



Shear-wave splitting in a critical crust: III. Preliminary report of multi-variable measurements in active tectonics

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Abstract

This is a preliminary report on two sets of recent observations from a region of active tectonics that provide comparatively direct evidence for the critical state of the fluid-saturated microcracked crust. The first data set from crosshole seismics in a controlled source stress-monitoring site (SMS) shows that the crust of the Earth is highly compliant and responds to low-level changes of tectonic stress at substantial distances. The second set of data from earthquake seismograms shows that the seismically active Húsavík–Flatey Fault plane is pervaded by critically high pore-fluid pressures, which cause 90° flips in the polarisations of seismic shear waves. We suggest that both sets of observations confirm previous hypotheses for a compliant crack-critical (CCC) crust. This is a new understanding of low-level pre-fracturing deformation that has fundamental implications for a range of applications in solid earth geophysics. These applications range from monitoring hydrocarbon production with time-lapse seismics to monitoring tectonic stress in situ rock and stress-forecasting the times and magnitudes of impending large earthquakes.

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1. Introduction

“Make a better instrument or measure in a place where no one else has been and a great discovery will come your way.” Press (1979).

This is the third International Workshop on Seismic Anisotropy (IWSA) where we have suggested that the fluid-saturated grain-boundary cracks and low aspect-ratio pores in the Earth’s crust are so closely spaced that they form critical systems verging on (fracture) criticality, breakdown, and deterministic chaos. We call this a compliant crack-critical (CCC) crust. Since

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in situ rocks at depth are subject to high temperatures and pressures and are essentially inaccessible, proving criticality in the response of in situ rock to small changes of stress has proved difficult, and most of the evidence is indirect. At the first of these three workshops, 8IWSA, we reported (Crampin, 1998) the large range of phenomena (currently increased to more than 20) where the anisotropic poro-elasticity (APE) model for the evolution of fluid-saturated microcracked rock matches, at least approximately, the behaviour of various configurations of cracks, stress, and shear-wave splitting (Zatsepin and Crampin, 1997; Crampin and Zatsepin, 1997; Crampin, 2000a). APE models the evolution of fluid-saturated grain-boundary cracks and low aspect-ratio pores under changing conditions where the driving mechanism is fluid migration by flow or dispersion between neighbouring microcracks at different orientations to the stress field. In general, the detailed response of in situ rocks is so poorly quantified at depth that the match of APE modelling cannot be adequately tested. Nevertheless, since the underlying assumption of APE is that the fluid-saturated cracks in in situ rock form a CCC system verging on fracture criticality and failure (Crampin and Zatsepin, 1997), even the approximate match of APE to a large range of phenomena is confirmation, albeit indirect, that the cracks in the crust are a CCC system.

Crampin and Chastin (2001) at 9IWSA reported the successful modelling (in effect, prediction with hindsight) of the response of the reservoir to two CO₂ injections by Angerer et al. (2000, 2002). One of the pressures was high enough to cause 90° flips in shear-wave polarisations in the injected reservoir, where the faster split shear wave flipped from approximately parallel to approximately orthogonal to the direction of maximum horizontal stress. In both injections, the match of modelled to observed shear-wave splitting for the evolution of the fluid-saturated cracks was almost exact, and this study is the best calibration of in situ APE modelling to date. Again, the necessary underlying assumption is a CCC crust. Pressures that are high enough to cause 90° flips will be referred to as critical pressures.

Crampin and Chastin (2001) also reported the first successful stress forecast of the time and magnitude of an $M=5$ earthquake in SW Iceland by Crampin et al. (1999). Monitoring the effects of increasing tectonic

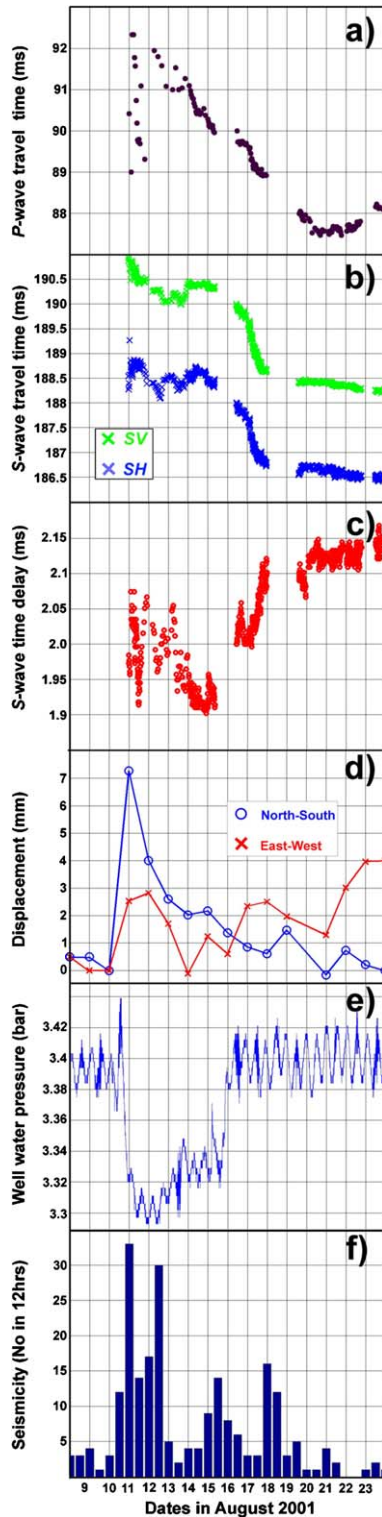
stress on shear-wave splitting using small earthquakes as the shear-wave source allowed the time and magnitude of the impending earthquake to be estimated successfully. Note that magnitudes M refer to the Icelandic Bulletin magnitudes approximately equivalent to mb .

Here, we present two sets of observations from Northern Iceland. The detailed analyses will be reported elsewhere. We present measurements of variations of seismic velocities at a stress-monitoring site (SMS) showing high sensitivity of P-, SV- and SH-wave velocities, and shear-wave splitting that correlate with several other geophysical observations and with distant low-level seismicity. The velocities were measured horizontally at approximately 500 m depth between two wells 315 m apart. Since the direction was parallel to a major strike-slip fault, the sagittal plane was a symmetry plane so that shear waves were split into SV- and SH-wave orientations.

The second data set shows observations of 90° flips in the polarisations of shear-wave splitting above small earthquakes at seismic stations close to a major fault plane, which we suggest indicates the critical pressures associated with all seismically active faults. These 90° flips have now been analysed and modelled (Crampin et al., 2002) and support the inferences in this paper. Both sets of observations show effects that are critically dependent on the existence of a CCC crust.

2. The stress-monitoring site experiment

The European Commission-funded SMSITES Project is developing a stress-monitoring site (Crampin, 2001) on the onshore extension of the Húsavík–Flatey Fault (HFF), which is a transform fault in the Tjörnes Fracture Zone of the Mid-Atlantic Ridge in Northern Iceland. The aim was to transmit shear waves along specific stress-sensitive directions in order to try to identify the small changes in microcrack geometry, which APE shows are the most immediate effects of accumulating stress, before failure by fracturing occurs. We shall call such low-level modifications *pre-fracturing deformation*. The range of directions most sensitive to small changes of stress, known as Band-1, is the double-leafed solid angle with ray paths 15–45° on either side of the average crack plane (Crampin, 1999). It can show theoretically



that the time delays of shear waves in these directions respond to changes in crack aspect ratios, which are the most sensitive crack parameter to small changes of stress (Crampin, 1999). This is in contrast to Band-2, ray paths within 15° of the average crack plane, where shear-wave time delays are sensitive to (principally) changes in crack density. Changes in crack density generally occur only for comparatively large changes of stress (Crampin, 1999).

The borehole source is the downhole orbital vibrator (DOV) of Geospace Engineering Resources International. The DOV sweeps an eccentric cam in clockwise and counterclockwise directions exerting a rotating radial force on the borehole wall (Daley and Cox, 2001). Signals from the DOV may be processed to yield shear-wave radiation equivalent to a point force in specified orientation relative to an on-board gyroscope. An earlier version of this source (the Conoco orbital vibrator or COV) produced signals that were analysed for shear-wave splitting in a reverse VSP (Liu et al., 1993).

Fig. 1 shows geophysical observations in and around the SMSITES location. Fig. 2 shows shear-wave polarisations at seismic stations in Iceland 1996–2000. Fig. 3 shows shear-wave polarisations at several seismic stations around SMSITES for the year 2001 including polarisations at three new stations, BRE, FLA, and HED.

3. Observations of sensitivity

As part of the setting-up procedure for SMSITES, we activated the source and receiver recording system by repeated sweeps of the DOV every 12–20 s and stacking every 100 sweeps for 24 h a day for 13 days (11–24 August 2001) with only minor interruptions. Both DOV and receivers were at about 500 m depth in wells 315 m apart. The DOV had a peak response at

Fig. 1. Variations at the SMSITES SMS from 8 to 24 August 2001: (a) P-wave traveltimes in milliseconds; (b) traveltimes of SV-waves (green crosses) and SH-waves (blue crosses) in milliseconds; (c) time delay (SV–SH) in milliseconds; (d) GPS displacements around Húsavík in millimeters, North–South (blue circles) and East–West (red crosses); (e) pressure at 33 m depth in water well on Flatey Island in bars showing ocean tides and anomalous ~ 1 m drop in water level; (f) 12 hourly histogram of seismicity within 100 km of SMSITES, Húsavík.

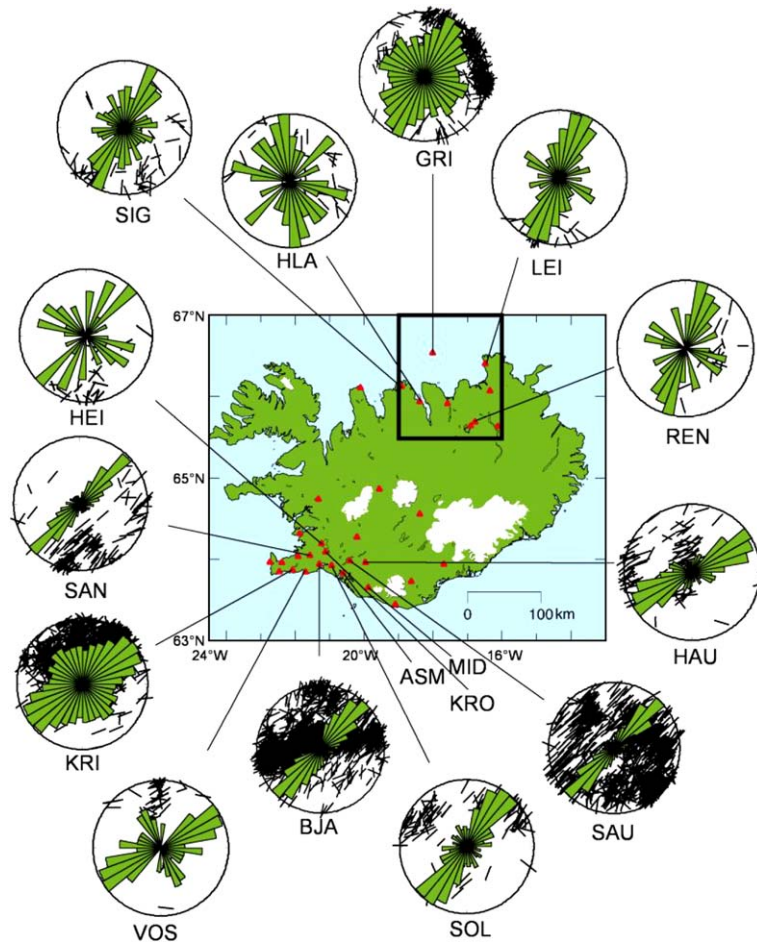


Fig. 2. Equal-area rose diagrams (green petals) of shear-wave polarisations in the shear-wave window above small earthquakes recorded by the seismic network in Iceland for 5 years (1996–2000) superimposed on equal-area polar projections out to 45° of the individual polarisations. The white areas are ice caps (after Crampin et al., 2002).

~ 250 Hz and is highly repeatable. The stacked signals were found to have stability in travel times with a resolution of at least $\pm 20 \mu\text{s}$. Well logs and cores indicate that the ray paths are near the top of a 200-m-thick layer of sandstone sandwiched between heavily fractured basalts.

We had expected to see possible variations due to source instabilities and possibly the effects of earth or ocean tides. What we observed (Fig. 1a) was an abrupt 5-ms increase in P-wave travel times and then a linear decrease over 10 days and (Fig. 1b) classic S-shaped relaxation curves in travel times of both vertically and horizontally polarised shear waves with amplitudes of about 2 ms and durations of about 4

days. The simple relaxation curves of both shear waves suggests that shear waves are propagating along comparatively simple ray paths without too many complications. The difference between the two shear waves, the shear-wave splitting, also shows a 10% variation over about 6 days.

It was found that these phenomena coincide in time with a series of some 106 small earthquakes ($M \leq 2.8$) on the Grimsey Lineament transform fault some 70 km NNW of SMSITES. The total energy released by these earthquakes is approximately equivalent to one $M=4$ earthquake. This would be a comparatively small earthquake with an expected fault slip of millimeters on a fault plane possible 100 m in diameter.

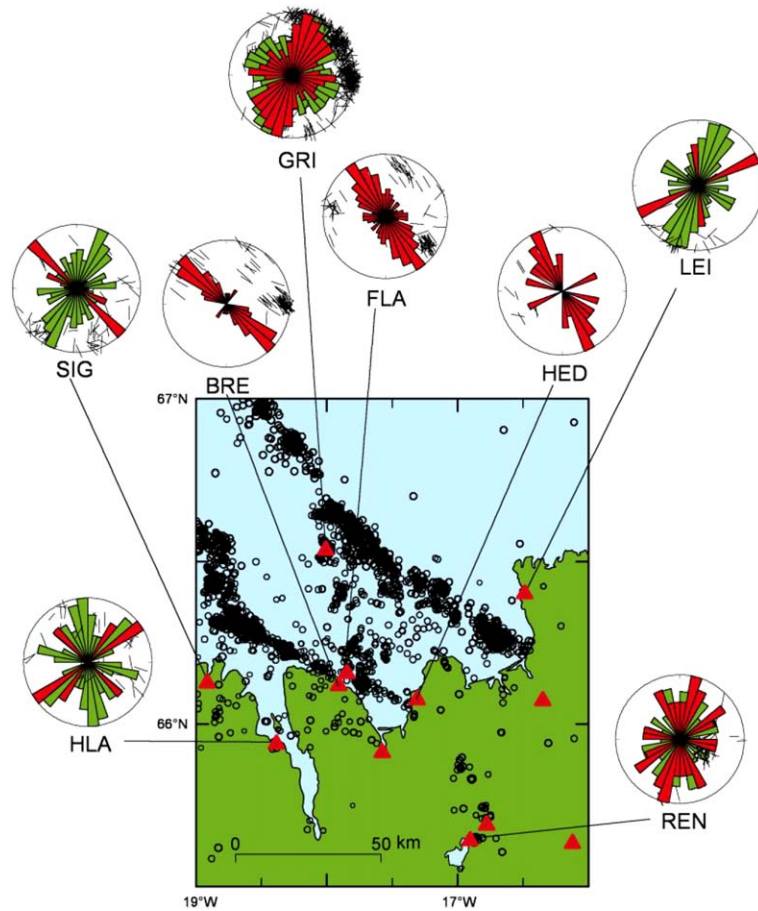


Fig. 3. Rose diagrams of shear-wave polarisations in the boxed area in the figure: years 1996–2000 (green petals, as in Fig. 2), and year 2001 (red petals). BRE, FLA, and HED are new seismic stations installed in January 2001 for the SMSITES Project. The SMSITES site is located close to seismic station HED (after Crampin et al., 2002).

This is comparatively small-scale activity with a small source zone, which conventional geophysics suggests would have significant effects only in the immediate vicinity of the source. Thus, the sensitivity of the seismic measurements to this minor stress release at considerable distance is remarkable and we believe has not previously been observed.

The Húsavík–Flatey Fault has been subject to large earthquakes in the past, and there have been several geophysical investigations by the Icelandic Meteorological Office and others, as well as by the SMSITES project. This means that the area is comparatively well instrumented. Fig. 1 shows seven variations correlating with the distant low-level swarm activity.

3.1. Seismic effects

3.1.1. Variations of P-wave travel times

Fig. 1a shows variations in P-wave travel times. Recording began on 11 August. The travel times are scattered but suggest an increase in travel time of about 4 ms. Immediately following the highest value, the travel times begin an almost linear decrease from 11 to 21 August, with possibly a small break of slope on August 16 coinciding with one of the gaps in recording. The two gaps in recording were when the DOV was thought (mistakenly) to be overheating and the tool was allowed to cool. The amplitude of the decrease is about 5 ms over about 10 days. The amplitudes and durations of the various variations

are listed in Table 1. Since the seismic measurements at SMSITES began on 11 August and the seismic activity on Grímsey Lineament began on 10 August, there was no direct indication of velocity variations before the seismic activity had started.

3.1.2. Variations in SV-wave travel times

The SV-wave travel times show irregularities during the first 3 days of recording (11–13 August), but are constant during 14 August, and from 15 to 19 August follow an S-shaped relaxation curve before levelling off on 20 August with possibly some indication of a further gradual decrease. The amplitude of the S-shaped decrease is about 2 ms over about 4 days (green crosses, Fig. 1b).

3.1.3. Variations in SH-wave travel times

The SH-wave travel times again show irregularities during the first 3 days of recording, although the initial variations are somewhat different in detail. They show a similar S-shaped relaxation curve to that of the SV-waves, but are about 2 ms earlier. Similar to the SV-waves, the amplitude of the S-shaped decrease is about 2 ms over about 4 days (blue crosses, Fig. 1b).

3.1.4. Variations in SV–SH anisotropy

The difference between the travel times of SV and SH fluctuates during the first 3 days (when the SV- and SH-wave travel times themselves show irregularities), but shows an irregular increase from 15 to 19

August during the S-shaped relaxation curves in Fig. 1b. At the end of the increase, the difference levels off on 20 August to about 2.15 ms. The amplitude of this increase is about 0.2 ms over about 5 days (Fig. 1c).

Note that this 10% change (Table 1) in the time delays between the split shear waves is the largest percentage seismic variation during the stress-induced changes in Fig. 1. This is a further demonstration that the time delay in shear-wave splitting is a highly sensitive parameter (Crampin, 1999).

3.1.5. Seismicity

The histogram of earthquakes in 100 km² around the SMSITES Site from 8 to 24 August 2001 shows a 2.5-day swarm of 106 earthquakes (10–12 August) located on a 10-km segment of the Grímsey Lineament approximately 70 km NNW of SMSITES and 10 km NNE of the Island of Grímsey. The remaining seismicity is distributed along the Grímsey Lineament with a few earthquakes on the HHF, but about 50% of the activity is still from the same 10 km segment of the Grímsey Lineament (Fig. 1f).

The largest earthquake is $M=2.8$, and the total energy release of the initial burst of activity is approximately equivalent to the energy released from one $M=4$ event. Note that the area in Fig. 3, showing seismicity in the year 2001, currently has comparatively low-level seismic activity, typically of about three or four events per day, so that the first and last 2 or 3 days in Fig. 1f are close to the background level.

Table 1
Summary of associated variations

Nature of phenomenon	Figure number	Approximate size or amplitude	Approximate duration (days)	Seismic variation (%)
Linear decrease in P-wave traveltimes	1a	5 ms	10	6
S-shaped decrease in SH-wave traveltimes	1b (blue)	2 ms	4	1
S-shaped decrease in SV-wave traveltimes	1b (green)	2 ms	4	1
Variations in SV–SH times (anisotropy)	1c	0.2 ms	6	10
East–West GPS deformation ^a	1d (red)	3 and 4 mm	4 and 9	–
North–South GPS deformation	1d (blue)	7 mm	11	–
Water-level decrease at Flatey	1e	1 m	5	–
Seismicity: initial burst of activity on Grímsey Lineament 10–12 August 2001, 10 km NNE of Grímsey	1f	106 events, $M \leq 2.8$	2.5	–

^a EW GPS deformation takes place in two phases (hence, two amplitudes and two durations).

3.2. Changes in strain from Global Positioning System (GPS) displacements

3.2.1. Variations in East–West GPS displacements

GPS displacements from stations either side of the HFF in an East–West direction show a change in strain of about 4 mm in two phases (red crosses, Fig. 1d). Initially, a 4-day 3-mm pulse returning to the initial level which is followed by a 9-day increase, which then levels off to an offset of 4 mm. The initial rise and fall is associated with the larger North–South strain, below. The 9-day increase in strain marks the return to the customary dextral movement of the HFF.

3.2.2. Variations in North–South GPS displacements

GPS displacements across the fault in a North–South direction from stations either side of the HFF show an abrupt 7-mm increase followed by an approximately exponential decrease in strain over 10 days relaxing back to approximately zero displacement (blue circles, Fig. 1d).

3.3. Changes in water level in well on the Island of Flatey

3.3.1. Water pressure variations in well on Flatey

The pressure measurements are at about 33 m depth in a water-filled well on the small island of Flatey, close to the seismic station FLA, in Fig. 3, and immediately above the seismicity of the HFF. Pressure monitors the water level above the sensor. Since 1 bar (0.1 MPa) is approximately equivalent to a pressure of 10 m of water, the ~ 0.1 bar decreasing pulse in pressure represents a ~ 1 -m drop in water level. The 40-cm peak-to-peak sinusoids are tides. Since such tides are visible on pressure measurements in water wells in Iceland only when the wells are near the coast, the effects appear to be due to oceanic tides. The 1-m decrease starts with an initial increase approximately coinciding with the onset of seismic activity in Fig. 1f. The offset decreases gradually over 4 days and, on the fifth day, rapidly returns to the background level. Well pressures are recorded continuously, and it is worth noting that this abrupt decrease in pressure is the only significant pulse in 15 months of records. Over the 15 months, there are broad increases in November 2000 and November 2001 due presumably to autumn precipitation. There was

negligible rainfall during the recording period in August 2001 (Fig. 1e).

4. Discussion of sensitivity to small changes of stress

Fig. 1 displays what is, in effect, a time-lapse survey of eight variables. A summary of the amplitude and duration of these various changes is listed in Table 1 together with the percentage change in seismic variations. There are several remarkable features. There is a wide variation in the duration of the changes. For example, the linear decrease in P-wave travel times is over about 10 days, whereas the S-shaped decreases in both SH- and SV-waves are over about 4 days. One initially might expect that seismic P- and S-waves propagating along similar ray paths would respond to similar features of the rock mass. The different durations of their response clearly indicate that P- and S-waves respond to different phenomena and sample different features of rock deformation. The whole range of eight different phenomena is believed to be a unique data set, and their interpretation is likely to place constraints on the interpretation of the response of in situ rock to small changes of stress in time-lapse studies.

The water level in the well on Flatey appears to respond to variations in the tectonic regime. It is well known that changes of water level in wells may be associated with earthquakes (Roeloffs, 1988), although the nature of the association is not fully understood. The changes may be precursory, co-seismic, or post-seismic, and the duration and polarity of change may vary widely and can occur at substantial distances from the seismic activity. Sometimes, the polarity can be associated with fault-plane compressions and dilations, but in general, the effects are thought to be local to the particular well and to be related to interactions of tectonic stress with local faults or fractures at different orientations anywhere near the open section of the well. Although local anomalies may have effects, the observations in Fig. 1 suggest that it is the whole rock mass that responds to changes. Clearly, the rock mass responds to pre-seismic and post-seismic disturbances in ways which have previously not been identified. The 7-mm extension in strain shown by the North–South GPS

measurements, if interpreted as an increase in aspect ratio of fluid-saturated microcracks over the 200-m-thick layer of permeable sandstone, is the correct order of magnitude to account for the 1-m drop in water level in the well on Flatey as the increase in microcrack capacity to absorb water ($200 \times 0.007 = 1.4$ m).

Another remarkable feature is the near coincidence of the various interactions. The initial increase in pressure in water level at Flatey approximately coincides with the onset of seismicity on the Grimsey Lineament some 50 km north of the well. This suggests that the rock mass responds almost immediately to strain changes at ~ 50 km from Flatey. In principle, the GPS measurements could determine delays in response more exactly, but this has not yet been done.

A further remarkable feature of the variations in Fig. 1 is the accuracy of the seismic travel-time measurements. Due to stacking and the highly repeatable DOV source, there are very well-observed variations in seismic velocities at substantial distances from comparatively small-scale stress release by an earthquake swarm. These show that the rock mass is extremely compliant and responds to very small changes in conditions, even in a regime that is principally composed of crystalline basalts, which might be thought to have minimal compliance. Such compliance is not expected in the brittle upper crust of conventional geophysics, but such sensitivity is implied by the anisotropic poro-elasticity (APE) model of rock deformation. Consequently, the variations in Fig. 1 provide strong evidence confirming the APE mechanism of deformation in a CCC crust: that the immediate effect of low-level pre-fracturing deformation is fluid migration by flow or dispersion along pressure gradients between neighbouring grain-boundary cracks and low aspect-ratio pores at different orientations to the stress field. This will particularly effect shear-wave propagation and shear-wave splitting (Crampin, 1999). The particular sensitivity of shear waves is supported by the classic S-shaped relaxation curve which suggests that shear waves are displaying a fundamental property of the deformed rock mass: the poro-elastic response of fluid-saturated microcracks to small changes of stress (Zatsepin and Crampin, 1997). The interrelationship of P-waves and shear waves is not yet understood and is probably the

most interesting and potentially most informative feature of this data set, once the compliance of the CCC crust has been accepted.

The underlying assumption of APE is that fluid-saturated cracks are so closely spaced that they are critical systems with great sensitivity to small changes and with potential for large-scale disruption at fracture criticality. These observations of sensitivity from Iceland are a direct confirmation that microcracked crust is a critical system.

Note that by closely spaced cracks, we mean crack densities between about $\epsilon \approx 0.015$ and $\epsilon \approx 0.045$, where $\epsilon = Na^3/v$ and N is the number of cracks of radius a in volume v (Crampin, 1994). This is a very narrow crack range and is equivalent to crack distributions where each crack is approximately a crack diameter, and a crack radius, respectively, from eight other cracks in a uniform three-dimensional distribution of approximately similar-sized cracks. An image of such distributions can be found for example in Crampin (1994, 1999) and elsewhere. Note also that such effects are almost independent of porosity (Zatsepin and Crampin, 1997). A similar range of implied crack densities is found from shear-wave splitting in 30% porosity sandstones and in 1% porosity granites. This suggests, and an albeit limited number of observations tends to confirm, that progress towards fracture criticality is also largely independent of rock type and porosity.

Thus, it appears that all fluid-saturated rocks, in at least the upper half of the crust, contain a universal distribution of microcracks with a very limited range of crack densities. Such remarkable universality is characteristic of critical systems verging on criticality where the behaviour near (fracture) criticality is characterised by the criticality rather than the physics of the subcritical medium (Bruce and Wallace, 1989).

It is interesting to question why we see changes at 70 km from a comparatively small earthquake, but do not see changes from much smaller earthquakes at a distance of only a few kilometers. The increase of time delays before earthquakes and volcanic eruptions that allowed an earthquake to be stress-forecast are thought to monitor the accumulation of stress (Crampin, 1999; Volti and Crampin, 2003a,b). As they are independent of the eventual source zone, they are not earthquake precursors. Earthquakes are only symptoms of an abrupt release of energy. However, pre-

cursory changes of stress are indicated by decreases in shear-wave splitting time delays in Band-1 of the shear-wave window 4 days before the $M=5$ earthquake that was stress-forecast in SW Iceland (Volti and Crampin, 2003b). Similar precursory changes have also been seen elsewhere (Crampin, 1999) and are found in laboratory experiments (Gao and Crampin, 2003). This suggests that the behaviour of the earthquake's source zone is the driving mechanism for this precursory stress release. The actual earthquakes themselves merely mark successive possibly minor releases of stress during the overall stress-release process. Thus, the effects of the individual 106 earthquakes on the Grímsey Lineament, correlating with the observed changes, may be controlled by effects of the overall source zone which has an equivalent energy release to one $M=4$ earthquake at ~ 70 km distance. If we equate the effects of one unit decreases in magnitude (approximately equivalent to a factor of 10 decreases in energy) with factors of 10 decreases in distance, we would expect approximately similar effects for, say, $M=4$ at 70 km, $M=3$ at 7 km, $M=2$ at 700 m, $M=1$ at 70 m, and $M=0$ at 7 m. Since small earthquakes near Húsavík are likely to have magnitudes $M < 2$ and are usually at several kilometers depth, the effects are likely to be smaller than those for an $M=4$ at 70 km and appear to be below the observational limit.

5. 90° flips in shear-wave polarisations

We now report the second data set from the SMSITES Project: records of shear-wave polarisations at three new seismic stations installed near the HFF. The polarisations of the faster split shear wave, propagating at less than 45° to the vertical in crack distributions at depth in the crust, are typically aligned parallel to the average strike of the distributions of fluid-saturated microcracks. These are aligned perpendicular to the direction of minimum compressive stress which, below a critical depth (usually between 500 and 1000 m), is horizontal so that the cracks are approximately vertical striking parallel to the direction of maximum horizontal stress. This means that the polarisations of shear-wave splitting observed in the shear-wave windows of seismic stations throughout Iceland (Fig. 2) are approximately parallel to the

direction of maximum horizontal tectonic stress. This direction varies from NE to SW in SW Iceland to NNE to SSW in North–Central Iceland in the two seismic regions where transform zones of the Mid-Atlantic Ridge run onshore. (The shear-wave window is the cone of arrivals, effectively 45° about the vertical, within which shear waves are not distorted by S-to-P conversions at the free surface; Booth and Crampin, 1985.)

Fig. 2 shows rose diagrams superimposed on polar plots out to 45° of the polarisations of faster split shear wave for all earthquakes within the shear-wave window of seismic stations in Iceland for earthquakes in the 5 years 1996–2000. Fig. 3 shows similar plots for stations in the boxed area in Fig. 2 with green petals for polarisations for earthquakes for the 5 years 1996–2000, as in Fig. 2, and red petals for the year 2001. The red petals at the three new seismic stations (BRE, FLA, and HED), installed by the SMSITES Project in January 2001 close to the HFF, are approximately orthogonal to the green petals. Note that the red petals (2001) at stations SIG and LEI have different normalisations to the green petals (1996–2000) and refer to very few earthquakes and are probably not significant.

APE modelling has shown that as pore-pressure increases, the polarisation of the faster split shear waves flips from parallel to perpendicular to the maximum horizontal stress when the pore pressures approach the value of the maximum horizontal stress, at what we call critical pressures (Crampin et al., 2002). This is a result of the changes in the three-dimensional distribution of crack aspect ratios as pore pressure approaches values when the rock would hydraulically fracture. Angerer et al. (2000, 2002) called such phenomena 90° flips. It is well known that high pore-fluid pressures are needed to relieve frictional stress on lithostatically clamped faults before slippage and earthquakes can occur, and we interpret the changes in shear-wave polarisations in Fig. 3 as indicating 90° flips caused by critical pressures around the seismically active HFF fault plane.

Such 90° flips have previously been observed in vertical seismic profiles in a critically pressurised reservoir in the Caucasus Oil Field (Crampin et al., 1996; Slater, 1997) and in reflection surveys (Angerer et al., 2000, 2002) of a critically pressurised CO_2

injection. These 90° flips have also been observed above small earthquakes immediately above the San Andreas Fault in California by Liu et al. (1997), who recognised the significance of 90° flips, and also by Peacock et al. (1988) and Crampin et al. (1990, 1991), although at that time, the significance of the 90° flips had not been established.

The three stations, BRE, FLA, and HED in Fig. 3 showing 90° flips, close to the surface break of the HFF, were installed by the SMSITES Project in January 2001. The stations were sited near to the fault in anticipation of observing 90° flips in shear-wave polarisations caused by high pressures prior to a larger earthquake on the HFF. However, we now believe that all earthquakes require critical pressures to allow slippage on fault planes. The seismicity in Fig. 3 shows that HFF has a high level of small-scale seismicity and suggests that high pore-fluid pressures are pervasive around probably all seismically active fault zones.

6. Discussion of 90° flips

The recognition of 90° flips in shear-wave polarisations in critically pressurised regions of seismically active fault planes provides an explanation for the large ($\pm 80\%$) scatter invariably observed in measurements of time delays of shear-wave splitting above small earthquakes (for example, in Volti and Crampin, 2003a,b). Crampin et al. (2002) use APE to model shear-wave polarisations in highly pressurised rocks. They show that 90° flips occur when pressures are sufficiently close to critical pressures. Further, it can be argued that all seismically faults require critical pressures to permit fault slip and earthquakes. Previously, 90° flips have been observed directly at the surface only at two places on the San Andreas Fault in California (Liu et al., 1997; Peacock et al., 1988) and here on the HFF. The critical pressurised zone is likely to persist over much of the ray path to the surface only on such major faults, where the flips in polarisations are seen at the surface.

In contrast on smaller faults, critical pressures are likely to pervade only the region immediately around the fault plane which will not extend to the surface. Close to the fault plane, the shear waves will show 90° flips, but the remaining path length away from the

fault to recorders at the surface will not be critically pressurised and will display the conventional stress-parallel shear-wave polarisations orthogonal to the 90° flips. This means that the polarisations at the surface will display the typical stress-parallel polarisations. However, the time delays will depend on the relative proportion of the ratio critically to normal-pressurised segments of ray path. Following an earthquake and slip on a critically pressurised fault, stress will be released, and the geometry of the triaxial stress and pore-fluid pressure will be modified. Consequently, the critical pressures will be redistributed so that the proportion of the critically to lower pressurised segments of the ray paths will be changed with possibly seriously modified time delays after every earthquake. Thus, these repeated critically pressurised modifications will continue, and the earthquake swarm or foreshock or aftershock will persist as long as the critical-pressurised regions remain. When the critical fluid pressures disperse, along faults or fractures or by other mechanisms, the seismic activity will stop. APE can be used to model these effects and shows that varying proportions of critically high-pressurised rocks on seismically active fault planes cause 90° flips and varying time delays that can easily explain the observed $\pm 80\%$ scatter.

7. Conclusions

The behaviour of both sets of SMSITES observations can be described and modelled by APE: the observations of sensitivity by implication, and the 90° flips directly. A major assumption of the APE model is that the crust is so densely permeated by fluid-saturated stress-aligned microcracks that the cracks form critical systems. This means that the success of APE in modelling a large range of phenomena including the sensitivity and the 90° flips in this paper provides further direct confirmation that the crust of the Earth is a CCC system (Crampin and Chastin, 2001).

The important implications and applications of the CCC crust for academic and exploration seismics have been discussed elsewhere (Crampin, 1998, 1999, 2000a,b; Crampin and Chastin, 2001) and will not be repeated here. This section will only refer to the new observations of sensitivity and 90° flips.

7.1. Sensitivity to small changes of stress

Large earthquakes release substantial amounts of stress which has accumulated deep in the crust. Previously, it was not known previously how the Earth stores such stress: how a sample of stressed rock deep in an earthquake preparation zone in the crust differs from an unstressed sample. The answer appears to be in the pre-fracturing deformation of fluid-saturated grain-boundary cracks and pores as modelled by APE. APE shows that shear-wave splitting monitors the mechanism for storing and releasing stress and can identify the approach of fracture criticality and failure by fault slip and earthquakes.

Note that the seismic effects are induced by small earthquakes, equivalent to one $M=4$, at 70 km distance. These effects are clearly seen at several hundred times the conventional source dimensions. These displays exceptional sensitivity of the rock mass to small disturbances at large distances.

The importance of these phenomena for the oil industry is that the effects are extremely sensitive to small changes of stress and may be modified by distant tectonic or other disturbances. This means that the possibly subtle effects of moving oil–water fluid fronts in time-lapse seismics could be misinterpreted or concealed.

7.2. Significance of 90° flips

The demonstration in this paper and in Crampin et al. (2002) that large seismically active faults are pervaded by (critically) high pore-fluid pressures confirms that slippage at depth always requires faults or fractures to be pervaded by critically high pore-fluid pressures. These lead to 90° flips in the immediate vicinity of the fault with the remaining ray path reverting to typical alignments parallel to the maximum horizontal stress. This provides an explanation for the otherwise inexplicable $\pm 80\%$ scatter in time delays typically observed above small earthquakes (Crampin et al., 2002).

7.3. Overall implications

In Fig. 1 and Table 1 the percentage change in shear-wave splitting time delays (10%) is greater than the change in P- and S-wave travel times (6% and 1%,

respectively). This confirms that shear-wave splitting and shear-wave anisotropy are sensitive diagnostics of the CCC crust, and that the CCC crust is not a stable phenomenon. APE implies that shear-wave splitting is the most sensitive monitor of the temporally and spatially varying geometry of the distribution of the stress-aligned fluid-saturated distribution of grain-boundary cracks and pore throats. Roeloffs (1988) cites eight examples of earthquakes of magnitudes between $M=5$ and $M=6$ in China and USA associated with precursory water-level variations at distances between 100 and 360 km from the eventual epicentre. This paper indicates that those earthquakes would also be likely to have associated seismic and GPS strain variations. In particular, the behaviour of shear-wave splitting appears to be highly sensitive to the detailed deformation of the CCC crust.

This “new geophysics” of the CCC crust has substantial implications for the whole behaviour of the solid Earth. In situ rocks are compliant crack-critical and descend into deterministic chaos whenever fracture criticality approaches and rocks fracture, fault, and earthquakes occur. In particular, the seismic observations reported here imply that current seismic resolution is probably near its limits in resolution. Increased resolution and sensitivity is likely to monitor the compliance of the CCC crust, and the comparative simplicity of the conventional brittle elastic crust will be lost. This has important implications for hydrocarbon reservoir characterisation, hydrocarbon recovery, and stress-forecasting earthquakes (Crampin, 2000b; Crampin and Chastin, 2001). Substantially improved recovery and calculation (even prediction) of the response of the reservoir to some recovery operations may now be possible by being able to understand and model the changes (Angerer et al., 2000, 2002).

It is usually the aim of seismic surveys to maximise resolution and measurement accuracy. We have shown that resolution and accuracy in conventional seismics is limited by system criticality. We suggest that, excluding shear-wave splitting, current techniques have probably reached the limit of conventional interpretation. Unless surveys with similar recording geometry are repeated exactly, it is unlikely that temporal changes due to critical systems will be identified correctly, and that criticality changes will be misinterpreted, possibly as spurious move-

ment of fluids in time-lapse surveys of hydrocarbon production for example. Accurate repetition of measurements of shear-wave splitting are likely to be the most diagnostic indicators of the presence of critical systems.

There are two principal conclusions.

- (1) Substantially improved resolution and improved hydrocarbon recovery are unlikely to come from improving conventional techniques. Reservoirs and crustal rocks are cracked, compliant, and critical, and the implications of the new geophysics of the crust must be accepted, and opportunities exploited, particularly by single- or dual-well imaging techniques and using the calculability of anisotropic poro-elasticity.
- (2) The science and technology of stress-monitoring sites for monitoring the stress buildup before large earthquakes has been confirmed, indicating that appropriate stress-monitoring sites should be able to stress-forecast the times and magnitudes of impending large earthquakes.

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