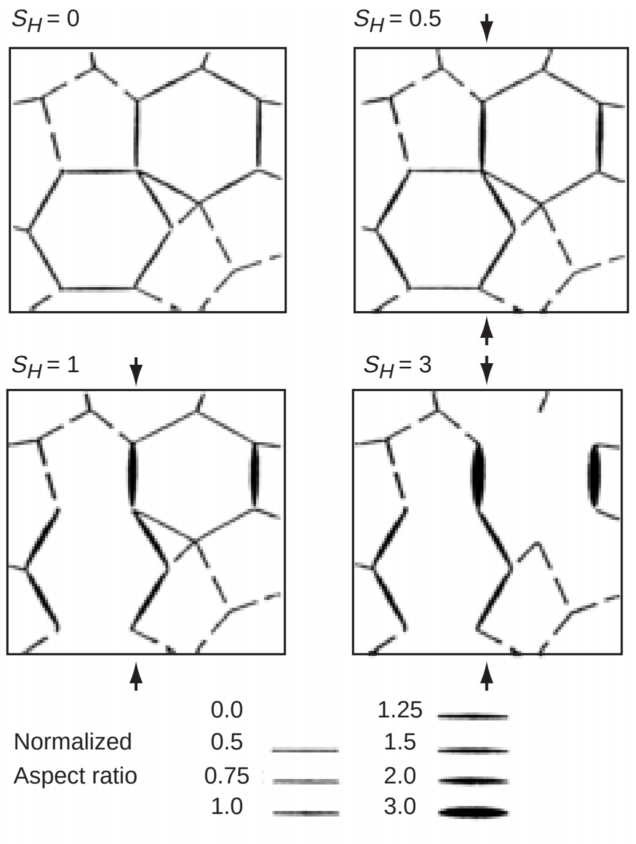

Figure 2

Schematic illustration of the evolution of crack aspect-ratios of initially random distributions of vertical cracks for four values of increasing differential horizontal stress normalized to the critical value at which cracks first begin to close (after Crampin and Zatsepin, 1995). Pore-fluid mass is preserved and aspect-ratios are correct for a porosity of ϕ = 6%. Behaviour is described in the text.

(TIV-anisotropy), so that the solid hexagons in the top left cartoon, show an isotropic (effectively randomly-oriented) distribution of vertical cracks under zero differential horizontal stress, $s_H = s_h = 0$, where each crack has the same aspect ratio. Each cartoon in Figure 2 shows crack distributions with equalized pore-fluid pressure (no pressure gradients) and the volume of pore fluid is conserved between cartoons.

When the maximum horizontal differential stress increases to $s_H = 0.5$, top right, cracks perpendicular to s_H have greater pressure normal to the crack face than cracks parallel to s_H, so that fluid migrates along the pressure gradients between neighbouring intergranular microcracks. The distributions of crack aspect-ratios are modified as in the cartoon. Some cracks become thinner and some swell and become fatter until the pressure is equalized, but for low levels of differential stress all cracks are open and there are *no significant elastic changes and no significant anisotropy.* As differential stress increases, s_H, reaches a critical level, s^c, bottom left in Figure 2, (normalized to $s_H = s^c = 1$), when cracks normal to s_H first begin to close. The shear-wave velocity-anisotropy immediately jumps to about 1.0% (Crampin and Zatsepin, 1997a), close to the ~1.5% lower-limit observed in ostensibly-intact rock as reported above (Crampin, 1994). Such jumps in behaviour, typical of non-linear systems, are known as bifurcations (see Section 4, below). As s_H continues to increase, bottom right, the anisotropy also increases.

At a level of about 5.5% shear-wave velocity-anisotropy, fracture criticality at the percolation threshold is reached for fluid-saturated distributions of stress-aligned cracks (Crampin and Zatsepin, 1995, 1997a). This 5.5% is the fracture criticality (another bifurcation) estimated from Figure 1 as between 4.5% and 10% with crack density $0.045 < \varepsilon < 0.1$.

Note that APE models a distribution of initially three-dimensionally randomly-oriented cracks. The random distribution of *vertical* cracks in Figure 2 (top-left) is drawn merely for convenience and simplicity of illustration. The image of the initially random distribution of cracks at zero differential stress in Figure 2 (top-left) is very close to skeletons of porous rocks with similar porosities (ϕ = 6%). The ubiquity of observations of shear-wave splitting suggest that similar distributions are present in almost all rocks independent of porosity, although rock skeletons can only be produced for a comparatively narrow range of porosities: at lower porosity, skeletons are too weak to be self-supporting; and at higher porosities, skeletons are too opaque to be easily distinguishable.

Note also that the percolation threshold is the statistical likelihood that through-going fractures exist in a crack distribution. Originally, percolation theory was a purely geometrical concept of random distributions of cracks in unstressed rock. Fracture criticality, ≈ 5.5%, can be viewed as the dynamic equivalent of the percolation threshold in a stressed in situ rock, when the strength of fluid-saturated microcracked rock is taken into account (Crampin and Zatsepin, 1997a). Fracture criticality is the level of cracking at which microcracks begin to coalesce into through-going fractures so that shear-strength is lost and seismic events are triggered.

3 APE-MODELLING

Numerical modelling with APE is tightly constrained without free parameters (Crampin and Zatsepin, 1997a) yet matches the five general effects cited in Part 1.5 remarkably well. Table 2 lists these and other examples where observations are either closely matched by numerical modelling with APE, or where temporal changes in shear-wave splitting are the changes expected by APE but where the controls are inadequate for precise numerical modelling to be meaningful. The reader is referred to the cited references for detailed discussions. There are two classes of phenomena: Items 1 to 7 are observations of static anisotropy; whereas 8 to 13 are observations of changes in shear-wave splitting implying variations in microcrack geometry induced by changing conditions. It is the ability to model this dynamic (temporal) response of rock that provides the most important applications discussed in the Section 5.

The general match of APE-modelling in Table 2 is, at least, consistent with observations over an enormous range of frequencies (from MHz in the laboratory (Crampin *et al.*, 1997) to kHz-5 Hz in the field (Holmes *et al.*, 1993; Crampin *et al.*, 1986b; respectively)), and dimensions from wavelengths of a few millimetres in the laboratory (Crampin *et al.*, 1997) to 80 cm-hundreds of kilometres in the field (Holmes *et al.*, 1993; Heffer and Bevan, 1990; respectively). The list is rapidly increasing (note the number of recent publication dates in the listed references).

APE-modelling appears to be a good first-order approximation for the equation of state of non-fracturing deformation. It also confirms that the mechanism of deformation for fluid-rock interactions is fluid migration along pressure gradients between neighbouring intergranular microcracks and low aspect-ratio pores at different orientations to the stress field (Brodie and Rutter, 1985; Rutter and Brodie, 1991).

Note that APE-modelling was specifically set up for low-porosity rocks, however, Zatsepin and Crampin (1997) show that the degree of shear-wave splitting and polarizations are largely independent of crack shape (and hence porosity) and crack size. This is because the effect of pore shape can be approximated by a common effective-stress-coefficient tensor multiplier which can be factored out of the equations. The principal effects of large porosity rocks is on the attenuation and dispersion of both *P*- and shear-waves which is being investigated

TABLE 2

Match of APE-modelling and observations

(Notation: APE-anisotropic poro-elasticity; SWTD-shear-wave time-delays; SWVA-shear-wave velocity-anisotropy)

OBSERVATIONS OF STATIC ANISOTROPY	Ref. (obs).	Ref. (APE)
Field observations of SWVA (below 1 km depth)		
1) SWVA in all rocks independent of porosity and geology	[1]	[2]
2) Minimum SWVA in intact rock: obs. ≈1.5%; APE ≈1.0%	[1]	[2]
3) Maximum SWVA in intact rock: obs. ≈4.5%; APE ≈5.5%	[1]	[2]
4) Narrow range of crack density	[1]	[2]
5) Proximity of fracture criticality (percolation threshold) ≈5.5%	[1]	[2]
Other field observations		
6) Fracture criticality limit specifies crack distributions with a range of dimensions over 9 orders of magnitude	[3]	[4]
7) π/2 shear-wave polarization changes in over-pressurized reservoir	[5]	[5]
OBSERVATIONS OF CHANGES IN ANISOTROPY		
Field observations of SWVA		
8) Changes in SWVA before and after pumping tests	[6]	£
9) Changes in SWVA before and after CO_2-flood in oil reservoir	[7]	$
Temporal changes in SWTD before earthquakes		
10) Variations of time-delays before earthquakes	[8]	[2]
Temporal changes in SWTD before eruption		
11) Variations in SWTD for 5 months at 160 km before 30th Sept., 1996, Vatnajökull eruption, Iceland	[9]	£
Variations of shear waves in laboratory stress-cells		
12) Variations of SWVA and permeability (uniaxial pressure)	[10]	[11]
13) Variations of (isotropic) shear-wave velocities to changes in confining pressure and pore-fluid pressure for oil-, water-, and gas- (dry) saturations of sandstone cores	[12]	[12]

[1] Crampin (1994)
[2] Crampin and Zatsepin (1997a)
[3] Heffer and Bevan (1990)
[4] Crampin and Zatsepin (1996) Crampin (1997a)
[5] Crampin *et al.* (1996)
[6] Crampin and Booth (1989)
[7] Davis *et al.* (1997)
[8] Booth *et al.* (1990), Crampin *et al.* (1990, 1991), Liu *et al.* (1997), Gao *et al.* (1998)
[9] Crampin *et al.* (1998)
[10] King *et al.* (1994)
[11] Zatsepin and Crampin (1996)
[12] Crampin *et al.* (1997).

£ Effects compatible with APE $ Analysis by APE in progress

(Chapman *et al.*, 1998), where crack and pore dimensions are important, and to the velocities and anisotropy of *P*-waves, with typically minor effects on shear waves (Crampin, 1993b). These theoretical inferences are supported by the agreement of APE-modelling with shear-wave splitting in a range of rock types. Shear-wave splitting is dependent on microcracks and low aspect-ratio pores and the success of APE-modelling is associated with the self-organization of the microcracked rockmass (Section 4.2).

Note also that currently APE-modelling is set up for variations in stress, pore pressure, temperature, and fluid properties of acoustic velocity, density, and viscosity. In principle, any property, including chemistry, whose behaviour and effects can be estimated could be incorporated into APE.

4 EVIDENCE FOR CRUSTAL CRITICALITY

Direct interpretation of the cartoons in Figure 2 shows that distributions of stress-aligned fluid-filled microcracks even in intact rock are comparatively close to fracture criticality. There is factor of less than two (1.86) between the normalized crack dimensions in the minimum (~1.5%) azimuthal anisotropy observed below 1 km and the normalized dimensions of cracks that are clearly unstable near the surface (~10%). This suggests that almost all (crustal) rocks are geometrical close to failure by fracturing, if conditions acting on the rockmass change appropriately. This also suggests that the evolution of fluid-filled microcracks is a critical phenomena (Ma, 1976) which is the rationale for the anisotropic poro-elasticity (APE) model of Zatsepin and Crampin (1997).

The abrupt changes from no anisotropy to ~1.5% anisotropy at the critical stress sc and the onset of fracture criticality at ~5.5% in the description of Figure 2 are bifurcations typical of non-linear systems as they approach deterministic chaos (Turcotte, 1992). At criticality, in such systems, the effects of negligibly close initial conditions may diverge exponentially as conditions evolve. Bak and Tang (1989) were the first to suggest that the crust was close to a critical state which they named *self-organized criticality* or SOC. This was based on the scale-invariant nature of the magnitude frequency relationships displayed by earthquake distributions. Such scale-invariant distributions are intrinsic to a great many phenomena associated with cracks in the Earth, some of which are listed in Table 3.

TABLE 3

Examples of self-similar (scale-invariant) distributions in crustal rocks

DISTRIBUTION	Ref.
World-wide earthquakes	
1) Cumulative number/seismic moment	[1]
a) shallow-depth < 70 km	
b) 70 km ≤ intermediate depth ≤ 280 km	[1]
c) deep > 280 km	[1]
2) Cumulative number/energy: all earthquakes	[2]
Local earthquakes	
3) Seismic moment/corner frequency	[3]
4) Source radius/seismic moment	[3]
Microcracks, fractures, faults	
5) Frequency/crack spacing	[4]
6) Frequency/aperture	[4]
7) Cumulative number/crack length	[5]
Roughness and wear on faulted surfaces	
8) Wavelength/power spectral density	[6]
9) Profile length/root-mean-square roughness	[6]
10) Displacement/thickness	[6]
Volcanoes	
11) Cumulative number/fissure length	[7]
12) Cumulative number/dike thickness	[7]
13) Cumulative number/time between successive eruptions	[7]
Distribution of properties in well-logs	
14) Length data interval/sonic log	[8]
15) Length data interval/resistivity	[8]
16) Length data interval/gamma activity	[8]

[1]	Kagan (1992)	[5]	Heffer and Bevan (1990)
[2]	Bak and Tang (1989)	[6]	Power *et al.* (1988)
[3]	Grasso (1993)	[7]	Grasso and Bachèlery (1995)
[4]	Barton and Zoback (1992)	[8]	Leary (1991)

One of the largest range of scale-invariance is the distribution of dimensions and frequency of linear features ranging form microcracks, through joints and fractures, to faults and photo-lineaments documented by Heffer and Bevan (1990). This is reproduced in a modified form in Figure 3, where the distribution is nearly scale-invariant over approximately 9 orders of magnitude. This range is close to the largest range of dimensions possible in the crust of the Earth. The large dots are values of the scale-invariant fracture criticality limit of Figure 1 (Crampin, 1994; Crampin and Zatsepin, 1997a). The match of fracture criticality

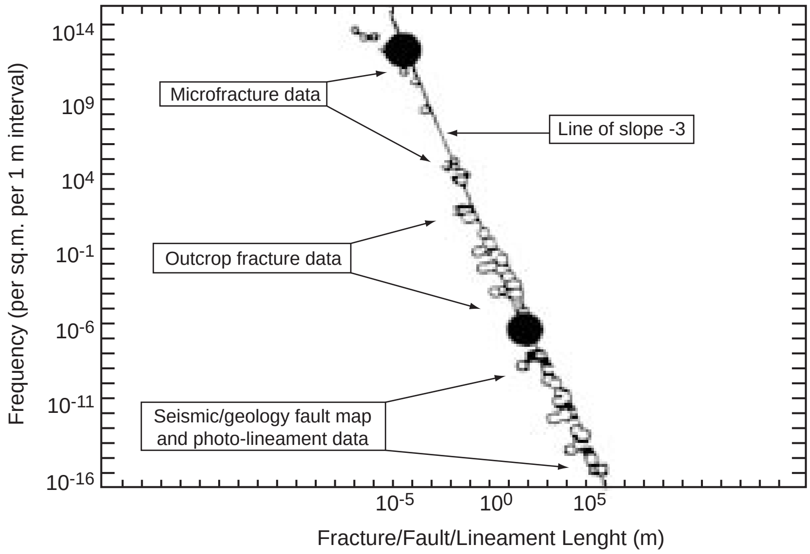

Figure 3

Frequency of microcracks, cracks, fractures, faults, and lineaments with crack length (after Heffer and Bevan, 1990). Dots are two values of the (dimensionless) fracture criticality limit in Figure 2 of Crampin (1994).

based on seismic shear-wave propagation in the Earth over the enormous range of linear dimensions suggests that fluid-migration around intergranular microcracks derived from the small-scale physics of Figure 1 and observations of shear-wave splitting defines the whole distribution of cracks in the crust.

4.1 Implications of Criticality (Pre-Fracturing Deformation)

The significance of the identification of stress-induced intergranular-scale fluid migration as the small-scale physical phenomenon driving self-organized criticality in the crust, is that the (pre-fracturing) evolution of the fluid-saturated microcrack rock can be calculated by APE and be monitored by appropriate observations of shear-wave splitting.

- The implication for rock physics and reservoir monitoring is that much of the response of rock to changing conditions is calculable, and the future behaviour predictable. This means that, when known conditions are changing, there is now an underlying mathematical basis for predicting the response of the (uniform) rockmass.
- Much of the non-catastrophic (pre-fracturing) deformation of the rockmass is controlled by the opening and closing of microcracks and low aspect-ratio pores (EDA-cracks) in the stress-aligned fluid-filled void-space. Figure 2, suggests that crack aspect-ratios are very sensitive to minor changes in conditions.
- Since shear waves are sensitive to crack aspect-ratios and are controlled by the same parameters as microscale deformation, analysis of shear-wave splitting is a comparatively direct way of monitoring the non-catastrophic (pre-fracturing) deformation of microcrack geometry.
- Fracture criticality, associated with the percolation threshold for stressed fluid-saturated finite-strength rock, marks the level at which microcracks begin to coalesce and trigger earthquakes, rockbursts, and large-scale faulting. Observed shear-wave splitting suggests that almost all rocks are geometrically close to fracture criticality.
- Proximity to fracture criticality implies that rock is highly stress-sensitive and responds to changing conditions in ways that can be identified by observations of shear-wave splitting. In particular, progression towards criticality and consequent fracturing can be monitored with shear-wave splitting.
- Proximity to criticality is one of the condition for self-organized criticality (Bak *et al.*, 1988).

These various phenomena show that despite the enormous complexity and heterogeneity of the Earth's crust, many parameters of the distribution of EDA-cracks is, at least in some respects, remarkably simple. This is difficult for at least one Earth scientist to understand, and it is tempting to invoke some general principle to explain the extraordinary stability of shear-wave splitting in the Earth.

4.2 Self-Organized Criticality

The wide range of properties having self-similar distributions in Table 3 implies that much of the behaviour of the crust, particularly behaviour associated with cracks, is close to a critical state compatible with the proximity to fracture criticality in Figure 1.

In particular, the microscale physics of EDA-cracks is the microscale physical manifestation of the SOC of crustal rock (Crampin, 1997a). Bak and Tang (1989) recognized the self-organized criticality of seismicity, which is phenomenological evidence for the self-organized criticality of cracks in the Earth's crust, but Bak and Tang did not identify the crucial microscale interaction. The identification of the microscale criticality of SOC of crustal rocks as stress-induced modifications to EDA-crack geometry is important because:

- the behaviour can be calculated by APE, and is largely independent of rock-type;
- details of the deformation can be monitored with shear waves, and in particular;
- the approach of criticality can be recognized by appropriate changes in shear-wave splitting.

The theory for SOC for critical systems is not yet wholly defined (Jensen, 1998), and other phenomena may also yield scale-invariant distributions as in Table 3 (O'Brien and Weissman, 1992). Nevertheless, the evidence listed in this review in Table 2 shows that the fluid-saturated microcracked crust is close to the critical state of fracture criticality, which reaches criticality in fracturing when seismic events occur and stress is released so that the system can relax to below criticality. Such cycling about criticality are the classical criteria for SOC.

The original hypothesis of SOC (Bak *et al.*, 1988) was that the behaviour of (critical) systems containing complicated interacting elements (such as the response of fluid-saturated microcracks to stress changes in the Earth) would display characteristic behaviour. The suggestion was that under very general conditions, dynamical systems organize themselves into complex states with a general (statistical) structure. The suggested reason for the remarkable match of APE-modelling to observations in Table 2, with the implication that the self-organized evolution of fluid-saturated microcracked rock can be modelled numerically is the self-organization of stress fluid-saturated EDA-cracks.

SOC is a phenomenon in what has been called the *New Physics* (Davies, 1989), where classical physics of linear or linearized equations applies to each individual phenomenon, yet the overall interaction of complicated interactive non-linear systems behaves differently in ways which are not yet fully understood. Although adequate for limited experiments, linearized physics does not describe the overall interactions and behaviour of: particle physics; turbulence; weather systems; geomagnetic reversals; cardiac fibrillations; dripping taps; insect populations; lasers; electrical circuits; chemical reactions; cars clustering on motorways (freeways); and power-law distributions of cracks in the crust (Fig. 3); amongst innumerable other examples.

Complicated interactive time-evolving systems self-organize themselves into distinctive patterns of behaviour characterized by self-similarity. In such systems, it is expected that only the smallest elements (in the crust this is the behaviour of fluid-saturated stress-sensitive microcracks) can be described by classical (linearized) physics. The physical manifestation of the driving force for these smallest elements in the Earth happens to be fluid migration along pressure-gradients around intergranular microcracks (Crampin, 1997a), which can be monitored with shear-wave splitting and modelled by APE. The reason APE is apparently successful in modelling such a wide range of phenomena is that it models the fundamental element of the self-organization of microcracks in the crust.

4.3 Implications of SOC in the Earth

There are several direct implications of SOC of fluid-filled microcracks in the crust.

- SOC systems are scale invariant and imply clustering at all scale lengths. This implies heterogeneity at all scale lengths so that geological parameters vary from place to place and do not have Gaussian statistics where averages are appropriate or necessarily meaningful. Inter alia, this specifically excludes the possibility of *accurate* prediction of the time, place, and magnitude of future large earthquakes (Geller *et al.*, 1997; Main, 1995).
- The interactions at all scale lengths of SOC systems include the possibility of long-range interactions at distances well beyond the limits expected for deterministic mechanisms. There have been several suggestions of such long-range correlations; for example, in regional seismicity in California

(Knopoff *et al.*, 1996), and in global seismicity (Lomnitz, 1996).

– Similar long-range correlations have been observed between water injection and hydrocarbon production rates in a variety of mature oil fields (Heffer *et al.*, 1995).
– The progress towards criticality in the interior of the rockmass can be monitored by analyzing seismic shear-waves propagating through the critical zone (Crampin, 1997a). This ability to monitor and recognize proximity to criticality well be unique in SOC systems.

4.4 Speculations on SOC

The scatter of polarizations and time-delays of shear-wave splitting, in the shear-wave window above small earthquakes for example, appears to be significantly greater than straight-forward geophysical errors would indicate. This may be due to the larger-scale SOC criticality interactions that cannot be modelled by classical physics.

If SOC does describe the interactions of fluid saturated EDA-cracks as the evidence presented here suggests, it implies that fluid-rock interactions are extremely sensitive to small changes in conditions, so that marginal changes could yield significant changes in shear-wave splitting. This would mean that repeated measurements of shear-wave splitting along identical ray paths might not give identical results, even when no significant change in conditions occurred. It is interesting that when changes of shear-wave splitting have been observed, during stress changes before earthquakes for example, the changing parameter (variations in time-delays caused by changes in crack aspect ratio) often shows less scatter than in the relaxed situation when there are no changes. This could be caused by negligible variations causing significant changes when there is no driving mechanism.

5 APPLICATIONS OF ANISOTROPIC PORO-ELASTICITY IN A CRITICAL HETEROGENEOUS CRUST: THE NEXT STEP

5.1 Applications

The ability to monitor, model, and predict future rockmass response by analyzing shear-wave splitting has a variety of possible applications. The next step is to make practical use of these applications in field conditions.

The starred items in the list of suggested applications, below, have some observational evidence supporting the application.

* Predicting the effects of operations during hydrocarbon production, such as the monitoring the movement of fluid-fronts as they progress across reservoirs. Moving fluid-fronts are driven by pressure gradients, and it has long been anticipated that the largest seismic effect would probably be the variations in shear-wave splitting caused by the pressure-induced change to crack aspect-ratios (Crampin, 1990). It is only now that technology allows appropriate observations to be made. The Reservoir Characterization Project of *Colorado School of Mines* conducted a repeated three-component three-dimensional reflection survey before and after a CO_2-flood in a carbonate reservoir in Vacuum Field, New Mexico. Davis *et al.* (1997) found that, as expected, the largest seismic effects associated with the moving fluid-front were the changes in the polarizations and time delays of split shear-waves. Applications of criticality to hydrocarbon production are discussed more fully in Crampin (1998).

– Identifying changing pore-fluid pressures and other parameters by the effects on shear-wave splitting during hydrocarbon production is likely to lead to improved understanding of fluid-fluid and fluid-rock interactions as fluid-fronts progress through reservoirs. A large variety of specific operations could be targeted: effects of temperature on water- and steam-floods; and the effect of temperature, viscosity, pressure, injection-rate, etc., on advancing fluid-fronts. Comparing calculated with observed effects is likely to be a powerful technique for improved understanding of production processes.

* The increasing likelihood of large earthquakes could be recognized by monitoring the build-up of deformation. This would not predict earthquakes (see first paragraph of part 5.2), but would forecast the earthquake in the limited sense suggested by Crampin and Zatsepin (1996). The approach of fracture criticality, and the consequent earthquake, could be recognized by monitoring shear-wave splitting as above small earthquakes. Such changes have been observed (with hindsight) by Crampin *et al.* (1990, 1991), Booth *et al.* (1990), Liu *et al.*

(1997), and Gao *et al.* (1998). More controlled investigations could be made by cross-hole observations between deviated boreholes (Crampin and Zatsepin, 1997b).

* Monitoring the injection of magma into the lower crust before volcanic eruptions (Crampin *et al.*, 1998).
– Determining the likelihood of rock bursts in deep mines (Crampin, 1997b).
– Identifying the approach of fracture criticality (the likelihood of failure by fracturing) in any situation where failure is possible such as landslides, rock falls, mine failures, building foundations, tunnel walls, and many others.
* Use APE to predict the effects of in situ conditions in reservoir rock by calibrating cores in laboratory stress-cells (Zatsepin and Crampin, 1996; Crampin *et al.*, 1997).

5.2 Techniques

Evidence suggests that shear-waves contain currently-unique information about the behaviour of fluid-rock interactions. What is required for the first two applications listed above, and for almost all other field applications, is high-frequency recordings of shear-waves over comparatively short ray paths. How best may we access this information in the Earth?

Seismic attenuation in the uppermost 1-2 km of the crust is so severe (Leary and Abercrombie, 1994; Leary, 1995) that shear-wave propagation from the surface is usually limited to frequencies less than about 20 Hz over kilometre-length ray paths, with a resolution of 100 s of metres. Cross-well seismology between neighbouring wells would only be marginally more satisfactory because of the well-dependent geometry and limited access to principally inter-well ray paths. The most satisfactory technique is likely to be the Uniwell configuration suggested by Peveraro *et al.* (1994), see also Crampin *et al.* (1993), where strings of three-component geophones and a source(s) are installed in a production well. Such technology is currently being developed and tested (Walter and Leary, 1998).

CONCLUSIONS

The match of APE-modelling to a large range of observations in Table 2 suggests that APE is a good first approximation to the non-catastrophic (pre-fracturing) deformation of fluid-saturated microcracked rock, and can be used to monitor the approach of failure at fracture criticality. Currently, APE has been used to model changes of stress and pore-fluid properties of pressure, temperature, density, and acoustic velocity. In principle, changes of any parameter, whose effects can be quantified either algebraically or numerically, can also be incorporated into APE.

Evidence suggests that some crucial features of fluid-rock interactions in extraordinarily complicated crustal structures behave rather simply. This appears to be because fluid-rock interactions are one of the large range of complicated non-linear interactions which self-organize themselves into characteristic statistical structures. This means that the evolving deformation of fluid-rock interactions can be modelled (by APE); actual effects monitored by seismic shear-wave splitting; and future response predicted (by APE). This permits some innovative applications, some of which are suggested in the previous section.

Seismic shear-waves, which almost always display stress-aligned shear-wave splitting, carry much more energy and much more information than *P*-waves. It is suggested that the results reviewed in this paper, that shear-wave splitting monitors the deformation of the rockmass, are a significant advance in understanding the propagation of seismic shear-waves and the deformation of *in situ* rock.

ACKNOWLEDGMENTS

I thank referees Leon Thomsen and Don Winterstein for their very detailed comments which helped me to improve this text.

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Final manuscript received in July 1998