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Seismic evidence for fluid-driven deformation

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Abstract

The behaviour of seismic shear waves shows that fluid–rock interactions control both low-level deformation of the intact rock mass before fracturing takes place, and the fracturing or faulting process itself in deep in situ rock. The splitting (birefringence) of shear-waves directly indicates that the pre-fracturing deformation of intact unfractured rock is the result of fluid movement along pressure gradients between adjacent microcracks at different orientations to the stress field. This is the mechanism for low-level pre-fracturing deformation of almost all in situ rocks. Further seismic evidence shows that fracturing and faulting at depth only occur when pore-fluid pressures on seismically active fault planes are sufficiently high to relieve frictional forces and allow asperities to be overcome. This is comparatively direct evidence that fluids control low-level small-scale (pre-fracturing) deformation of the intact rockmass, and that most if not all fracturing only occurs when fluid pressures on the fault plane are critically high.

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1. Introduction

Almost all in situ rocks contain fluid-saturated microcracks. In crystalline rocks the cracks are mostly grain-boundary cracks. In sedimentary rocks the cracks are thin pores and pore throats. Even at low porosity, these fluid-saturated microcracks are the most compliant elements of the rock mass and become aligned by the stress field. Such aligned microcracks are elastically anisotropic and the transversely polarised seismic shear-waves split, on propagating through such effectively anisotropic rock, into two approximately orthogonal polarisations that travel at different velocities and write characteristic signatures into the three-component seismograms. The

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only stable orientation for such cracks is, like hydraulic fractures (Hubbert and Willis, 1957), normal to the direction of minimum compressional stress. Since, once below the stress release and weathering anomalies in the uppermost few hundred metres, the minimum stress is typically horizontal so that the microcracks tend to be aligned parallel and vertical, striking in the direction of maximum horizontal stress. This means that shear-wave polarisations in the earth are observed to be approximately parallel to the direction of maximum horizontal stress (Crampin, 1994). Fig. 1 shows a schematic illustration of the phenomenon. Since the directions of tectonic stress are generally regionally coherent, seismic observations of the polarisations of the crack-induced shear-wave splitting are remarkably stable often over large heterogeneous volumes of rock.

The changes in stress-induced modifications to crack geometry as stress or any other parameter vary, may be subtle and exceedingly small, but the birefringence of shear-waves propagating through such aligned microcracks is exceptionally sensitive to the detailed geometry of distributions of fluid-saturated microcracks. Consequently, systematic changes in shear-wave splitting during the build up of stress before earthquakes have been seen, with hindsight, before about 10 earthquakes (Volti and Crampin, 2003a, 2003b), and the time and magnitude of one earthquake have been successfully stress-forecast (Crampin et al., 1999). These various results are reviewed by Crampin (1999).

Fluid-saturated microcracks in in situ rocks are very compliant. At depths below a few hundred metres, the microcracks are under high temperatures and pressures. Consequently, in situ rock directly accessed by drilling and coring has been subject to such intense pressure, temperature, and drilling-fluid traumas that the original microcrack distribution is typically irretrievably lost.

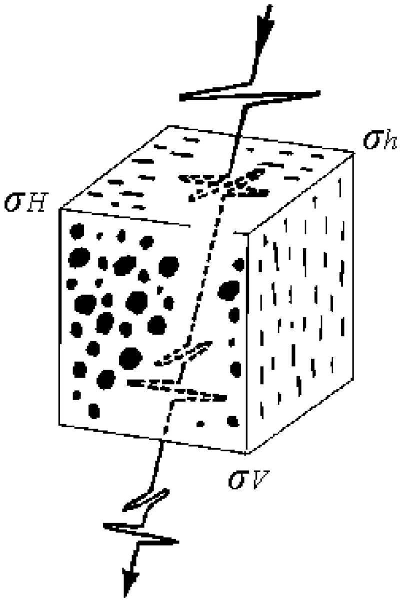

Fig. 1. Schematic illustration of shear-wave splitting on propagation through distributions of fluid-saturated stress-aligned microcracks.

This means that the only way to image the microcrack geometry in in situ rocks is by seismic techniques. The travel times of the most commonly observed seismic *P*-waves, with particle vibrations parallel to the ray path, are sensitive to many phenomena, including structural interfaces, seismic velocities, rock density, cracks, crack-orientations, crack aspect ratios, and more. This general sensitivity means that it is very difficult to invert *P*-waves for any particular effect. Witness the thousands to millions of source receiver ray paths in *P*-wave reflection surveys used by the seismic exploration industry to outline oil reservoirs a few hundred to a few thousand of metres below the surface.

The travel times of seismic shear-waves, sometimes called *S*-waves, with particle vibrations perpendicular to the direction of the ray path, are similarly sensitive to many phenomena. The distinction is that shear-waves are split into two polarisations by the stress-aligned microcracks within most rocks, and the polarisations, and details of this birefringence are controlled almost exclusively by the microcrack distribution. This means that shear-wave splitting can be directly inverted for microcrack geometry. Consequently, shear-wave splitting is remarkably informative about microcrack distributions. The phenomenon is illustrated in Fig. 1 which shows that the polarisation of a single shear-wave arrival gives some measure of the direction of maximum horizontal stress, and the delay between the two split shear-waves gives some measure of the amount of cracking along the particular ray path.

2. Demonstration that fluids control low-level deformation

Shear-wave splitting writes easily recognisable signatures into three-component seismograms that are widely observed and provide critical information about the current state of fluid-saturated microcrack geometry along the ray path. The key to the cause of the splitting is that the fast split shear-wave at the surface is typically polarised approximately parallel to the direction of maximum horizontal stress for propagation within about 35° of the vertical. Only hexagonal anisotropic symmetry with a horizontal axis of symmetry, or a minor perturbation thereof, can produce such parallel polarisations for nearly vertically propagating shear waves (Crampin, 1981). The only source of such symmetry common to most sedimentary, igneous, and metamorphic rocks is stress-aligned fluid-saturated microcracks, aligned perpendicular to the direction of minimum horizontal compressional stress. Thus observations of shear-wave splitting directly indicate the effects of low level (pre-fracturing) deformation of the rock mass. Once below the stress release and stress relaxation in the uppermost few hundred meters the minimum stress is horizontal yielding parallel vertical microcracks as in Fig. 1. This means that the widely observed near-parallel shear-wave polarisations throughout most rocks are monitoring the parallel vertical alignments of the distributions of fluid-saturated microcracks, where the microcracks are aligned by the microscale movement of fluids along pressure gradients between microcracks at different orientations to the stress field (Crampin and Zatsepin, 1997; Crampin, 1999).

Crampin (1994) reviewed all reports of digitised or digitisable shear-waves recorded on three-component receivers. Such stress-aligned shear-wave splitting was invariably observed except for a few well-understood exceptions. There have been many similar observations of azimuthally oriented shear-wave splitting (Winterstein, 1996; Crampin, 1996) in many different geologic and tectonic environments. The only exceptions where azimuthal anisotropy is not seen are shales and clays which have such a pronounced lithology of horizontal platelets filling the pore space that the rocks typically show strong transverse isotropy with a vertical axis of symmetry and there is almost no azimuthal anisotropy discernible (Crampin, 1999). Thus most rocks display stress-aligned shear-wave splitting with similar orientations and similar percentage of shear-wave velocity anisotropy independent of geology, tectonics, and porosity: the polarisations and percentages of velocity anisotropy of shear-wave splitting observed in 30% porosity sandstones are similar to those observed in 1% porosity granites.

This universality is because distributions of fluid-saturated microcracks are so closely spaced in all fluid-saturated rocks that they are critical systems verging on fracture-criticality and fracturing (Crampin, 1994). Such critical systems are part of the New Physics (Bruce and Wallace, 1989), where the behaviour of physical systems near criticality are almost independent of the behaviour of the underlying non-critical physics (Crampin, 1998; Crampin and Chastin, 2001; Crampin et al., submitted for publication). This universality allows the evolution of fluid-saturated microcracks under changing conditions to be modelled by anisotropic poro-elasticity (APE) (Zatsepin and Crampin, 1997; Crampin and Zatsepin, 1997). The mechanism for deformation is fluid movement along pressure gradients between adjacent grain-boundary cracks, low aspect-ratio pores, and pore throats at different orientations to the stress field.

Numerical modelling with APE matches a large range of different static and dynamic phenomena (currently well over 20) referring to cracks, stress, and seismic shear-waves, and innumerable individual observations. There are no contrary observations. This suggests that the APE mechanism is a good first order response to low-level deformation before fracturing and faulting and earthquakes occur. We call this pre-fracturing deformation. In particular, APE shows that changes in shear-wave splitting directly model and are controlled by the same parameters as control pre-fracturing deformation.

Thus the presence of shear-wave splitting along ray paths in almost all rocks directly demonstrates that low-level pre-fracturing deformation of the intact rock mass is controlled by fluids moving along pressure gradients between neighbouring microcracks. Fig. 2 gives a schematic but numerically accurate illustration of the mechanism of anisotropic poro-elasticity modifying the geometry of fluid-saturated microcracks. Hexagons are elastically isotropic, so that the two hexagons of solid microcracks are, initially, under zero differential stress, a small selection of randomly oriented microcracks. As stress changes, pressure gradients are set up in response to the crack orientation and the stress field. The mechanism of deformation is that the change in pore-fluid pressure, however slight, modifies the aspect-ratios of the distributions of microcracks and tends to align the cracks normal to the direction of minimum stress, just like hydraulic fractures. Crampin (1999) gives a more complete description of the behaviour in Fig. 2.

The vertical stress generally increases with the overburden. Once below the depth where the vertical stress becomes greater than the minimum horizontal stress, the minimum stress direction is horizontal and microcracks tend to align vertically, perpendicular to the direction of minimum horizontal stress, and strike parallel to the direction of maximum horizontal stress. This critical depth is typically between 500 and 1000 m. On propagating through distributions of approximately parallel cracks the faster split shear-wave is polarised parallel to the cracks, below this critical depth the faster split shear-wave would be expected to be aligned approximately in the direction of maximum horizontal stress. This is what is observed (Crampin, 1994) and demonstrates both

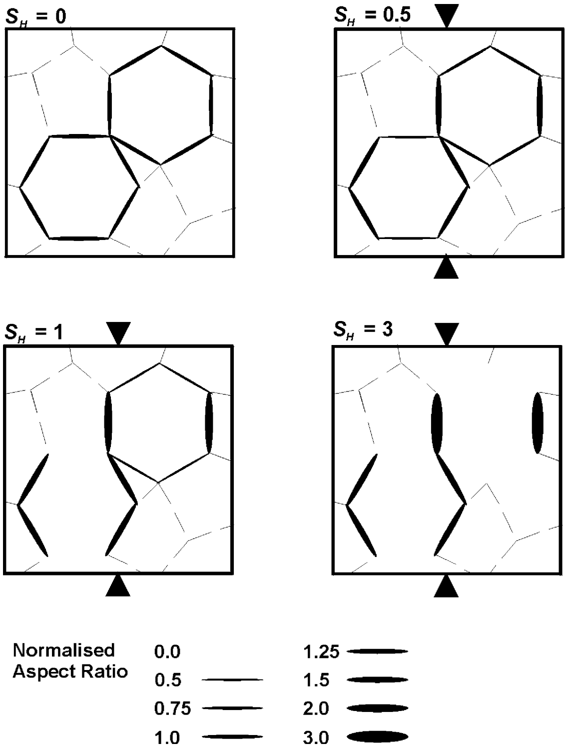

Fig. 2. Schematic but numerically accurate illustration of the evolution of an initially random distribution of vertically aligned fluid-saturated microcracks with a preserved porosity of 5% under increases of horizontal differential stress. There is zero shear-wave velocity anisotropy until the value, normalised to one, when increasing stress, S_H, closes cracks normal to the minimum differential stress. A more complete description of the behaviour is in Crampin (1999).

the suitability of APE-modelling for calculating rock evolution and that fluid–rock interactions control low-level in situ deformation.

3. Demonstration that fluids control active deformation of fracturing and faulting

The faster polarisations of shear-waves propagating approximately parallel to distributions of stress-aligned fluid-saturated parallel microcracks are aligned parallel to the plane of the cracks when the cracks are filled with *low-pressure pore-fluids* (Zatsepin and Crampin, 1997). APE-modelling shows (Crampin and Zatsepin, 1997) that when the same distributions of stress-aligned microcracks are filled with critically *high-pressure pore-fluids*, the polarisation of the faster split shear-wave does a *90°-flip* and becomes orthogonal to the plane of the crack. That is, the faster and slower split shear-waves exchange polarisations. The physical cause of such flips is that the increasing pressure acting on the aspect ratios of a distribution of vertical parallel microcracks marginally reorganises the crack geometry such that the polarisations of near vertically propagating faster split shear-waves to do a 90°-flip. The polarisations become parallel to the direction of minimum, not maximum, horizontal stress (Crampin et al., 2002). Such 90°-flips have been observed in an over-pressured oil reservoir in the Caucasus Oil Field (Crampin et al., 1996), and in a high-pressure CO_2-injection in a carbonate reservoir (Angerer et al., 2002) (Angerer et al. is the best calibration of APE-modelling in in situ rock to-date).

Such 90°-flips have also been observed in shear waves above small earthquakes at two locations above the San Andreas Fault in California (Crampin et al., 1990; and Liu et al., 1997). Recently 90°-flips have been observed above the Húsavík-Flatey Fault of the Tjörnes fracture zone of the Mid-Atlantic Ridge in north central Iceland (Crampin et al., 2002, 2003a). Fig. 3 shows the shear-wave polarisations at seismic stations in Iceland for the years 1996–2000. Rose diagrams of the faster split shear-waves are generally polarised NE–SW in agreement with the directions of maximum horizontal stress throughout Iceland. Fig. 4 shows that the polarisations at three Stations FLA, BRE, and HED in north-central Iceland installed during the European Commission-funded SMSITES Project close to the Húsavík-Flatey Fault are fault parallel and approximately orthogonal to the general alignment of split shear-waves in Iceland. The San Andreas and Húsavík-Flatey Faults are both major strike–slip features where the fault planes extend throughout most of the crust. High-pressure fluids are expected on seismically active fault planes to relieve frictional forces and force asperities apart so that fault movement is possible. The interpretation of the 90°-flips is that they are caused by critically-high pore-fluid pressures pervading the fluid-saturated microcracks surrounding the fault planes (Crampin et al., 2002).

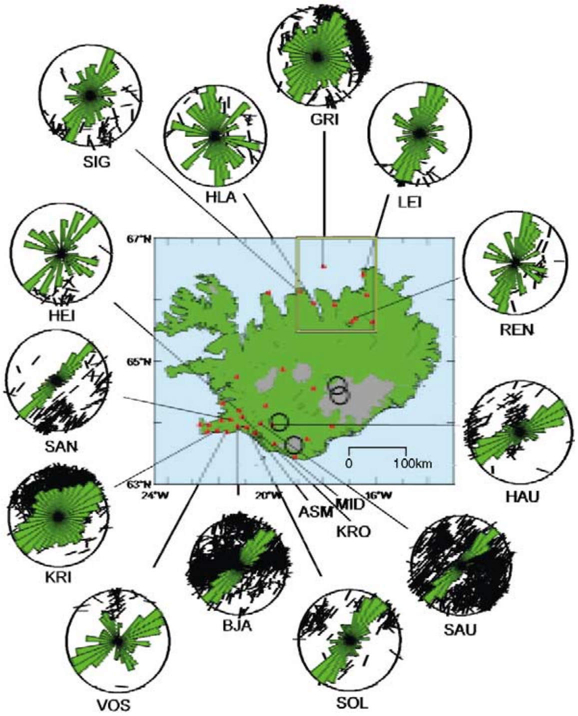

Fig. 3. Equal-area rose diagrams (green petals) of shear-wave polarisations in the shear-wave window of small earthquakes recorded by the seismic network in Iceland for the 5 years 1996–2000 superimposed on equal-area polar projections out to 45° of the individual polarisations (after Crampin et al., 2003a).

Another seismic effect indicates that critically high fluid-pressures are present on all or most seismically active fault planes. The average time-delay between split shear-waves, in the solid angle of ray path directions known as Band-1 (Crampin, 1999), is sensitive to changes of aspect ratio in the crack distribution, and this is observed to increase as stress accumulates before earthquakes. However, there is always a very large scatter in time-delays of about ±80% about the mean (Crampin, 1999). Fig. 5 from Volti and Crampin (2003b) shows an example of this scatter in the variations of time delays at Station BJA in SW Iceland for the 4 years. This figure includes the data which allowed the time and magnitude of a $M=5$ earthquake to be successfully stress-forecast (Crampin et al., 1999). It difficult to explain this scatter by conventional non-critical seismic or geophysical effects (Volti and Crampin, 2003a).

The new interpretation of the scatter (Crampin et al., 2003b) is that all seismically active faults have critically high fluid pressures in the microcracked rock surrounding the fault plane. Consequently, since ray paths from all earthquakes start on seismically active fault planes however small, shear-wave splitting must be expected to show 90°-flips near the source. However, most small earthquakes rupture only small segments of fault planes. Consequently, although 90°-flips occur in the critically high fluid-pressures on the fault at each small earthquake source, the larger

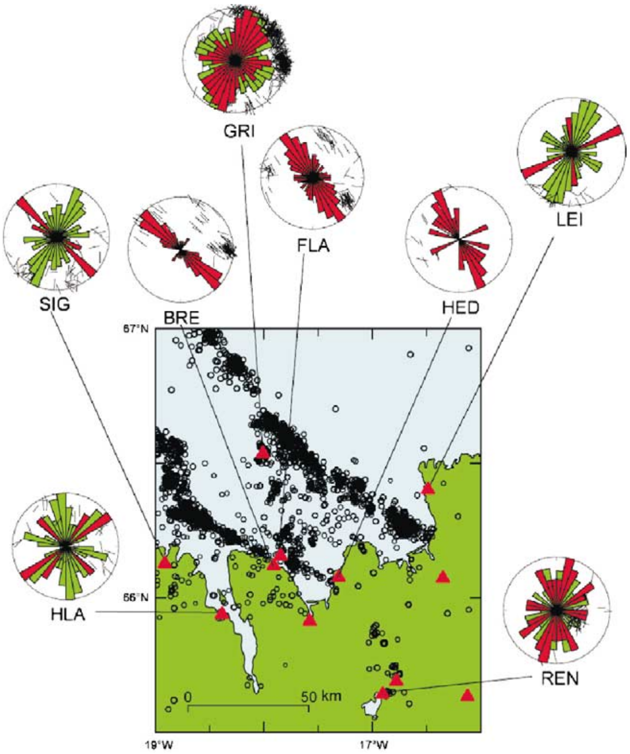

Fig. 4. Seismicity within 100 km of the SMSITES location (near Station HED) for 2001, and rose diagrams of shear-wave polarisations in the boxed area in Fig. 3: years 1996–2000 (green petals); and year 2001 (red petals). Stations BRE, FLA, and HED are new stations installed for the SMSITES Project sited specifically to search for 90°-flips (after Crampin et al., 2003a).

part of the ray path will be through the normally pressurised continuation from the fault to the surface, where shear-wave splitting will show the normal stress-aligned polarisations. This means that the polarisations observed at the surface will be the usual stress-aligned polarisations, but the time-delays will be the difference between the normally-pressured and high-pressurised segments of the ray paths. The observed time-delays are the sum of the time-delays of the normal polarised segments, being positive, say, and the 90°-flipped segments being negative. These effects have been modelled using APE (Crampin et al., 2003b). Since every earthquake releases stress and reorganises the crack geometry and the triaxial stress field, Crampin et al. (2003b) show that comparatively small changes in parameters can easily cause the observed 80% scatter.

Note that, although we believe we understand the source of the scatter, our knowledge of the crack and stress distributions and our knowledge of the in situ crack geometry is minimal, and

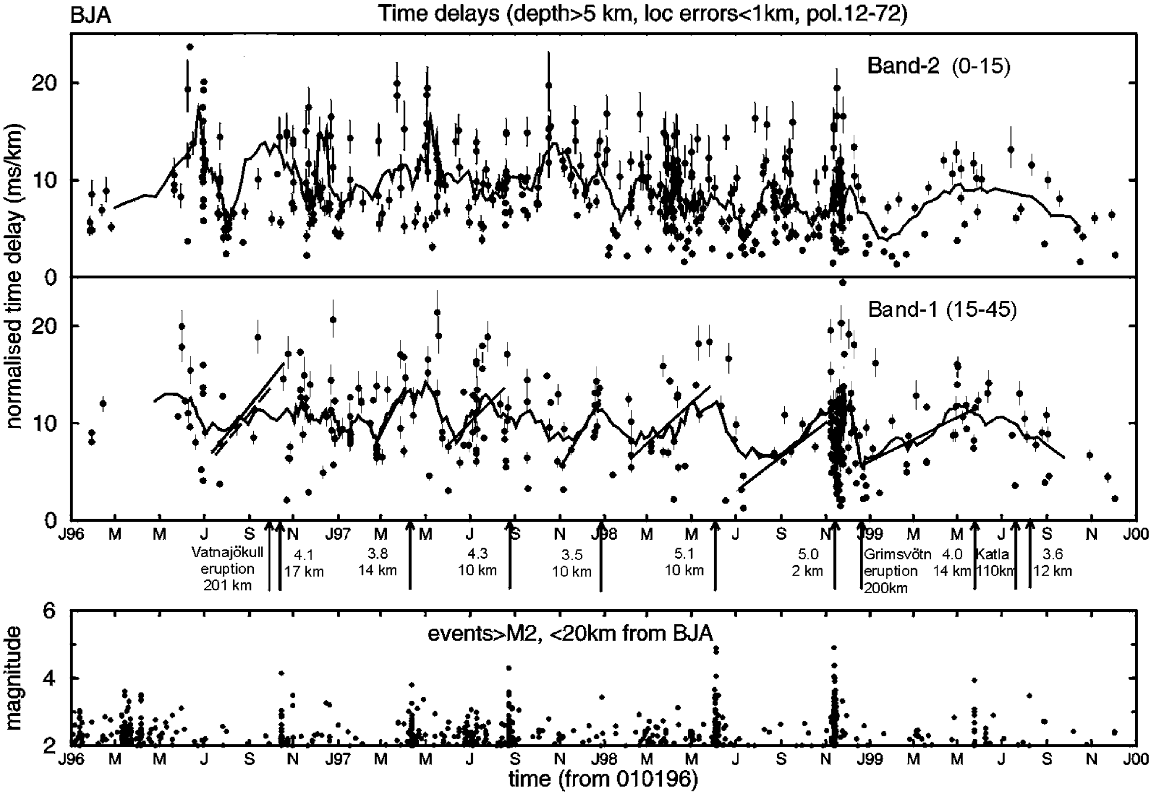

Fig. 5. Upper two diagrams show observations of time delays at Station BJA in SW Iceland for the 4 years 1996–1999 along ray paths in Band-1 (angles 15–45° to plane of microcracks), sensitive to crack aspect-ratios and increases of stress, and in Band-2 (angles ±15°), sensitive to crack density. The curve is a nine-point moving average, and the straight lines are least-squares fits starting at a minimum in the nine-point average and ending when there is a larger earthquake or volcanic eruption marked by arrows. The figure includes the data that stress-forecast the $M = 5$ earthquake in November 1998. The lower diagram shows magnitudes of small earthquakes within 20 km of BJA (after Volti and Crampin, 2003b).

far too little to be able to correct for the scatter. Thus although we cannot eliminate the scatter, the scatter is a convenient reminder that all seismically active faults are surrounded by microcracked rock containing critically high pore-fluid pressures.

Note that the large scatter in time-delays is only when earthquakes are used as source of shear-waves. In contrast, measurements of shear-wave splitting in vertical seismic profiles or reflection surveys using controlled-source technology displaying time-delays in rocks away from earthquake source zones and seismically active faults are remarkable for the smooth variation in time-delays (Li and Crampin, 1991; Yardley and Crampin, 1993). They show no sign of the scatter in Fig. 5.

4. Discussion

In the past, it was not known how stress accumulates in the Earth, and how the physical characteristics of stressed in situ rock differed from unstressed rock. The widespread observations of stress-aligned shear-wave show that almost all in situ rock has an internal geometry of microcracks aligned perpendicular to the direction of minimum horizontal stress. The magnitude of the differential stress acting on the in situ rock controls the microcrack aspect ratio: the greater the stress, the marginally larger the crack opening. The (APE) mechanism that aligns the in situ cracks is fluid movement by flow or dispersion along pressure gradients between neighbouring microcracks at different orientations to the stress field. Since this is the immediate response of even marginal changes of stress, or other conditions, fluid–rock interactions are seen to be an intrinsic part of every deformation process in in situ rock.

High pore-fluid pressures are recognised as being necessary in seismically active fault planes to relieve frictional stress and allow fracturing and earthquakes to occur on lithostatically clamped faults. Various scenarios have been suggested (Sibson, 1981, 1990; Rice, 1992; Hickman et al., 1995). Movement on faults without high pore-fluid pressures would cause heating and high heat flow which is not observed. One difficulty is that in situ rock is largely inaccessible, and until now it has not been possible to recognise the presence of high pore-fluid pressures in deep in situ rock. Gudmundsson et al. (2001) inferred high fluid-pressures in active tectonic areas from the width of veins in surface outcrops. The 90°-flips in split shear-waves polarisation which are observed above major faults and implied by the large scatter in time delays between split shear-waves are direct evidence of critically high fluid-pressures on all or most seismically active fault planes. Again fluid-driven processes are intrinsic to all active faulting and fracturing.

5. Conclusions

Seismic shear-waves in almost all rocks below 500–1000 m depth display stress-aligned polarisations indicating that in situ rocks contain distributions of stress-aligned fluid-saturated microcracks, grain-boundary cracks, low aspect-ratio pores, and pore throats. Anisotropic poro-elastic (APE) modelling confirms that the immediate response of in situ rocks to changing conditions is to modify this microcrack geometry by the movement of fluids along pressure gradients between neighbouring microcracks at different orientations to the stress field. These modifications can be monitored by shear-wave splitting, and observations of shear-wave splitting shows that the pre-fracturing response of in situ rock to low level deformation is controlled by fluid saturated microcrack geometry.

In associated phenomena, both the polarisations and the scatter in time-delays of shear-wave splitting above small earthquakes indicate that all seismically active fault planes, where earthquakes originate, are pervaded by critically high pore-fluid pressures. Since all earthquakes above a magnitude of $M_L = -1$, say, show this scatter, it appears that all earthquake-induced faulting is stimulated by high pore-fluid pressures surrounding the fault planes. Consequently, fluid pressures play a major part in both the low-level (pre-fracturing) deformation of the intact rock mass, and the fracturing and faulting of earthquakes. We have no evidence about source dynamics of very small earthquakes and acoustic events.

Note that critically high pore-fluid pressures surrounding seismically active fault planes are soon going to be examined directly. The San Andreas Fault Observatory at Depth (SAFOD) Project (USGS, 2002) is planned to drill into the San Andreas Fault, and the NanTroSEIZE Project is to drill into seismically active faults offshore in the Nankai Trough (Kimura et al., 2002). The critically high pressures indicated by shear-wave splitting suggest that drilling engineers should proceed cautiously when approaching active faults, as very high pressures may be present in the microcracked rock surrounding the fault plane. However, although high pressures are expected, the seriousness of potential blow-outs is controlled by the quantity of high-pressure fluid available and the permeability. Drilling into a major seismically active fault where considerable quantities of fluid may be available could be serious.

A further problem is that drilling into an active fault zone may release, or at least modify, the high pore-fluid pressures that we have shown are a necessary feature of earthquake faulting. This would mean that the SAFOD observatory, for example, would modify the behaviour it was intended to observe.

Acknowledgements

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