Changes in shear wave splitting before the 2010 Eyjafjallajökull eruption in Iceland

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SUMMARY
We use shear wave splitting (SWS) above microearthquakes to monitor stress variations before the 2010 March and April flank and summit eruptions of Eyjafjallajökull volcano in Iceland. SWS time delays before Eyjafjallajökull show characteristic variations similar to those seen before earthquakes. The time delays display a nearly linear increase before the eruption, an abrupt change of slope and a rapid nearly linear decrease until the flank eruption begins. Similar variations before earthquakes are interpreted as stress-accumulation increases, and stress-relaxation decreases as microcracks coalesce onto the eventual fault plane. The changes in SWS before Eyjafjallajökull are interpreted as a similar stress-accumulation increase, as magma penetrates the crust, and stress-relaxation decrease as microcracks coalesce onto the magma conduit prior to magma release. We suggest that the remarkable similarity between stress changes before eruption and earthquake is strong evidence for the New Geophysics of a critically microcracked crust.

Key words: Self-organization; Earthquake interaction, forecasting, and prediction; Volcano seismology.

1 INTRODUCTION
The dispersive ash-cloud summit eruption of Eyjafjallajökull volcano, Iceland, from 2010 April 14, caused severe disruption to air traffic for 6 d across NW Europe. In contrast, the Fimmvörðuháls flank eruption 3 weeks earlier had only local effects. Eyjafjallajökull volcano is fed by magma chambers associated with the opening of the mid-Atlantic Ridge and is one of a chain of volcanoes stretching northwards across Iceland. Its nearest active neighbour is the much-larger Katla volcano ~25 km to the east. It is thought that Eyjafjallajökull and Katla are related tectonically as historically major eruptions of Eyjafjallajökull are associated with eruptions of Katla (Sturkell et al. 2008).

Both eruptions of Eyjafjallajökull were of unusually long duration: ~20 d for the flank eruption; and ~39 d for the summit eruption (Gudmundsson et al. 2011). Sigmundsson et al. (2010) interpret and model these long durations as interactions between magma chambers prior to the eruptions.

Several geophysical techniques have been used to monitor volcanic activity in Iceland. Global Positioning System measurements, geodetic measurements, seismo-tectonics studies and microearthquake locations have provided information about the behaviour of volcanoes and led to a better understanding of processes before volcanic eruptions and earthquakes (Bergerat et al. 1998; Sturkell et al. 2003, 2010; Sigmundsson et al. 2010; Tarasewicz et al. 2012; among others).

In this paper, we use shear wave splitting (SWS) above small earthquakes to monitor stress changes associated with the eruption of Eyjafjallajökull. We show that the behaviour of stress before the volcanic eruption is similar to the behaviour before earthquakes, as is expected in the New Geophysics of a critically microcracked Earth (reviewed by Crampin & Gao 2013).

2 SHEAR WAVE SPLITTING
SWS, analogous to optical birefringence, caused by seismic anisotropy is widely observed for shear wave propagation in almost all sedimentary, igneous and metamorphic rocks in the Earth’s crust (Crampin 1994; Crampin & Peacock 2008). Typically the observed SWS is aligned parallel to the direction of maximum horizontal stress, and this parallelism immediately identifies the cause of the SWS. The only anisotropic symmetry system with parallel shear wave polarizations is hexagonal symmetry (aka ‘transverse isotropy’) with a horizontal axis of cylindrical symmetry (referred to as ‘HTI-symmetry’); and the only source of HTI symmetry common to almost all rocks in the Earth’s crust is stress-aligned fluid-saturated vertical microcracks (Crampin & Peacock 2008).
Thus observations of stress-aligned SWS immediately indicate pervasive distributions of stress-aligned fluid-filled vertical microcracks in almost all crustal rocks. In the uppermost ~400 km of the mantle where stress-aligned SWS with HTI symmetry is also observed (Savage 1999), the anisotropy is likely to be caused by intergranular films of hydrated melt (Crampin 2003).

Note that even when seismic anisotropy is claimed to be due to mineral alignments (from observations of P-wave velocity anisotropy, say, Brocher et al. 1989; Brocher & Christensen 1990), typically the anisotropy can more generally be attributed to stress-aligned fluid-saturated vertical microcracks (in a complex geological terrane, Crampin 1991).

Fluid-saturated microcracks are the most compliant elements of \textit{in situ} rock, and the deformation (evolution) of microcracks under changing conditions can be modelled by anisotropic pore-elasticity (APE) showing that the parameters that control microcrack deformation also control SWS (Crampin & Zatsepin 1997; Crampin 1999a), so that SWS directly monitors stress-induced changes to microcrack geometry (Crampin 1978, 1981, 1999a). Observation of SWS at the surface indicates that the polarization directions of the faster split shear wave are typically parallel to the local direction of maximum horizontal stress (Crampin 1994, 1999a). APE shows that changes in stress modify crack aspect ratios where an increase in stress increases aspect ratios, which affects SWS by increasing the average time delay between two split shear waves in Band-1 directions of the shear wave window (Crampin 1999a). Band-1 directions, sensitive to microcrack aspect ratios, is the double-leafed solid angle of ray path directions between 15° and 45° either side of the average crack plane. The geometry of Band-1 directions is outlined in Fig. S1.

Band-2 directions, within the solid angle 15° either side of the average crack plane (Fig. S1), are sensitive to changes of both crack density and aspect ratio and are difficult to interpret meaningfully (Crampin 1999a; Volti & Crampin 2003a,b). [Note that Band-1 and Band-2 directions are defined for shear wave incidence within the shear wave window (Booth & Crampin 1985) on a plane horizontal free-surface of a homogeneous half-space (Fig. S1). Shear waves are sensitive to topographic irregularities and we shall find that the topographic and geological irregularities at Station GOD, closest to Eyjafjallajökull, extend Band-1 sensitivity to aspect ratios to the whole of the straight line 45° shear wave window.]

Changes in SWS have been observed, retrospectively, before volcanic eruptions (Bianco et al. 1998, 2006; Miller & Savage 2001; Volti & Crampin 2003a,b; Del Pezzo et al. 2004; Gerst & Savage 2004; Savage et al. 2010; Keats et al. 2011; Roman et al. 2011; Johnson & Savage 2012; Johnson & Poland 2013). However, changes in SWS before eruptions are typically complicated by irregular local topography and geology around recording stations. This will be discussed in Section 8.1.

Temporal variations of SWS have also been observed retrospectively before some 15 earthquakes worldwide, where the average time delay in Band-1 directions is observed to increase before impending earthquakes, which is interpreted as stress accumulation (Gao et al. 1998; Volti & Crampin 2003a,b; Gao & Crampin 2004; Crampin & Peacock 2008; Crampin & Gao 2012). On one occasion, an M 5 earthquake in SW Iceland was successfully stress forecast 3 d before it occurred (Crampin et al. 1999, 2004a, 2008), where we use the term ‘earthquake stress-forecast’ rather than ‘earthquake prediction’ or ‘earthquake forecast’ to emphasize the different methodology (Crampin 1999b).

Figure 1. Map of Iceland showing the neo-volcanic zones in purple (after Angelier et al. 2004): NVZ, WVZ and EVZ are the Northern, Western and Eastern Volcanic Zones, respectively. SISZ is the South Iceland Seismic Zone. Yellow arrows indicate plate motion with respect to mid-Atlantic Ridge. Red arrows refer to directions of regional extension. The box outlines the area of the Eyjafjallajökull and Katla volcanoes.

3 GEOLOGY AND EARTHQUAKE ACTIVITY

3.1 Geology

Iceland is on an offset of the mid-Atlantic Ridge, where the North American and European tectonic plates are moving apart at ~25 mm yr\(^{-1}\), and has frequent earthquakes and volcanic eruptions. The neo-volcanic zones in Iceland are a Northern Volcanic Zone (NVZ), a Western Volcanic Zone (WVZ) and an Eastern Volcanic Zone (EVZ; Einarsen & Sæmundsson 1987) shown in Fig. 1 (after Angelier et al. 2004). The divergence is taken up by the two parallel rift zones, WVZ and EVZ. EVZ and WVZ are connected in the south by the South Iceland Seismic Zone (SISZ). Eyjafjallajökull volcano is located south of the intersection of EVZ and SISZ.

Eyjafjallajökull, at the SW end of EVZ, is a 1650 m-high stratovolcano with a crater 3–4 km in diameter. The vents trend EW, and eject basalt and andesite lavas. The EW elongated Eyjafjallajökull volcano is linked to the much larger and more dangerous Katla volcano through east–west striking faults and eruptive fissures (Sturkell et al. 2003, 2010; Pedersen & Sigmundsson 2004, 2006). Eyjafjallajökull volcano has erupted several times since the last ice age, with major eruptions occurring in 1612, from 1821 to 1823 and in 1921. Several previous eruptions of Eyjafjallajökull have been associated with eruptions at Katla, and the eruption of Eyjafjallajökull 2010 March to April generated international interest in possible future eruption of Katla.

3.2 Earthquake activity

The seismicity map (Fig. 2a) shows seismic activity around Eyjafjallajökull from 2009 January to 2010 June spanning the March and April eruptions. The map shows the six nearest stations of the seismic monitoring network. Fig. 2(b) is the magnitude–time distribution of microearthquakes around Eyjafjallajökull, 2009 January to 2010 June, from Iceland Meteorological Office, IMO, catalogue data. The earthquake magnitudes are small: 98 per cent being less than M 2.5, with only five events larger than M 3; the largest being an M 3.6 earthquake during the flank eruption. The depths of
Figure 2. (a) Seismicity from 2009 January to 2010 June around Eyjafjallajökull volcano. Stars are Eyjafjallajökull and Katla volcanoes and Fimmvörðuháls flank eruption, marked E, K and F, respectively. Triangles are the six nearest stations of the nine-station seismic monitoring network. (b) Magnitude–time distribution of seismicity from 2009 January to 2010 June, where F and E mark onsets of the flank and the summit eruptions, respectively.

The seismic activity increased during 2009, and from the beginning of 2010, some 3000 earthquakes were recorded beneath the volcano before the initial eruption. On 2010 March 20, a basaltic fissure eruption began at Fimmvörðuháls on the eastern flank of Eyjafjallajökull and continued until 2010 April 12 (Tarasewicz et al. 2012). In 2010 April, seismic activity increased with thousands of small earthquakes beneath the volcano, interpreted as the emplacement of intrusions at depth. On 2010 April 14, an explosive eruption began at the summit of Eyjafjallajökull, some 8 km west of the previous flank eruption and continued intermittently for ~39 d (Sigmundsson et al. 2010). Stevenson et al. (2012) describe the extensive distal deposition of tephra from the summit eruption. Following the summit eruption, seismic activity decreased, and by the end of 2010 June had returned to the level before the eruptions.

4 DATA PROCESSING AT SEISMIC STATION GOD

Three-component waveforms of shear waves recorded at the free surface are similar to (but twice the amplitude of) the incidence waveforms only within the shear wave window, which has a critical radius of incidence of ~35° for a flat isotropic half-space with a Poisson’s ratio of 0.25 (Booth & Crampin 1985). Outside this critical angle, incident shear wave forms are heavily distorted by S-to-P conversions. However, because of curved wave fronts and near-surface low-velocity layers (caused by weathering, stress release and other phenomena), the critical angle can effectively be increased. In this paper, we use 45° as the straight-line (source-to-receiver) critical angle of the shear wave window.

4.1 Station GOD

Of the six seismic stations in Fig. 2(a), only Station GOD sited midway between Eyjafjallajökull and Katla recorded sufficient shear wave arrivals within the shear wave window to monitor variations of SWS. GOD is located on a broad ice-free ridge of Katla where the comparatively flat local topography (Fig. 3) around the station allows SWS to be monitored and time delays interpreted. Earthquakes in the shear wave window at GOD have a magnitude range from $M_0$ to $M_3$, and a range of depths from immediately below the ice (0 km) to 23 km (Fig. 4).

Tarasewicz et al. (2011) have suggested that, because of the absence of seismic stations in the ice fields immediately above the swarm of small earthquakes, the IMO earthquake locations are too deep (by a factor averaging about two). However, if the 89 earthquakes we analyse were shallower by a factor of two, most of the earthquakes to the west of GOD in Fig. 4 would be outside the shear wave window for GOD, and the shear wave arrivals would be expected to be highly disturbed. This is not observed. Similarly, since we normalize time delays by focal depths, decreasing focal depths by a factor of two would make the time delays at GOD larger than those elsewhere in Iceland. We have found that normalizing traveltimes by the length of the ray paths provides a convenient generalization that allows stress-accumulation increases and

Figure 3. Map (2.5 km × 2.5 km) of 100 m contours and cross-sections of the topography at station GOD with 1:1 scale. Blue is the Mýrdalsjökull ice cap overlying Katla as of 2009 February.
Changes in SWS before Eyjafjallajökull

Figure 4. Seismicity map and cross-sections of hypocentres from 2009 January to 2010 June within the 45° shear wave window at GOD. Black triangles are seismic station GOD. Stars are Eyjafjallajökull and Katla volcanoes and the Fimmvörðuháls flank eruption, marked E, K and F, respectively. Black circles are the tight cluster of earthquakes beneath the flank eruption with approximately the same location.

Crack-coalescence decreases to be visible despite the large scatter invariable associated with SWS above small earthquakes (Crampin et al. 2004b). (This normalization is justified in the Appendix.) The regular behaviour of shear waves and SWS above the earthquakes at GOD suggests that focal depths are within the effective shear wave window. It is possible that seismic arrivals within the shear wave window of station GOD provide, at least locally, enough control to determine accurate focal depths. This is supported by the events associated with the flank eruption, shown in black in Fig. 4. They are expected to be close to each other, and are located within a ~2-km-diameter spherical volume, which suggests that both depths and epicentre locations have comparatively small relative errors. This tight cluster of events is discussed in Section 8.2.

4.2 Data processing

The complexity of the topography near Eyjafjallajökull makes it difficult to accurately measure and assess SWS parameters (see Section 8.1). Several techniques have been developed to measure polarizations and time delays of seismic SWS (Crampin & Gao 2006). Visual inspection of particle-motion diagrams is subjective, but potentially most accurate. Visual inspection avoids cycle skipping, which is a common problem in automatic and semi-automatic analyses of SWS (Crampin & Gao 2006). Almost all shear wave arrivals within the shear wave window show abrupt changes in direction and linear motion in particle motion diagrams strongly diagnostic of some form of anisotropy-induced SWS. In many records, however, the arrivals of shear wave could not be picked accurately because of the complexity of shear waves and disturbances by P- and S-generated phases. Using visual inspection, at 100 samples per second, we analyse 20 sample points before and 40 sample points after visually picked shear wave arrivals (from IMO catalogue data), in four 20-sample polarization diagrams. A typical example is shown in Fig. 5: the near-linear polarization of shear waves following the shear wave arrival is assumed to be the polarization of the faster split shear wave, S1 (Diagram 2). The next abrupt change of direction is assumed to be the arrival of the slower split shear wave, S2 (Diagrams 2 and 3). The estimated time delay in seconds is time(S2) minus time(S1), which in Fig. 5 equals 16 samples (0.16 s).

To eliminate the effects of severe shallow irregularities, especially interactions with the surface ice layers, we process earthquakes only for depths between 3 and 20 km within an effective straight-line shear wave window of 45° (Fig. 4) with signal-to-noise ratios

Figure 5. An example of visual measurement of polarization direction of the faster wave and time delay of two split shear waves. (a) Three-component seismograms at station GOD of M 1.03 earthquake, 2010 March 16, at 100 samples per second (marked ‡ in Table S1). From top, seismograms are vertical, N–S, and E–W components. The four vertical lines mark three 20-sample segments starting 20 samples before the IMO-picked shear wave arrival. (b) The four diagrams are polarization diagrams of the shear waves in the marked segments in (a), in a 1:1 scale. Diagram (1) is the polarization diagram 20 samples before the shear wave arrival. Diagram (2) is the polarization diagram of 20 samples after the shear wave arrival. Diagram (3) is the polarization diagram of the next 20 samples. Diagram (4) is an enlargement of (1). Arrows mark directions of particle motion. Larger dots mark start of each trace. S1 is the start of faster and S2 the slower split shear wave arrivals.
We obtain 89 reliable estimates of SWS parameters at GOD station from 2009 January to 2010 June. The parameters of the earthquakes, time delays and normalized time delays are listed in Table S1.

5 POLARIZATION DIRECTIONS OF THE FASTER SPLIT SHEAR WAVES

Fig. 6 is an equal-area polar projection of polarizations of the faster split shear wave arrivals within the effective 45° shear wave window at Station GOD, showing polarizations mostly in the NE direction, with minimal scatter. NE polarization directions are typical of SWS polarizations in SW Iceland (Volti & Crampin 2003a,b). The surface topography around GOD in Fig. 3 has undulations with an ∼10° slope in EW direction, which may disturb events in the western edge of shear wave window. The polarizations in Fig. 6 show a concentration of events at the western edge associated with the flank eruption. The nearly uniform NE polarizations suggest that the selected shear waves are not seriously affected by topography at GOD and the use of the effective critical angle of 45° appears justified. The uniformity suggests that the earthquakes are within the shear wave window at GOD, so that Band-1 sensitivity to aspect ratio extends to the whole of the straight line 45° window. The small number of nearly orthogonal polarizations in blue are probably 90° flips in polarizations caused by ray paths passing through volumes with the critical pore-fluid pressures found on all seismically active fault planes (Angerer et al. 2002; Crampin et al. 2002, 2004b), and presumably in pressure-driven eruptions. The inset to the left-hand side shows (enlarged) polarizations of the tight cluster of small earthquakes beneath the flank eruption.

Polarization directions of faster split shear waves are typically parallel to the strike of nearby, high-angle microcracks and parallel to the direction of the maximum horizontal compressional stress (Crampin 1994; Crampin & Peacock 2005, 2008). Microcracks open normal to the direction of 'minimum' compressional stress, which, below near-surface stress-release and weathering anomalies, is typically horizontal. Consequently, microcracks tend to be aligned vertically with HTI symmetry so that initial SWS polarizations are parallel to the direction of 'maximum' horizontal stress (Crampin 1999a).

The NE–SW stress field has been observed in southern Iceland in other geophysical studies (Bergerat et al. 1998; Volti & Crampin 2003b; Angelier et al. 2004). These include focal mechanisms of swarms of small earthquakes in the South Icelandic Seismic Zone (SISZ), where the main fault trends are close to NS and NE–SW (Bergerat et al. 1998). Relocated microearthquakes under the Fimmvörðuháls flank volcano at Eyjafjallajökull typically align with several NE–SW striking dykes, and are again consistent with the polarization direction of faster shear wave from SWS (Tarasewicz et al. 2012). This also indicates that, as expected, the strike of dykes is parallel the direction of the local stress field.

6 VARIATION OF TIME DELAYS BETWEEN SPLIT SHEAR WAVES

Fig. 7(a) shows temporal variations of SWS time delays in Band-1 and Band-2 directions from 2009 January to 2010 June, where the black data points refer to the tight cluster of earthquakes in Fig. 4 below the flank eruption. Fig. 7(b) shows the 'classic' Band-2 time delays from Fig. 7(a) to demonstrate that at Station GOD, Band-1 aspect-ratio sensitivity appears to extend to the whole of the straight line 45° shear wave window.

Deriving error bars from visual analysis is problematical. The error bars on Eyjafjallajökull time delay data points are based on errors of the normalizing path length, and are standard errors (multiplied by six to make them visible in the plots). Normalizing time delays to ms km⁻¹ is justified in the Appendix.

The time delays in Fig. 7(a) have marked variations from about 250 d (8 months) before the flank eruption. The time delays show an approximately linear increase from ∼250 to ∼30 d before the flank eruption, when there is an abrupt change of slope at a level of time delays of about 23 ms km⁻¹. The normalized time delays then decrease linearly to the start of the flank eruption, where the time delays are at about the same level as at the start of the increase. This range of normalized SWS time-delay variations up to 23 ms km⁻¹.
is approximately 50 per cent greater than the range of normalized SWS typically found before earthquakes elsewhere in Iceland (Volti & Crampin 2003b; Crampin & Gao 2012). This difference is thought to be due to different behaviour of volcanic seismicity and seismic velocities in the volcanic edifice beneath Eyjafjallajökull from that found elsewhere in Iceland. Alternatively, it could be that the time-delay normalizing seismic depths from IMO location data are too shallow, although Tarasewicz et al. (2011) suggested they were too deep.

Similar increases and decreases in time delays have been observed retrospectively before two other volcanic eruptions: the 1996 Vatnajökull–Gjálp eruption, in Iceland (Volti & Crampin 2003b), and a 2001 Etna eruption, in Sicily (Bianco et al. 2006); and before ∼16 earthquakes worldwide (Crampin et al. 1990, 2008; Gao et al. 1998; Gao & Crampin 2004; Crampin & Gao 2005, 2012). The characteristic time-delay increases and decreases are observed to be very similar before both earthquakes and volcanic eruptions.

The decrease in time delays for earthquakes is interpreted as stress relaxation as microcracks coalesce onto the eventual fault plane (Crampin & Gao 2013). The decrease in time delays for eruptions is interpreted as stress relaxation as microcracks coalesce onto the conduit for the eruption of magma.

Previously, Voight (1988) interpreted the linearity in various observations of seismicity before eruptions as power laws, opening the possibility of prediction of volcanic eruptions. Thus, Voight is an early recognition of the effects of the critical rockmass, which leads to the New Geophysics (Crampin & Gao 2013). However, Voight did not identify the source of the criticality (which we identify as distributions of closely spaced fluid-saturated stress-aligned microcracks), and his suggestions were not followed up by other investigations.

In previous studies of SWS, the splitting at largely horizontal free surfaces behaved very differently in Band-1 and Band-2 directions of the shear wave window. APE shows that increasing stress increases crack aspect ratios, and hence, increases the average SWS time delay in Band-1 directions in Fig. S1 (Crampin 1999a). Theoretically, for a horizontal free surface, time delays in Band-1 directions are sensitive to crack aspect ratios and hence to changes of stress, whereas time delays in Band-2 directions are sensitive both to crack aspect ratios and crack densities (Crampin 1999a). Observationally, time delays in Band-2 directions typically do not display characteristic behaviour before earthquakes or volcanic eruptions and are generally ignored (Volti & Crampin 2003b; Crampin & Peacock 2008). Fig. 7(a) shows that at Station GOD, the small number of Band-2 data points in Fig. 7(b) overlap Band-1 points in Fig. 7(a) almost exactly. This is presumably due to the local variations of structure and topography modifying ray path interactions with the free surface, where ray path curvature tends to eliminate most Band-2 directions at GOD. This suggests that the measurements are realistic and that we have estimated a reliable selection of data points.

7 COMPARISON OF TIME DELAYS BEFORE EYJAFJALLAJÖKULL ERUPTION AND BEFORE A NEIGHBOURING EARTHQUAKE

Fig. 8 compares variations in SWS time delays before (a) Eyjafjallajökull eruption with (b) variations before a neighbouring earthquake in Iceland, some 12 yr earlier. The left-hand side (LHS) of Fig. 8(a) shows the data points of Fig. 7(a), with a least-squares regression line. There is a red-dotted box outlining the decreasing stress-relaxation data points. The right-hand side (RHS) shows the data in the red-dotted box with an expanded timescale in days. Fig. 8(b) shows similar variations for an M 5 earthquake 1998 November 11, in SW Iceland (from fig. 1c, Gao & Crampin 2004) with similar format and stress-accumulation (LHS) and stress-relaxation (RHS) notation. This earthquake was the successfully stress-forecast event (Crampin et al. 1999, 2004a, 2008), and is some 90 km west of GOD.

There are strong similarities between Fig. 8(a) for Eyjafjallajökull volcano and Fig. 8(b) for the M 5 earthquake. The actual levels of normalized time delays, and the slopes and durations of the stress-accumulation and stress-relaxation regression lines are different, as would be expected of different phenomena with necessarily different magnitudes and timescales. However, the characteristic linear stress-accumulation increases and stress-relaxation decreases are remarkably similar and imply that the fundamental behaviour of stress variations before volcanic eruptions and earthquakes is similar.

These similarities are important as the numbers of data sets are limited, and we need to fully evaluate what data we have. There are 15 retrospective observations of SWS changes before earthquakes ranging from an M 1.7 earthquake swarm event in N Iceland to the
8 DISCUSSION

8.1 Effects of the shear wave window

Observations of shear waves and SWS at the free surface need to be recorded within the shear wave window (incidence angles at surface recorders less than $\sin^{-1}V_s/V_p \approx 35^\circ$, Booth & Crampin 1985) to avoid severe disruption of shear waveforms by S-t-P conversions at the free surface. Waveforms of shear waves recorded outside the window are far too irregular and sensitive to minor topographic irregularities to be usefully analysed (Booth & Crampin 1985). Since, seismic stations monitoring volcanoes are typically sited on highly irregular topography, we were fortunate that one station, GOD at Eyjafjallajökull, immediately above seismicity (Fig. 2a), was located on a broad shallow ridge with comparatively flat topography (Fig. 3), so that many shear wave arrivals were in effective Band-1 directions on a broad shallow ridge with comparatively flat topography (Crampin et al. 1999, 2004a; Crampin & Gao 2013).

There are currently just three reports of (retrospective) observations of SWS changes before volcanic eruptions that can be interpreted in terms of stress accumulation and stress relaxation (Volpi & Crampin 2003b; Bianco et al. 2006; and this paper). Thus, Fig. 8, confirming that variations in SWS before 16 earthquakes and three eruptions are similar, as expected from the New Geophysics of Crampin & Gao (2013), suggests that the stress before ‘all’ volcanic eruptions, as has been found before ‘all’ earthquakes, has uniform behaviour and effectively extends each set of observations (Crampin & Gao 2013). This indicates that the times, magnitudes, and in some circumstances fault-breaks, of impending earthquakes and the times of volcanic eruptions, can be stress forecast.

8.2 Temporal not spatial changes in SWS

The normalized time delays in Figs 7 and 8 are based on evolving seismicity with variable shear wave source event locations, and could contain a mixture of temporal changes (stress-induced changes to microcrack geometry) and spatial changes (migration of source events). This has sometimes caused controversy between those favouring shear wave source migration (Liu et al. 2004, 2005) and others (e.g. the map of fig. 1 of Savage et al. 2010). This severely limits interpretation of SWS. The simplicity of the immediately local topography around Station GOD (Fig. 3) in this study is an important attribute that makes interpretation of SWS possible. Stations MNT and ESP on the flanks of Mt Etna (Bianco et al. 2006) are also on locally flat topography.

The simple stress-accumulation and stress-relaxation analysis for ray paths in Band-1 directions (Fig. S1) within the shear wave window, also results in the polarizations of faster split shear waves being typically parallel to local directions of maximum horizontal stress, (with the possibility of occasional 90° flips in polarizations, as in Fig. 6, of shear wave ray paths passing through or near the critical pore-fluid pressures on all seismically active fault planes, Angerer et al. 2002; Crampin et al. 2002, 2004b). Observations of parallelism of SWS may be used to assess whether ray paths are within the shear wave window, as in Fig. 6. Shear waves arrivals outside the shear wave window, particularly through the irregular volcanic geology and topography around volcanoes, are subject to highly irregular internal interfaces (including numerous structure-induced internal shear wave windows, Liu & Crampin 1990), which severely disrupt shear wave polarizations. Such irregular behaviour makes meaningful interpretation of shear wave polarizations impossible.
20 d before the flank eruption in Fig. 7 (and the RHS of Fig. 8a), for the decreasing, stress-relaxation time delays. Fig. 11 shows the normalized time delays with variations between 5 and 20 ms km$^{-1}$ from Fig. 7 with the tight-cluster data points in black. The black-squares regression line is the same as Fig. 7(a).

Fig. 11 shows the typical large scatter in observations of time delays above small earthquakes due to 90° flips in shear wave polarizations caused by critically high pore-fluid pressures on all seismically active faults (Crampin et al. 2002, 2004b). The substantial scatter is caused by temporal variations in SWS along similar ray paths from earthquake to receiver passing through the narrow volumes of locally high pore-fluid pressure associated with all seismically active fault planes (Crampin et al. 2002, 2004b). Thus the scatter suggests that the variations are due to temporal variations in SWS, rather than spatial variations/migration of earthquake source events. However, a reviewer pointed out that the scatter could also be caused by small variations in location in regions of highly variable anisotropy having similar effects. Consequently, the issue in this example in Fig. 11 is to some extent unresolved.

However, the main argument for temporal variations is much stronger (Crampin & Gao 2005). Similar characteristic behaviour is seen before widely different events, as in Figs 8(a) and (b), and ~16 events earthquakes reported elsewhere (Crampin et al. 2008; Crampin & Peacock 2008; Crampin & Gao 2012, 2013) and two other eruptions (Volti & Crampin 2003b; Bianco et al. 2006). These temporal variations can be explained by the nearly universal behaviour of stress accumulation and stress relaxation before earthquakes and eruptions as modelled by anisotropic poroelasticity (Crampin & Zatsepin 1997). These arguments are expanded in Crampin & Gao (2005).

To explain these similar patterns of variations in SWS by spatial migration of shear wave source events, would mean that systematic patterns of hypocentral migration of source events occurred at arbitrary swarms of (source)events before impeding, possibly distant, large or larger earthquakes. The timing of these migrations of arbitrary swarms would need to be triggered by impending earthquakes that have no direct association with the source events, which may be at very large distances (as large as the width of the Eurasian Plate, Crampin & Gao 2012). This argument is we suggest untenable (Crampin & Gao 2005), and variations in SWS time delays are necessarily temporal variations in time delays rather than migrations of source events.

8.3 Variations between eruptions and earthquakes

As with each earthquake, each volcanic eruption modifies the stress and pressure regime surrounding the event, so that SWS, sensitive to stress-induced modifications of microcrack geometry, can be used to monitor stress changes before and after eruptions. In this paper, we have analysed SWS polarization directions and time delays at seismic station GOD, showing that polarization directions are compatible with other geophysical measurements: SWS time delays have an approximately linear stress-accumulation increase and linear stress-relaxation decrease before the Eyjafjallajökull eruption. Similar variations are observed before both eruptions and earthquakes.
For earthquakes, the durations of stress accumulation and stress relaxation are both proportional to the seismic magnitude (logarithm of radiated energy). Volcanic eruptions do not have a simple single measure of size. Eruptions vary substantially with: volume of ejected magma; nature of magma (acidic, ultrabasic, andesic, basaltic); rate of magma ejection from explosive (Plinian) to nearly continuous; among other phenomena. It must be expected that parameters vary substantially with varying types of eruption. The similarity between stress variations before earthquakes and the volcanic eruption in this paper suggests that the duration of stress accumulation before eruptions in Fig. 8(a) might be a useful measure of eruption size, as it is for earthquake magnitude in Fig. 8(b; Crampin & Gao 2013).

9 CONCLUSIONS

(1) The times of at least some types of eruptions can be stress forecast by using SWS above small earthquakes to monitor changes in stress accumulation and stress relaxation possibly days, weeks or months, before the actual eruption. For example, if the stress-relaxation decrease in Fig. 7(a) were recognized, half way into the 16-d width of the black-dotted box, say, the time of the impending (flank) eruption could be stress forecast as the time of intersection of the downward slope with the level of the initial (background) time delays. From the data in Fig. 7(a), this could have been estimated approximately a week before the flank eruption.

A major difficulty in this analysis is that the variations in SWS in Fig. 7(a) do not distinguish between an impending eruption and an impending earthquake, as is demonstrated in the similarities between Figs 8(a) and (b). Distinguishing eruptions from earthquakes would need to rely on observations of the other numerous precursory geophysical phenomena before eruptions, which are typically absent before earthquakes.

(2) Numerous geophysical phenomena are observed to vary before eruptions, but the variations in SWS time delays in Band-1 directions, presented here, are believed to be the first geophysical precursors that can directly give advanced warning of the time of, at least some types of, impending eruption.

(3) Similarities between eruptions and earthquakes in Fig. 8 suggest that the effects of stress changes on fluid-saturated microcracks are universal. They confirm a similarity between eruptions and earthquakes that has been suggested previously (Volti & Crampin 2003a,b; Bianco et al. 2006; Crampin & Peacock 2008) and are specifically expected in the New Geophysics. The similarities in the behaviour of SWS before eruptions and earthquakes lend strong support for the New Geophysics of a critically microcracked rock mass reviewed by Crampin & Gao (2013).

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Such normalized time delays show characteristic stress-accumulation increases and stress-relaxation decreases whenever there is appropriate ray path geometry and impending large or larger earthquakes nearby (Crampin & Peacock 2008; Crampin & Gao 2013). The SWS time-delay variations before the impending Eyjafjallajökull eruption in Fig. 7(a) also show the characteristic patterns of SWS behaviour as seen before earthquakes. Since these source events are from a comparatively small swarm of earthquakes, where depth is the largest difference in location (Figs 9 and 10), we are able to examine the justification for normalizing time delays to ms km$^{-1}$ by length of ray path.

Figs 9 and 10 plot focal depths for the same events and same time interval as appear in Fig. 7(a). There is a substantial variation of depths between $\sim$20 km and the limiting depth of 3 km both in the increasing and decreasing SWS time delays before the flank eruptions and in the time delays during and after the summit eruption. Despite this considerable variation in the length of the normalizing ray paths (varying by a factor $\sim$7), the normalized values in Fig. 7(a) follow the stress-accumulation increases and stress-relaxation decreases as seen before earthquakes with minimal scatter (Crampin & Peacock 2008) as expected from the fundamental new properties of New Geophysics in Table S2.

Table S1 lists the parameters of the shear wave source events. The reason for the smooth variations in Fig. 7(a) is that the ‘larger’ normalizing depths in Fig. 9(a) occur for earthquakes that have ‘larger’ values of time delays in Table S1, so the normalized values of time delay (ms km$^{-1}$) lie close to the smooth variations of the other normalized arrivals.

The underlying reason for this persistence is that the critical New Geophysics imposes fundamental new critical properties on conventional subcritical geophysics (Crampin & Gao 2013). One of the effects is that critical crack-induced anisotropy, as evidenced by the degree of SWS, is persistent and occurs, with a similar degree of splitting, in almost all in situ rocks, so that normalizing SWS time delays by path length (in the case of this study by depth) to ms km$^{-1}$ is justified as it retrieves the smooth values in Fig. 7(a). This persistence was noted (with astonishment) when the extent of SWS was first recognized (Crampin 1994), as the persistence appears to pervade almost all in situ rocks, certainly above small earthquakes.

Note that the effects of the New Geophysics of in situ rock pervaded by critical systems of fluid-saturated stress-aligned microcracks cannot be understood from experience based on conventional subcritical geophysics. A paradigm shift in understanding is required. Normalizing to ms km$^{-1}$ is justified as New Geophysics demonstrates that the degree of SWS is persistent throughout most rocks in the crust.

**SUPPORTING INFORMATION**

Additional Supporting Information may be found in the online version of this article:

**Figure S1.** Ray-path geometry for observing undisturbed waveforms of $SV$-waves and SWS in stress-aligned fluid-saturated microcracks at a horizontal free-surface. ABSCD is a crack-plane through distributions of parallel-vertical microcracks, where S is the recorder on a horizontal free-surface. Band-1 directions to the free-surface, where time-delays are sensitive to crack aspect-ratio (Crampin 1999a) are within the solid angle EFGH-to-S subtending 15° to 45° to the crack plane within the effective shear wave window. Band-2 directions to the free-surface, where time-delays are dominated by crack-density (Crampin 1999a), are within the solid angle ADEHG-to-S to the crack plane. Both Band-1 and Band-2 directions include equivalent solid-angle directions reflected in the far side of the imaged crack-plane ABCD.

**Table S1.** Properties of shear wave source events, time-delays (dt), and normalized time-delays (ndt) in Fig. 7(a).


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