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FAST TRACK PAPER

Indication of high pore-fluid pressures in a seismically-active fault zone

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SUMMARY

Polarisations of seismic shear-wave splitting observed above small earthquakes in Iceland are typically approximately NE to SW, parallel to the direction of maximum horizontal stress. In contrast, the polarisations of shear-waves at three new stations sited over the Húsavík–Flatey Fault, a major seismically-active transform fault in northern Iceland, are approximately NW to SE, orthogonal to the stress-aligned polarisations elsewhere. Modelling suggests that these 90°-flips in polarisations are caused by propagation through cracks containing fluids at high pore-fluid pressures within one or two MPa of the critical stress. These observations suggest that high pore-fluid pressures, which play a key role in earthquake source mechanisms, can be monitored by analysing shear-wave splitting above seismically-active fault planes.

Key words: 90°-flips, earthquakes, fault planes, high pressures, shear-wave splitting.

1 INTRODUCTION

It has long been recognised that high pore-fluid pressures are 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. In related phenomena, high pore-fluid pressures are needed to open cracks (by hydraulic fracturing) and the necessary driving pressures have been estimated from the thickness of mineral veins in outcrops in tectonic areas (Gudmundsson *et al.* 2001).

The polarisations of the seismic stress-aligned shear-wave splitting observed in almost all rocks are generally parallel to the direction of maximum horizontal stress (Crampin *et al.* 1980; Crampin 1994, 1999). However, in the presence of sufficiently high pore-fluid pressures, the polarisations become orthogonal to the maximum horizontal stress (Zatsepin & Crampin 1997) in what are known as 90°-flips (Angerer *et al.* 2000, 2002).

In situ rocks at depth are subject to high temperatures and pressures in corrosive environments and are consequently remote and difficult to access. Several experiments to drill active faults are planned but, to date, high pore pressures on fault planes have not yet been directly observed. Here we present observations of 90°-flips in the direction of shear-wave polarisations above a major seismically-active fault indicating high fluid-pressures in the region surrounding the fault plane. Such phenomena provide opportunities for monitoring pore-fluid pressure *in situ* and investigating earthquake source processes.

2 THE OBSERVATIONS

A four-year study of shear-wave splitting in Iceland (Volti & Crampin 2002a,b) reported splitting with the typical stress-aligned polarisations generally found elsewhere. Fig. 1 shows rose diagrams and polar plots of the polarisations of shear-wave splitting observed from 1996 to 2000 at the Iceland national seismic network. The shear waves are recorded in the shear-wave window immediately above small earthquakes when the angle of incidence at the surface is less than 45° so that the shear waves are not disturbed by *S*-to-*P* conversions. The average polarisations of the faster split shear-waves are approximately parallel to the direction of maximum horizontal stress which is parallel by the strike of the fluid-saturated microcracks pervasive in most rocks. These cracks, like hydraulic fractures (Hubbert & Willis 1957), are aligned perpendicular to the direction of minimum stress. At the surface the minimum stress is vertical. Below the critical depth, where the increasing vertical stress equals the minimum horizontal stress, the minimum stress is typically horizontal

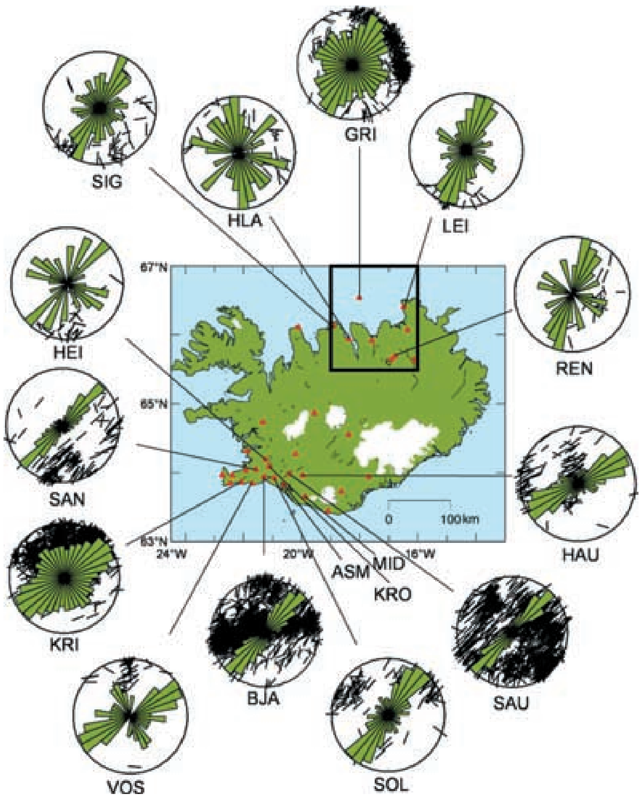

Figure 1. Normalised equal-area rose diagrams and equal-area polar plots (out to 45°) of the polarisations of the faster split shear-waves observed above small earthquakes at the national network of seismic stations (red triangles) in Iceland in years 1996 to 2000. Glaciers and ice caps shown in white.

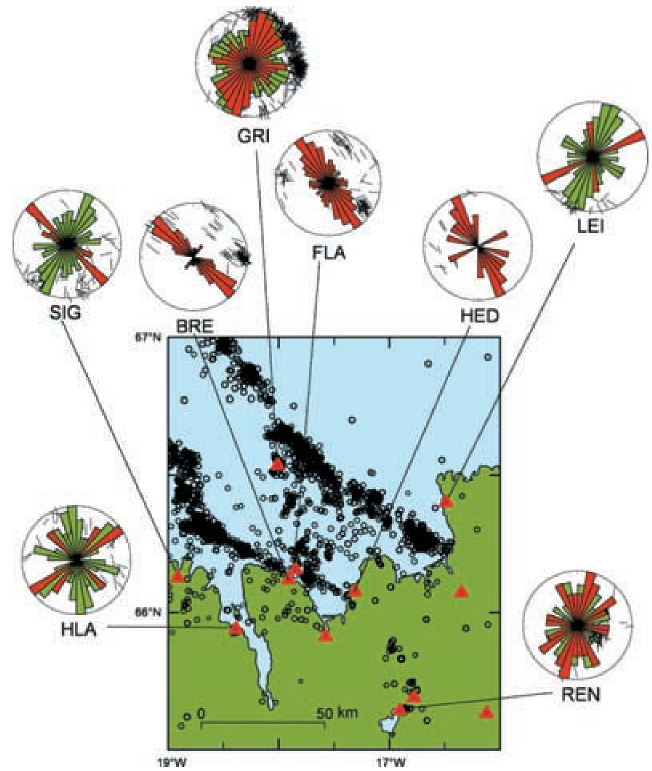

Figure 2. Rose diagrams and polar plots for the Tjörnes Fracture Zone outlined in Fig. 1. Green petals are polarisations for earthquakes in years 1996 to 2000, and red petals are polarisations in 2001 (with different normalisation values). Note green and red rose diagrams have different normalisations. Earthquake locations are shown for 2000 and 2001.

so that the microcracks, like hydraulic fractures, tend to be aligned vertically, striking parallel to the maximum horizontal stress.

Iceland is on an offset of the Mid-Atlantic Ridge and the two regions of high seismicity are the South Iceland Seismic Zone in South–West Iceland and the Tjörnes Fracture Zone in North-Central Iceland. The shear-wave polarisations in SW Iceland average NE–SW, whereas in the north, the polarisations average NNE–SSW, presumably reflecting regional differences in plate geometry and tectonic stress.

Fig. 2 shows an enlargement of the box in Fig. 1 for the Tjörnes Fracture Zone. The seismicity outlines the Húsavík–Flatey Fault to the south and the Grímsey Lineament to the north. The earthquakes NW of the Húsavík–Flatey Fault are at the southern end of the Kolbeinsey Ridge on the Mid-Atlantic Ridge. The three new seismic stations, BRE, FLA, and HED, immediately over the Húsavík–Flatey Fault, were installed (January 2001) specifically to search for 90°-flips, as part of the EC funded SMSITES Stress-Monitoring Site Project (Crampin 2001; Crampin *et al.* 2000).

The green petals of the rose diagrams are same shear-wave polarisations for the years 1996 to 2000 as in Fig. 1. The red petals are the polarizations for earthquakes during 2001. The 2001 (red) petals at Stations HLA, REN, and GRI have essentially the same distribution of polarisations as in Fig. 1 suggesting similar crack distributions. The red polarisations at Stations SIG and LEI are based on too few earthquakes to be significant. The most notable feature is that the polarisations at the new stations, BRE, FLA, and HED, are approximately orthogonal to the green petals and show the expected 90°-flips.

3 THEORETICAL MODELLING

Shear-waves propagating towards the surface typically split into two nearly orthogonal polarisations with the average orientation of the faster wave approximately parallel to the direction of maximum horizontal stress. Such shear-wave splitting (seismic birefringence) is caused by propagation through the stress-aligned fluid-saturated microcracks that pervade most rocks in the crust (Crampin 1994, 1999). The evolution of distributions of fluid-saturated cracks with changing stress can be modelled by anisotropic poro-elasticity (APE) (Zatsepin & Crampin 1997; Crampin & Zatsepin 1997), where the driving mechanism for alignment (deformation) is fluid flow or dispersion along pressure gradients between neighbouring grain-boundary cracks and low aspect-ratio pores at different orientations to the stress field.

Numerical modelling with APE shows that the polarisations of the faster split shear-waves, propagating in ray path directions approximately parallel to thin parallel vertical cracks, are parallel to the crack plane when the cracks are filled with fluids at low pore-fluid pressures. That is they are polarised parallel to the direction of maximum horizontal stress as observed in Fig. 1.

Fig. 3 uses APE modelling to show the effects of increasing pore pressure, p_f, on shear-wave velocity anisotropy for five different stress distributions. The axes of stress of minimum horizontal, maximum horizontal, and vertical differential stress, are, respectively: $s_h = 0$; $s_{Hi} = 12, 14, 16, 18, 20$ MPa for $i = 1$ to 5; and $s_V = 20$ MPa. Percentages of shear-wave velocity anisotropy $[(V_{\max} - V_{\min})/V_{\max} \times 100]$ are shown for a range of differential pore-fluid pressures from $p_f = 10$ MPa to $p_f = s_{Hi}$ for each of the different horizontal

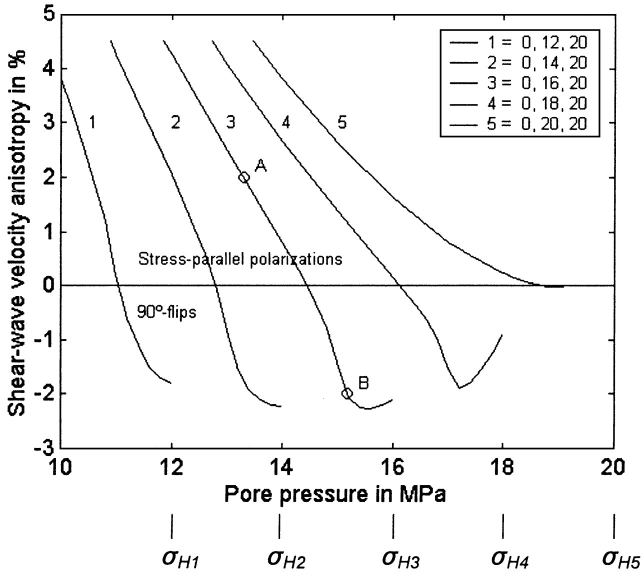

Figure 3. Variation of shear-wave velocity anisotropy with increasing pore-fluid pressure for five different sets of principal axes of stress showing 90°-flips in polarization as anisotropy becomes negative for pore-fluid pressures close to s_H. The inset shows the five different principal axes of differential stress, s_h, s_H, and s_V.

axes of stress. For low values of p_f, the faster split shear-wave is polarised parallel to s_H, but for values of p_f within 1 or 2 MPa of s_H, the anisotropy changes sign. The change of sign means that the faster split shear-wave (previously parallel to s_H) does a 90°-flip and becomes the slower wave (parallel to s_h). Such flips write easily recognisable signatures into the polarisations of three-component seismograms.

Note that Fig. 3 shows the shear-wave velocity anisotropy for specific values of pore-fluid pressure for local variations in p_f. The curves do not represent the evolution of crack geometry over a large range of changing p_f over a long period of time as non-elastic physical processes such as healing and hydraulic fracturing will disturb the modelled effects.

Thus the five curves in the figure end as pore pressure reaches the maximum horizontal stress for the particular set of principal axes of stress. This is the value when fracture criticality is reached at the percolation threshold when hydraulic fracturing and earthquakes occur (Crampin 1994, 1999; Zatsepin & Crampin 1997; Crampin & Zatsepin 1997). Note that initial crack densities and aspect ratios are chosen so that the maximum aspect ratio is well below levels of fracture criticality when fracturing occurs. In order to give some understanding of the cause of 90°-flips, Fig. 4 shows polar maps illustrating the properties of three-dimensional crack distributions for the two points A and B on Curve 3 in Fig. 3. The three diagrams are equal-area polar plots of (from the left) contours of relative aspect ratios, horizontal projections of the polarisations of the faster split shear-wave, and contoured plots of the time-delays between the split shear-waves. The diagrams show stress-parallel alignments in A, where crack distributions have symmetry close to transverse isotropy where the direction of minimum horizontal stress is approximately an axis of cylindrical symmetry. The high pore-fluid pressures in B, have reorganised the crack distributions and there is more pronounced orthorhombic symmetry. As a result, for nearly vertical propagation in the centre of the plots, there are 90°-flips. Fig. 4 has been calculated with APE (Zatsepin & Crampin 1997; Crampin & Zatsepin 1997), and plotted with ANISEIS (Taylor 2000).

4 DETAILED INTERPRETATION OF OBSERVATIONS

Station FLA is on the small island of Flatey, approximately 1 km north of the centre line of the Húsavík–Flatey Fault. BRE is onshore some 4 km to the south of FLA and allows us to estimate the extent of high pressures around the fault. Since BRE is not immediately above the Húsavík–Flatey Fault, yet shows uniform 90°-flips for ray paths from all earthquakes around the fault, this suggests that high pore-fluid pressures are pervasive around the fault plane. In particular, high pressures do not appear to be restricted to the immediate fault

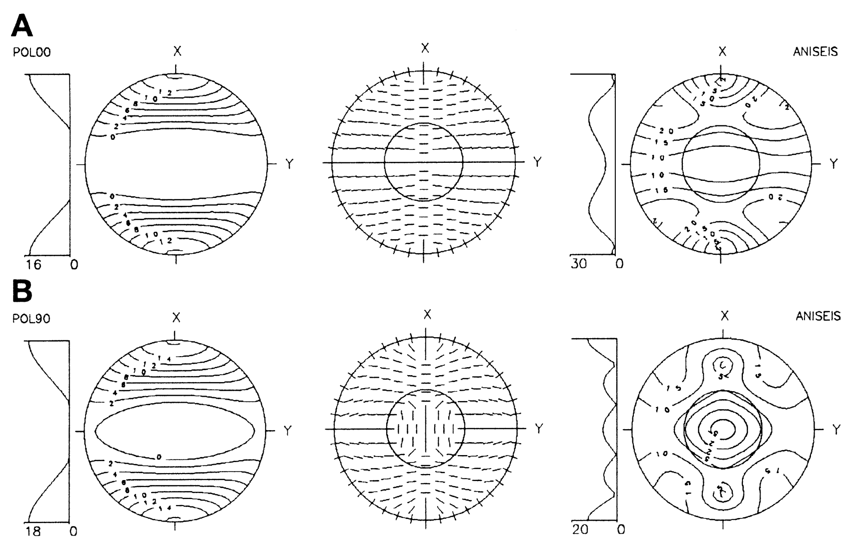

Figure 4. Properties of crack distributions at points A and B on Curve 3 in Fig. 3. Diagrams are equal-area polar diagrams (out to 90°) about the vertical, with principal axes of differential stress, s_h, s_H, s_V, oriented parallel X, Y, Z, respectively. Left—contours of distributions of relative aspect ratios (referred to crack-normals) where the zero contour is closed cracks, with section to the left; Middle—horizontal projections of the polarisation of faster split shear-wave at the free surface; Right—contoured time-delays between the split shear-waves in ms km^{-1}, with section to the left. The inner circles are shear-wave windows at ~35° for a uniform half-space where $V_P / V_S = 1.732$.

break but occur in a band at least 3 km either side of the fault and appear to extend beyond the immediate volume of fault gouge and breccia (the fault core). Note that station GRI is at least 10 km away from the Grímsey Lineament and does not show consistent 90°-flips. This puts a limit on the extent of high pore-fluid pressures on the Grímsey Lineament.

These results suggest that there are high pressures around the seismically-active Húsavík–Flatey Fault in a band several kilometres either side of the immediate fault-slip zone. These 90°-flip results are in excellent agreement with the current understanding of fluid transport in major fault zones (Gudmundsson *et al.* 2001).

Comparing Figs 1 and 2, the only distinguishing feature of the 90°-flips in Fig. 2 is that they are closely associated with the major HFF transform fault. Other observations of 90°-flips above earthquakes were also near the major San Andreas (Liu *et al.* 1997; Peacock *et al.* 1988). Thus it appears that 90°-flips above earthquakes are only observed above major strike-slip faults which penetrate the whole crust and where high pore-fluid pressures may be expected to extend to close to the surface.

5 OTHER OBSERVATIONS OF 90°-FLIPS

Recognised theoretically using APE (Zatsepin & Crampin 1997), 90°-flips were first identified in the field in an overpressurised hydrocarbon reservoir in the Caucasus (Crampin *et al.* 1996; Slater 1997). 90°-flips were also observed by Angerer (Angerer *et al.* 2000, 2002), in a well-calibrated test of APE modelling. Angerer calculated (predicted with hindsight) the response of a reservoir to two CO_2-injection pressures. One injection was at a high pressure which caused 90°-flips in both modelled and observed polarisations. The match of model to observations in a fractured reservoir was excellent. The reason for this astonishing calculability is thought to be because fluid-saturated crack distributions in the crust are so closely spaced that they are critical systems with self-organised criticality verging on fracture criticality (Crampin 1999, 2000; Crampin & Chastin 2000) so that some measure of universality is present (Bruce & Wallace 1989). Previous case studies of 90°-flips above small earthquakes are few (Liu *et al.* 1997; Miller & Savage 2001; Peacock *et al.* 1988, although 90°-flips had not been recognised in 1988) and do not have the consistency and reliability of the observations in Fig. 2.

A reviewer commented that 90°-flips could also be caused by small variations in the polarisations of the initial radiated shear-waves as in Rümpker & Sliver (1998), or by variations of foci and heterogeneous anisotropy. Although, as is common in geophysics, other sources of anomalies cannot be entirely excluded, we suggest in this case they can be rejected as the large number of observations in Fig. 1, which are not associated with major faults and do not show 90°-flips despite comprehensive variations in foci and heterogeneous anisotropy.

6 DISCUSSION

The new stations, BRE, FLA, and HED, were sited above the Húsavík–Flatey Fault in expectation that 90°-flips might indicate increases of pore-fluid pressures precursory to larger earthquakes. In retrospect, since all crustal earthquakes involve fracturing and faulting, high pressures and 90°-flips must be expected around even small earthquakes. If this is correct, why are 90°-flips so seldom observed?

Shear-wave splitting with stress-parallel polarisations is typically observed above small earthquakes on comparatively small fault planes surrounded by (presumably) comparatively small volumes of high pore-fluid pressure. Consequently, although 90°-flips in polarisations are expected in the high pressures near the source itself, the remainder of the ray path, through lower-pressurised cracks, will have the conventional stress-parallel polarisations. Thus 90°-flips associated with high pressures will only be observed at the surface when substantial parts of the ray paths are in high-pressure zones. This is likely only near major strike-slip faults where the fault extends throughout the crust to the surface and high pressures can be expected close to the surface, as on the San Andreas Fault (where 90°-flips are observed; Liu *et al.* 1997; Peacock *et al.* 1988) and the Húsavík–Flatey Fault in this paper. The 90°-flips observed by Miller & Savage (2001) were associated with a volcanic eruption, where again high pressures from feeder dykes would necessarily extend to the surface.

90°-flips in the high pressures near a source on a small fault will revert to stress-parallel polarisations as the wave leaves the high-pressure zone and propagates through the lower pressures away from the fault. This means that the shear-wave splitting observed at the surface is a combination of 90°-flips and conventional stress-aligned polarisations in proportion to the ratio of high- to low-pressure segments of the ray path. Since every small earthquake modifies the stress field and modifies the distribution of high pore-fluid pressures, the scatter in shear-wave splitting time-delays (see, for example, Volti & Crampin 2002b) is expected because of the varying proportions of high- to low-pressure path segments.

In appropriate circumstances monitoring 90°-flips on large faults could provide valuable information about the behaviour of high fluid pressures in earthquake source mechanisms, which have previously been inaccessible. The observations in this paper further confirm the compliance and stress-sensitivity of crustal rocks and the validity of APE-modelling.

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