A review of retrospective stress-forecasts of earthquakes and eruptions

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Abstract

Changes in shear-wave splitting (SWS) monitor stress-induced changes to the geometry of the stress-aligned fluid-saturated microcracks pervading almost all sedimentary, igneous, and metamorphic rocks in the Earth’s crust and upper mantle. Changes in SWS implying stress–accumulation and stress–relaxation (suggesting crack-coalescence) before large earthquakes have been observed retrospectively in the rock mass surrounding large or larger earthquakes. In one case, the time, magnitude, and fault-plane of a M 5 earthquake in SW Iceland, was successfully stress-forecast 3 days before it occurred. Similar characteristic behaviour of shear-wave splitting has been observed retrospectively before ~17 other earthquakes and before three volcanic eruptions. These retrospective stress-forecasts have been published in different formats in different journals. For clarification, this paper redraws all observations of stress–accumulation and stress–relaxation in a consistent normalised format that allows the overall similarities in behaviour to be recognised before earthquakes and volcanic eruptions. Such behaviour, inconsistent with conventional sub-critical geophysics, confirms the compliance of the New Geophysics of a critically microcracked Earth, where the microcracks are so closely-spaced that they verge on failure and hence are critical-systems that impose a range of fundamentally-new properties on conventional sub-critical geophysics. One of the implications of New Geophysics is that there are similarities in the behaviour of stress before earthquakes and volcanic eruptions. The normalised formats show such similarities and include the opportunity to stress-forecast both earthquakes and eruptions.

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1. Introduction

Worldwide observations of shear-wave splitting (SWS) show that rocks throughout the upper- and lower-crust and upper mantle are pervaded by distributions of stress-aligned fluid-saturated typically-vertically-oriented microcracks (Crampin, 1994; Helbig and Thomsen, 2005; Crampin and Peacock, 2008). In the uppermost ~400 km of the mantle, where SWS is also observed (Savage, 1999), the ‘microcracks’ are arguably intergranular films of hydrated melt (Crampin, 2003). The degree of observed shear-wave velocity anisotropy (SWVA) shows that microcracks are so closely-spaced that they verge on fracturing and the occurrence of earthquakes (Crampin, 1994; Crampin and Peacock, 2008). Phenomena that verge on failure are critical-systems in a New Physics (Davies, 1989) (hence a New Geophysics) which imposes a range of sub-critical physics/geophysics with wholly-new implications and applications (Davies, 1989). Appendix A is a brief outline of New Geophysics (Crampin and Gao, 2013) and Table A1 lists some of these fundamentally-new properties. We shall show that the criticality of the microcrack geometry and application of these properties allows earthquakes and volcanic eruptions to be stress-forecast, where the process is referred to as stress-forecasting, rather than forecasting or predicting earthquakes and eruptions, to emphasise the different methodology.

After 35 years since SWS was first identified in the crust (Crampin et al., 1980) and upper mantle (Ando et al., 1980), there is still discussion over the cause of SWS in both crust and mantle. Suggestions have included various combinations of preferentially-oriented: anisotropic mineral grains; multiple layers; small scale inhomogeneities, joints, cracks, and microcracks; lattice-preferred orientation; shape-preferred orientation; and others (Svitak et al., 2014; Xie et al., 2015). However, two over-riding observational constraints restrict possible causes. (1) The preferred orientations of SWS in the upper- and lower-crust, and the upper-most ~400 km of the mantle (Savage, 1999), are parallel in the direction of maximum horizontal stress. (2) Changes in SWS have been observed, particularly changes in SWS time-delays (Crampin et al., 1999, 2008; Crampin and Gao, 2013).

1. The preferred orientations of SWS: anisotropic symmetry systems demonstrate (Chen et al., 1993) that only symmetry system with (stress) aligned parallel polarizations within the shear-wave window at a horizontal free surface is hexagonal symmetry (transverse-isotropy) with a horizontal axis of symmetry (HTI) in the direction of minimum stress. The only geological phenomenon with such HTI-symmetry are the pervasive distributions of vertically-oriented microcracks striking parallel to the direction of the maximum stress (perpendicular to the direction of minimum stress) which is typically horizontal (Crampin, 1994; Crampin and Peacock, 2008). Distributions of parallel vertical thin layers or metamorphic re-crystallisation in slates and schists, may also have TIH-symmetry, but such formations are rare and seldom uniform over tens of kilometres of lateral and vertical extent as observed by SWS.

2. Changes in SWS: Fluid-saturated stress-aligned microcracks are the only geological phenomenon which responds almost immediately to small changes of stress (Crampin, 1994, 1999).

Consequently, the only common geological phenomenon that satisfies the two observational criteria are distributions of stress-aligned fluid-saturated microcracks (intergranular films of hydrated melt in the mantle), and the cause of SWS is necessarily stress-aligned fluid-saturated microcracks (Crampin, 1994; Crampin and Peacock, 2005, 2008).

Swarms of small earthquakes are used as the source of shear-waves. By analysing changes in SWS within the shear-wave window at the surface, we monitor changes in the stress-induced behaviour of microcracks along shear-wave ray-paths in the rock mass above the swarm. [The shear-wave window is specified in Appendix B.] These changes typically show stress-accumulation before impending events that may be very close: ~2 km either side of a flank eruption on Mt Etna, Sicily (Bianco et al., 2006); ~2 km from the epicentre in the first successfully-stress-forecast (M 5) earthquake in SW Iceland (Crampin et al., 1999, 2004a, 2008); or very distant, changes in SWS before the 2004 Mw 9.2 Sumatra Earthquake were observed in Iceland at a distance of ~10,500 km, the width of the Eurasian Plate, from Indonesia (Crampin and Gao, 2012). Such extreme sensitivity is expected in critical-systems (Property P8 Sensitivity in Table A1).

Retrospective observations of stress-forecast earthquakes have been published in different formats in different journals. For clarification, this paper re-draws all known observations of stress-accumulation and stress-relaxation before the 18 earthquakes listed in Table 1, and before three volcanic eruptions listed in Table 2, where the SWS time-delays are plotted in a consistent normalised format in Figs. 1 and 2 so that overall similarities in behaviour may be recognised. These figures have minimal descriptions and the reader is referred to the original publications listed in Table 1 and 2 for comprehensive discussions. Fig. 1 displays in one diagram the characteristic behaviour before impending earthquakes that shows observations of SWS can stress-forecast the time, magnitude and in some circumstances location of impending earthquakes. Fig. 2 shows similar behaviour before volcanic eruptions.

2. Observations of stress-accumulation and stress-relaxation (crack coalescence)

Observations of SWS time-delays above swarms of small earthquakes are subject to a large scatter (sometimes referred to as a “±80%” scatter Crampin, 2006). Controlled-source signals in exploration seismics do not show such scatter (Li and Crampin, 1991). The scatter is the result of 90°-flips (Angerer et al., 2002) in SWS polarisations whenever shear-waves penetrate or exit the critically-high pore-fluid-pressure envelopes surrounding all seismically-active fault-planes (Crampin et al., 2002, 2004b). Such 90°-flips reverse the sign of time-delays, and the combination of flipped and unflipped observations on different but closely-spaced ray-paths accounts for the ±80% scatter seen in all observations of SWS time-delays above swarms of small earthquakes (Crampin et al., 2004b), including the observations in Figs. 1 and 2. Although the behaviour can be modelled and calculated given known initial conditions in controlled-source environments (Angerer et al., 2002), the observed scatter above small earthquakes cannot generally be exactly matched or eliminated, as the scatter depends critically on miniscule details of the initial conditions at depth in the rock mass, which are essentially unknown and unknowable (Crampin et al., 2002, 2004b).
Earthquakes release stress by slippage on fault-planes, which can only occur when sufficient strain-energy has accumulated for release by the appropriate magnitude earthquake. Apart from repetitive bi-diurnal tidal effects, the principal changes of strain and stress in the Earth are caused by interactions at the boundaries of tectonic plates: plate generation and spreading at oceanic ridges; and plate subduction at plate margins as plates are thrust beneath each other. Initially stress-accumulation from interactions at plate boundaries is widely distributed and independent of the location, mechanism, and circumstances of the eventual stress-release by impending earthquakes (Crumplin, 1994, 1999; Crumplin and Peacock, 2000; Peacock and Crumplin, 2000), and the uppermost ~400 km

2.1. Stress-accumulation

Earthquakes can only occur when sufficient strain-energy has accumulated for release by the appropriate magnitude earthquake. Apart from repetitive bi-diurnal tidal effects, the principal changes of strain and stress in the Earth are caused by interactions at the boundaries of tectonic plates: plate generation and spreading at oceanic ridges; and plate subduction at plate margins as plates are thrust beneath each other. Initially stress-accumulation from interactions at plate boundaries is widely distributed and independent of the location, mechanism, and circumstances of the eventual stress-release by impending earthquakes (Crumplin, 1994, 1999; Crumplin and Peacock, 2000), and the uppermost ~400 km

Table 1
Seismic stations (Fig. 1) where retrospective earthquake stress-forecasts have been observed in order of increasing earthquake magnitude with duration in of stress-accumulation and stress-relaxation. The successful stress-forecast is included as Eq. No. 10.

<table>
<thead>
<tr>
<th>Eq. No. (Fig. No)</th>
<th>Magn</th>
<th>Earthquake identifier; Recording location</th>
<th>Year</th>
<th>Seismic station</th>
<th>Duration of stress-acc (days)</th>
<th>Duration of stress-rel (days)</th>
<th>Refs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>M1.7</td>
<td>Swarm event; N Iceland</td>
<td>2002</td>
<td>BSE</td>
<td>&gt;0.055</td>
<td>0.036</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>M2.5</td>
<td>Swarm event; N Iceland</td>
<td>2002</td>
<td>BSE</td>
<td>&gt;0.021</td>
<td>0.046</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>M3.4</td>
<td>SW Iceland; SW Iceland</td>
<td>1997</td>
<td>BJA</td>
<td>47</td>
<td>z</td>
<td>[2]</td>
</tr>
<tr>
<td>4</td>
<td>M3.6</td>
<td>Dongfang; Hainan, China</td>
<td>1992</td>
<td>GAC</td>
<td>21</td>
<td>z</td>
<td>[3]</td>
</tr>
<tr>
<td>5</td>
<td>M3.8</td>
<td>Enola Swarm; Arkansas, USA</td>
<td>1982</td>
<td>MHC</td>
<td>&gt;4.5</td>
<td>012</td>
<td>[4]</td>
</tr>
<tr>
<td>6</td>
<td>M3.8</td>
<td>SW Iceland; SW Iceland</td>
<td>1997</td>
<td>BJA</td>
<td>40</td>
<td>z</td>
<td>[2]</td>
</tr>
<tr>
<td>7</td>
<td>M3.4</td>
<td>Parkfield; California, USA</td>
<td>1988</td>
<td>VC</td>
<td>&gt;200</td>
<td>z</td>
<td>[5]</td>
</tr>
<tr>
<td>8</td>
<td>M4.4</td>
<td>SW Iceland; SW Iceland</td>
<td>1997</td>
<td>BJA</td>
<td>83</td>
<td>18</td>
<td>[2]</td>
</tr>
<tr>
<td>9</td>
<td>M5.1</td>
<td>SW Iceland; SW Iceland</td>
<td>1998</td>
<td>BJA</td>
<td>117</td>
<td>z</td>
<td>[2]</td>
</tr>
<tr>
<td>10</td>
<td>M5.0</td>
<td>SW Iceland; SW Iceland</td>
<td>1998</td>
<td>BJA</td>
<td>127</td>
<td>44</td>
<td>[7,8,9]</td>
</tr>
<tr>
<td>11</td>
<td>M5.1</td>
<td>SW Iceland; SW Iceland</td>
<td>1999</td>
<td>[SAR]</td>
<td>121</td>
<td>z</td>
<td>[7]</td>
</tr>
<tr>
<td>12</td>
<td>M5.3</td>
<td>Shidan; Yunnan, China</td>
<td>1992</td>
<td>BS</td>
<td>z</td>
<td>18</td>
<td>[10]</td>
</tr>
<tr>
<td>13</td>
<td>M5.9</td>
<td>Xiuyan; Liaoning, China</td>
<td>1999</td>
<td>[SAR]</td>
<td>136</td>
<td>z</td>
<td>[14]</td>
</tr>
<tr>
<td>14</td>
<td>M6.0</td>
<td>North Palm Springs; CA, USA</td>
<td>1985</td>
<td>[SAR]</td>
<td>1100</td>
<td>69</td>
<td>[11,12,13]</td>
</tr>
<tr>
<td>16</td>
<td>M6.6</td>
<td>SW Iceland; SW Iceland</td>
<td>2000</td>
<td>[SAR]</td>
<td>151</td>
<td>21</td>
<td>[15]</td>
</tr>
<tr>
<td>16</td>
<td>M6.6</td>
<td>SW Iceland; SW Iceland</td>
<td>2000</td>
<td>[SAR]</td>
<td>151</td>
<td>21</td>
<td>[15]</td>
</tr>
<tr>
<td>17</td>
<td>M6.7</td>
<td>Chi-Ch; Taiwan</td>
<td>1999</td>
<td>[SAR]</td>
<td>151</td>
<td>21</td>
<td>[15]</td>
</tr>
<tr>
<td>18</td>
<td>M7.2</td>
<td>Sumatra; Iceland</td>
<td>2004</td>
<td>[SAR]</td>
<td>1260</td>
<td>275</td>
<td>[17]</td>
</tr>
<tr>
<td>18</td>
<td>M7.2</td>
<td>Sumatra; Iceland</td>
<td>2004</td>
<td>[GRI]</td>
<td>1105</td>
<td>442</td>
<td>[17]</td>
</tr>
<tr>
<td>18</td>
<td>M7.2</td>
<td>Sumatra; Iceland</td>
<td>2004</td>
<td>[GRI]</td>
<td>1105</td>
<td>442</td>
<td>[17]</td>
</tr>
<tr>
<td>18</td>
<td>M7.2</td>
<td>Sumatra; Iceland</td>
<td>2004</td>
<td>[GRI]</td>
<td>1105</td>
<td>442</td>
<td>[17]</td>
</tr>
<tr>
<td>18</td>
<td>M7.2</td>
<td>Sumatra; Iceland</td>
<td>2004</td>
<td>[GRI]</td>
<td>1105</td>
<td>442</td>
<td>[17]</td>
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<tr>
<td>18</td>
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<td>2004</td>
<td>[GRI]</td>
<td>1105</td>
<td>442</td>
<td>[17]</td>
</tr>
<tr>
<td>18</td>
<td>M7.2</td>
<td>Sumatra; Iceland</td>
<td>2004</td>
<td>[GRI]</td>
<td>1105</td>
<td>442</td>
<td>[17]</td>
</tr>
</tbody>
</table>

Table 2
Seismic stations (Fig. 2) where retrospective stress-forecasts of three volcanic eruptions have been observed in chronological order with durations of stress-accumulation and stress-relaxation. Format as in Table 1.

<table>
<thead>
<tr>
<th>Eq. No. (Fig. No)</th>
<th>Earthquake identifier; Recording location</th>
<th>Year</th>
<th>Seismic station</th>
<th>Duration of stress-acc (days)</th>
<th>Duration of stress-rel (days)</th>
<th>Refs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>Vatnajökull (Gjálp); SW Iceland</td>
<td>1996</td>
<td>BJA</td>
<td>80</td>
<td>z</td>
<td>[1]</td>
</tr>
<tr>
<td>1b</td>
<td>Vatnajökull (Gjálp); SW Iceland</td>
<td>1996</td>
<td>BJA</td>
<td>80</td>
<td>z</td>
<td>[1]</td>
</tr>
<tr>
<td>1c</td>
<td>Vatnajökull (Gjálp); SW Iceland</td>
<td>1996</td>
<td>BJA</td>
<td>80</td>
<td>z</td>
<td>[1]</td>
</tr>
<tr>
<td>2a</td>
<td>Etna flank; Etna, Sicily</td>
<td>2001</td>
<td>[ESP]</td>
<td>130</td>
<td>3</td>
<td>[2]</td>
</tr>
<tr>
<td>2b</td>
<td>Etna flank; Etna, Sicily</td>
<td>2001</td>
<td>[ESP]</td>
<td>130</td>
<td>3</td>
<td>[2]</td>
</tr>
<tr>
<td>3a</td>
<td>Eyjafjallajökull; SW Iceland</td>
<td>2010</td>
<td>GOD</td>
<td>190</td>
<td>40</td>
<td>[3]</td>
</tr>
</tbody>
</table>

* Magnitudes listed as originally reported; many are IMO Station body-wave magnitudes Mg.
* Multiple recording stations for any earthquake in brackets, where earthquake 'N' is identified by 'Na', 'Nb', etc.
* Complicated by three earthquakes (M 5.2, 5.9, 5.3) within 2 months, where stress response cannot be wholly separated.
* Absent or unreliable durations.
* Earthquake where changes in SWS time-delays (stress-accumulation) were first recognised Crumplin et al. (1999, 2004a).
* Complicated by three earthquakes (M 6.6, 5.7, 6.6) within 5 days, where stress response cannot be separated, and durations are for the combined magnitudes.
* SWS time-delays are time-delays between the top and bottom of a 200 m-deep borehole.

of the mantle (Crampin, 2003). Such stress–accumulation can be monitored by measuring changes in the average SWS time-delays in Band-1 directions (Appendix B) Crampin (1999), whenever there is an appropriate source of shear-waves. The most convenient natural sources of shear-waves are swarms of small earthquakes. Monitoring stress–accumulation above earthquake swarms typically monitors increasing stress originating at plate boundaries (Crampin and Peacock, 2008; Crampin and Gao, 2013). Since the increase of stress from interactions at plate boundaries is a semi-continuous process, stress–accumulation is the nearly-ubiquitous state of the Earth's crust, as is demonstrated by intermittent worldwide seismicity.

SWS suggests that increasing horizontal stress is the driving mechanism for crustal earthquakes (Crampin and Peacock, 2005, 2008; Crampin and Gao, 2013). Crampin (1999) shows that increasing stress increases the aspect-ratio of vertical microcracks.
aligned parallel to the direction of the (typically-horizontal) maximum tectonic stress. The seismic effect is to increase the average SWS time-delay in Band-1 directions in the shear-wave window at the free-surface (Crampin, 1999). Band-1 directions are shear-wave ray-paths to the free-surface in the shear-wave window (Booth and Crampin, 1985) within the double-leafed solid angle between 15° and 45° to the average crack plane. The source-to-recorder geometry is illustrated in Fig. B1 in Appendix B. As shown in Figs. 1 and 2, such stress–accumulation increases lead to robust observations, that are seen whenever suitable shear-wave source-to-receiver geometry is available before large or larger earthquakes (Crampin, 1994; Crampin and Peacock, 2008; Crampin and Gao, 2013), and before volcanic eruptions (Volti and Crampin, 2003a, 2003b; Bianco et al., 2006; Liu et al., 2014).

The least-squares regression lines for stress–accumulation in the left-hand diagrams of Figs. 1 and 2, are fitted to the scatter leading up to the time of the impending event. In the normalised

Fig. 1 (continued)

Fig. 2. Variations of SWS before volcanic eruptions in similar format to Fig. 1: variations of SWS time-delays (above swarms of small earthquakes) in uniform normalised plots of durations of observed stress–accumulation increases and stress–relaxation decreases for three volcanic eruptions specified in Table 2. In diagram 3), the Eyjafjallajökull eruption had two phases of unusually long duration: flank-eruption (yellow); and summit-eruption (blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
figures the slopes of these lines are approximately similar, despite the huge range of earthquake magnitudes from a $M_{w} 1.7$ swarm event to the 2004 $M_{w} 9.2$ Sumatra Earthquake. This result is function of Properties P3 Uniformity, and P7 Universality.

Stress–accumulation before two earthquakes (Table 1, Earthquakes Nos. 10 and 18) was recognised before the earthquakes occurred. Based on the implied stress–accumulation of SWS time-delay increases at seismic station BJA (Fig. 1, No. 10a), on 10th November 1998, the University of Edinburgh (UE) emailed Iceland Meteorological Office (IMO): ‘‘an event could occur any time between now (M > 5) and the end of February (M > 6).’’ Three days later, IMO emailed UE: ‘‘there was a magnitude 5 earthquake just near to BJA . . . this morning 10 38 GMT’’ (Crampin et al., 1999, 2004a, 2008). This was before stress–relaxation decreases had been recognised (Gao and Crampin, 2004). The magnitude of the stress-forecast earthquake was based on the duration of the stress–accumulation increase (the left-hand diagram in Fig. 1, No. 10a), where increasing SWS time-delays indicated that levels of fracture-criticality were approaching based on variations in SWS time-delays before other earthquakes in SW Iceland (Fig. 1, Nos. 3, 6, 8, 11a, 11b) (Crampin et al., 1999, 2004a, 2008). We claim this successful stress-forecast as the first scientifically predicted earthquake, as opposed to less accurate probabilistic estimates discussed by Kossobokov (2007) and others.

Note that Fig. 1, No. 10a is from Gao and Crampin (2004) who used a lower-magnitude-limit data-set for IMO earthquakes than Voltn and Crampin (2003a,b). Consequently, although the SWS effects are compatible with the variations in earthquake (v) in Fig. 2, No. 1b, the exact time-delay data in the figures are marginally different.

Stress–accumulation was also recognised before the 2004 $M_{w} 9.2$ Sumatra Earthquake had occurred (Fig. 1, Nos. 18a-to-18g) (Crampin and Gao, 2012). Recognising the possibility of stress–accumulation, a stress-forecast was emailed to IMO on 13th September, 2002. Updated stress-forecasts were emailed to IMO every two or three months (up to a total of 10 emails) until 22nd December, 2004 (listed in Table 1 of Crampin and Gao, 2012). The extreme sensitivity (Property P8) of SWS time-delays in New Geophysics had not been fully recognised at that time and the impending earthquake was incorrectly stress-forecast as a large ($M > 7$) earthquake in Iceland, rather than the impending $M_{w} 9.2$ Sumatra Earthquake in Indonesia at ~10,500 km from Iceland (Crampin and Gao, 2012). Consequently, although stress–accumulation was recognised before the time of the Sumatra Earthquake, the magnitude and location of the earthquake were not stress-forecast.

There has been speculation on stress–relaxation before the final rupture of an earthquake for many years, such as the dilatancy-diffusion hypothesis of Scholz et al. (1973), and Main et al. (1989) discuss the phenomenon in terms of $b$-value anomalies. We suggest that New Geophysics provides the overall physical basis of the process (Appendix A).

2.2. Stress–relaxation (tentatively interpreted as crack-coalescence)

Stress–accumulation before an impending earthquake typically continues until the stress-field responds to a weakness at an existing, or more rarely impending, fault plane, and pre-rupture stress–relaxation is observed as small earthquakes progressively concentrate stress in the surrounding rock mass by microcrack coalescence around the impending fault. Eventually a large volume of de-stressed weak rock is surrounded by stressed rock and the impending earthquake occurs as microcrack geometry reaches the threshold of fracture-criticality (Crampin, 1994; Gao and Crampin, 2004; Crampin and Peacock, 2008; Crampin and Gao, 2013).

Observations of stress–relaxation decreases are less robust than stress–accumulation increases. Whenever there is sufficient source data (sufficient numbers of small shear-wave-source-swarm earthquakes immediately before the impending event, which is usually at a distance and tectonically unrelated to the swarm events) to show the effects at a monitoring station, stress–accumulation increases typically change slope abruptly to stress–relaxation decreases. These decreases are tentatively interpreted as microcracks coalescing around the impending fault-plane for earthquakes (Gao and Crampin, 2004), or coalescing around the impending magma conduit for volcanic eruptions (Liu et al., 2014). Observing such stress–relaxation decreases requires sufficient shear-wave source events immediately before the impending event, and these are not always available so that observations of stress–relaxation are less robust.

Characteristic stress–accumulation increases in SWS time-delays, before earthquakes, have been recognised on the 28 time-delay diagrams before 17 earthquakes listed in Table 1 ranging in magnitude from a $M_{w} 1.7$ swarm-event in North Iceland (Fig. 1, No. 1) (Gao and Crampin, 2004) to the 2004 $M_{w} 9.2$ Sumatra Earthquake (Fig. 1, Nos. 18a-to-18g) (Crampin and Gao, 2012). One earthquake seismogram (Fig. 1, No. 12) shows stress–relaxation but stress–accumulation is hidden by earlier earthquakes (Fig. 1, No. 13).

Stress–accumulation increases are typically observed at seismic stations whenever there is appropriate source-to-recorder geometry and impending larger earthquakes. Stress–relaxation (crack-coalescence) decreases are less consistently observed: 16 (62%) of the 26 stress–accumulations in Fig. 1 show stress–relaxation; five (19%) possible stress–relaxations are hidden where there are insufficient small source-earthquakes immediately before the impending event to show stress–relaxation; and there are six earthquakes (23%), where increasing stress–accumulation appears to continue until the impending earthquake occurs.

Stress–relaxation is not well understood. Attributing decreases to crack-coalescence may be too simplistic: different source nucleation processes may modify stress–relaxation; and the inescapable large (±80%) scatter in time-delays above small (source) earthquakes (Crampin et al., 2004b) may disturb SWS time-delays at the monitoring site sufficiently to hide possible stress–relaxation decreases before impending larger earthquakes.

All changes in SWS time-delays noted in Table 1 were observed retrospectively apart from the two exceptions discussed in Section 2.1, above. Of the 26 records listed in Table 1, where stress–accumulation was observed, 16 recorded stress–relaxation decreases before earthquakes. Note that whenever the appropriate source-to-recorder geometry above swarms of small earthquakes is available, stress–accumulation increases before large or larger earthquakes have always been observed. There are no known exceptions (Crampin and Peacock, 2008).

Table 2 lists seismograms in Fig. 2 before three volcanic eruptions where stress–accumulation increases have been observed retrospectively. Stress–accumulation increases, similar to earthquakes, has been recognised on six seismograms before three volcanic eruptions, of which five seismograms also show stress–relaxation decreases.

2.3. Goodness-of-fit and error bars

The well-understood ±80% scatter of SWS time-delays (Crampin et al., 2002, 2004b) means that scatter in the data is so large that the least-squares regressions lines in Figs. 1 and 2 have irrelevant goodness-of-fit criteria. The value of the regression lines is justified by the uniformity of the diagrams in the Figs. 1 and 2 where, we suggest, the regression lines in normalised displays show similar overall behaviour for all earthquakes and eruptions irrespective
of the magnitude of the earthquake or eruption, the quality of the recorded time-delays, and the density and scatter of data points.

Meaningful error bars are difficult to determine in visually-assessed data. Consequently, error bars on SWS time-delay data points in Figs. 1 and 2 are based on earthquake location statistics and errors on the normalising individual ray-path distances. In many cases these error bars are too small to be visible. Details are in the individual references listed in Tables 1 and 2.

3. Summary of retrospective stress-forecasts

3.1. Retrospective stress-forecasts of earthquakes

Fig. 1 plots in a uniform normalised format all 29 observed variations with time of the durations of SWS time-delay variations before the 18 earthquakes, listed in Table 1. These are observations of: 16 possible retrospective stress-forecasts of earthquake times and magnitudes, sometimes at more than one seismic station; with two exceptions (Table 1, Earthquakes Nos. 10 and 18) where stress–accumulation was recognised before the event (Section 2.1).

The durations of the stress–accumulation increases in Fig. 1 have been normalised so that the rates of increase can be directly compared. All seismic stations [except Fig. 1, No. 12, M 5.3 and Fig. 1, No. 13, M 5.2 and M 5.9, where stress–accumulation was hidden by earlier earthquakes], show uniform (least-square regression-line) stress–accumulation increases before 17 earthquakes (two in real time). This is in the presence of the unavoidable ±80% scatter in SWS time-delays. These variations can be modelled as stress–accumulation before earthquakes, as expected in the New Geophysics of a critically-microcracked rock mass (Crampin, 1999, 2006; Crampin and Gao, 2013), but are inexplicable in terms of conventional sub-critical geophysics without devising special cases for each observation.

As discussed above, although stress–accumulation is well-understood and increases are consistently observed, stress–relaxation decreases are less robustly observed. As noted in Section 2.2, stress–relaxation decreases are present in 62% of the stress–accumulations, 19% are hidden by lack of source earthquakes, and 23% show increases continuing until the impending earthquake occurs without indicating stress–relaxation. Stress–relaxation is not a well understood phenomenon.

3.2. Retrospective stress-forecasts of volcanic eruptions

Using the same normalised formats as in Fig. 1, Fig. 2 plots the durations of the observed variations of SWS time-delays above swarms of small earthquakes before and after three volcanic eruptions (listed in Table 2) where stress–accumulation and stress–relaxation in SWS time-delays have been observed retrospectively. Other observations of changes in SWS before and after volcanic eruptions have been reported (Miller and Savage, 2001; Gerst and Savage, 2004; Keats et al., 2011; Johnson and Poland, 2013; amongst others). Unfortunately, these other observations do not have the consistent source-to-recorder-geometry (within the shear-wave window at the free surface) required for analysis of the stress–accumulation and stress–relaxation as in Figs. 1 and 2. Consequently, these other observations of changes in SWS before eruptions cannot be easily analysed or interpreted.

Interactions with the topographically irregular free-surface and sub-surface around volcanoes make the behaviour of SWS before volcanic eruptions more complicated than before most earthquakes. Consequently, each of the three examples in Fig. 2, Table 2, has strong individual characteristics. Fig. 2, Nos. 1a and 1c are of the 1996 Gjálp eruption beneath the Vatnajökull Ice Cap. The time-delay data points in Figs. 1 and 2 were used to show stress–accumulation at Stations BJA and SAU (Voltt and Crampin, 2003a, 2003b). There were no source events beneath BJA immediately before the eruption so the typical stress–relaxation decrease before earthquakes is only visible at SAU (Fig. 2, No. 1c).

Following the 1996 Gjálp, Vatnajökull, eruption, SWS time-delays measured at BJA showed an average decrease of ~2 ms/km/year which lasted 2 years (Fig. 2, No. 1b), which is interpreted as stress–relaxation as the Mid-Atlantic Ridge adjusts to the stress released by the Gjálp fissure eruption above the magmatic plume beneath the Vatnajökull Ice Cap. Variations in SWS time-delays for stress–accumulation before earthquakes is superimposed on this widespread average decrease: these local variations labelled (i)–(v) in Fig. 2, No. 1b, refer to earthquakes Fig. 1, Nos. 6, 8, 3, 11, and 10, respectively, which vary in magnitude from M 3.4 to 5.1.

The SWS time-delays above small earthquakes before the 2001 flank eruption of Mount Etna, Sicily, showed both stress–accumulation and stress–relaxation at two stations ESP and MNT (Fig. 2, Nos. 2 and 2b) (Bianco et al., 2006). Both stations were within ~2 km either side of the flank eruption.

Changes in SWS before the 2010 Eyjafjallajökull eruption, SW Iceland, were monitored retrospectively at Station GOD, ~8 km

![Fig. 2](image-url)

Fig. 2. Variations of logarithms (base 10) of duration in days against earthquake magnitude of SWS time-delays as specified in Table 1 for: (a) stress–accumulation increases; and (b) stress–relaxation (crack-coalescence) decreases.
east of the flank eruption (Fig. 2, No. 3) (Liu et al., 2014). Eyjafjallajökull was unusual in having two prolonged active phases: a flank eruption lasting ~20 days (plotted yellow); and a summit eruption lasting ~39 days (plotted blue) (Gudmundsson et al., 2011). The time-delays plotted in Fig. 2, No. 3, are from a tight swarm of small events associated with the flank eruption so the ray paths to GOD are almost identical which may be the reason there is less scatter than the ±80% usually observed. SWS time-delay variations within the shear-wave window at GOD (Fig. 2, No. 3) (Liu et al., 2014) before the Eyjafjallajökull eruption, are very similar to variations of SWS at BJA before the 1998 M 5 successfully stress-forecast earthquake (discussed in Section 2.1); compare Fig. 1, No. 10a with Fig. 2, No. 3. Eyjafjallajökull is ~90 km east of Station BJA, which has recorded stress–accumulation before seven earthquakes (Table 1, Nos. 3, 6, 8, 10, 11, 16, 18).

The strong similarities in stress variations before volcanic eruptions and earthquakes would be a remarkable coincidence in conventional sub-critical geophysics, but is directly compatible with many of the fundamentally-new properties expected of New Geophysics (listed in Table A1) that are imposed on conventional sub-critical geophysics. These similarities are strong support for several of the properties of the New Geophysics of a critically-microcracked crust and uppermost ~400 km of the mantle (particularly properties: P1 Self-similarity; P3 Uniformity; P7 Universality; and P8 Sensitivity; in Table A1). These critical properties are imposed on and may, in some circumstances, dominate the behaviour of sub-critical conventional geophysics.

4. Durations of stress increases and stress decreases

The association of changes in SWS time-delays and earthquakes is confirmed by the near linearity of logarithms of durations of both stress–accumulations increases and stress–relaxation decreases with earthquake magnitudes in Fig. 3. These are analogous to the linearity of the Gutenberg–Richter (1956) relationship both in earthquakes and in moonquakes (Crampin and Gao, 2015). Fig. 3 shows plots against magnitude of the log10 durations of: (a) stress–accumulation increases; and (b) stress–relaxation decreases of all reliable data in Table 1. The scatter is not unexpected as no attempt has been made to use a unified magnitude scale.

In Fig. 3a, the stress–accumulation for larger earthquakes $M > 6$, say, physically extends into the upper mantle which is expected to store and release stress in different ways from the crust, especially in different plate-generation and subduction regimes, which may have different rates of stress generation. This probably accounts for the scatter of the two black ‘Other Magnitude’ outliers on the right-hand-side of Fig. 3a. The $M_6$ outlier (Fig. 1, No. 15) is the duration of stress–accumulation before the 1986 North Palm Springs Earthquake on the San Andreas Fault in California, and the $M_w 7.7$ outlier (Fig. 1, No. 17) is the duration before the 1999 Chi-Chi Earthquake in Taiwan in the Philippine Subduction Zone. The two plate boundaries are unlikely to have similar rates of stress generation, and outliers are not unexpected.

Data for the open circles, in Fig. 3a, are the durations of the stress–accumulation increases before the 2004 $M_w 9.2$ Sumatra Earthquake (Fig. 1, Nos. 18a–18g). The points should be at an unspecified larger duration (indicated by the arrow-head to the right), unspecified because the initial time-delays are hidden by noisy data and may well extend to before data was available, so a good estimate of duration is not available. Extrapolation of the least-squares line as plotted (correlation-coefficient 0.70) through the remaining data points reaches $M_w 9.2$ at ~10,000 days (~27 years) which may be associated with the worldwide return period of $M > 9$ earthquakes (Crampin and Gao, 2012).

In contrast, in Fig. 3b for stress–relaxation decreases, the durations (open circles) for the Sumatra Earthquake are believed to be correctly located, which together with the duration of the $M_w 7.7$ Chi-Chi Earthquake (the other ‘Magnitude Outlier’), give an upward trend beyond the end of the least-squares line (correlation-coefficient 0.78) through the durations for the smaller earthquakes. The rates of change are thought to be the rates at which cracks in fracture networks coalesce. Since fracture networks for larger earthquakes extend into the hotter more-mobile upper-mantle it is expected that cracks in the mantle will coalesce faster than fracture networks in the cooler crust and will have relatively shorter durations leading to the upward trend for magnitudes above $M 7$ in Fig. 3b.

The approximate linearity of log10 durations for earthquakes less than about $M 7$ of both stress–accumulation and stress–relaxation would not be expected in conventional sub-critical geophysics and shows property P1 Self-Similarity, which is strong support for New Geophysics. Indeed, the well-known linearity of the well-established Gutenberg–Richter relationship (Bak and Tang, 1989; Main, 1995) is also a demonstration of the criticality of New Geophysics which cannot be matched in conventional sub-critical geophysics (Crampin and Gao, 2015). As discussed by Crampin and Gao (2015), it is well known that the linearity of the Gutenberg–Richter relationship implies criticality between the numbers and magnitudes of earthquakes. Previously criticality has been treated as a somewhat isolated phenomenon not fully understood. New Geophysics provides a physical basis and shows that the criticality of closely-spaced stress-aligned fluid-saturated microcracks pervades the crust and at least the uppermost ~400 km of the mantle, with the properties in Table A1.

5. Implications for successful (real-time) stress-forecasting of earthquakes and volcanic eruptions

5.1. Implications for successfully stress-forecasting earthquakes

Time-delay variations in the 29 listed SWS time-delay data sets (from 18 earthquakes) in Table 1 plotted in Fig. 1, where: one earthquake (Fig. 1, No. 10a) was successfully stress-forecast in real-time; one earthquake (Fig. 1, Nos. 18a–18g) had stress–accumulation recognised in real-time, but was not stress-forecast; and one earthquake (Fig. 1, No. 12) had stress–accumulation hidden by earlier earthquakes. The remaining 15 earthquakes show stress–accumulation increases observed retrospectively. The variations in SWS time-delays show that had time-delays been monitored in real time at seismic stations, where stress-forecasts were recognised retrospectively, the 15 earthquakes had the potential for also being successfully stress-forecast in real-time. Successful real-time stress-forecasts would have been particularly likely in those cases where there were sufficient shear-wave source data (sufficient small earthquakes in the swarm at the monitoring site) and the earthquakes were sufficiently large so that stress–relaxation decreases with durations of several days could also have been identified, before the impending events. The time-delays in Fig. 1, Nos. 8, 9a, 15, 16a, 16b, 17, and of course 10a and 18, show that the times, magnitudes (and possibly fault-breaks) of these earthquakes, could have been successfully stress-forecast in real time had they been monitored before the events.

5.2. Implications for successful stress-forecasting volcanic eruptions

In general, the stress-induced variations of SWS time-delays before eruptions are similar to the variations before earthquakes as expected in the properties in Table A1. In particular, the behaviour of SWS time-delays before the 2010 flank eruption of
Eyjafjallajökull, SW Iceland at Station GOD (Fig. 2, No. 3) is directly similar to the behaviour of SWS before the 1998 successfully stress-forecast earthquake (Fig. 1, No. 10a) at Station BJA, some ~90 km to the west of GOD. This correlation is discussed by Liu et al. (2014).

In this example, the stress–relaxation decrease at GOD reaches the original level of time-delays (5–10 ms/km) at the beginning of the stress–accumulation increase as the flank eruption begins (Fig. 2, No. 3). This means that, if SWS had been monitored in real-time, the time of the flank eruption could have been stress-forecast to within one or two days. Although, numerous phenomena typically indicate “unrest” before impending eruptions, “…immediate short-term eruption precursors may be subtle and difficult to detect” (Sigmundsson et al., 2010).

Consequently, the stress–relaxation decrease in the right-hand diagram in Fig. 2, No. 3 may well be the most definitive short-term indication of the time of an impending eruption yet suggested (Liu et al., 2014).

6. Discussion

The uniformity of the stress–accumulation increases in SWS time-delays in Fig. 1, and stress–relaxation decreases in well-over half the time-delay diagrams in Fig. 1, indicates that the time, magnitude, and in some cases location of many, perhaps most, large or larger earthquakes could be stress-forecast, if suitable sources of shear-waves were available and SWS monitored before the earthquakes occurred. As currently understood, SWS itself gives no direct indication of impending earthquake location. However, if an earthquake is stress-forecast by SWS, other anomalous behaviour may lead to fault-break identification, as was the case for the successfully real-time stress-forecast earthquake (Fig. 1, No. 10a) (Crampin et al., 1999, 2004a, 2008) - indication of an impending earthquake from records at Station BJA, SW Iceland, suggested correctly to co-author Ragnar Stefansson (IMO) that the impending earthquake would occur on the fault-plane of an earthquake 6 months earlier (Fig. 1, No. 11a) where low-level seismic activity was still ongoing. This realization allowed the time, magnitude, and fault-plane of the impending M 5 earthquake to be correctly stress-forecast (Crampin et al., 1999, 2004a, 2008).

Note that although stress–accumulation and stress–relaxation was identified in Iceland before the 2004 Mw 9.2 Sumatra Earthquake (Fig. 1, No. 18) (Crampin and Gao, 2012), similar changes have not been recognised before the 2011 Mw 9 Tohoku-Oki Earthquake, Japan. Unfortunately, financial constraints meant there has been no-one available to search the data. However the effects of the 2004 Mw 9.2 Sumatra Earthquake may be said to be marginal (Fig. 1, No. 18) and the Tohoku-Oki Earthquake is slightly smaller but slightly (~10%) less distant. Probably more crucially, half the great-circle path between Iceland and Tohoku-Oki is along the convoluted margin between the Eurasia and Arctic Plates, so that changes in SWS may not be easily transmitted towards Iceland instruments.

The problem of predicting an impending volcanic eruptions is different from predicting earthquakes in that the location is typically known (although the particular eruptive vent may not be) but, as with earthquakes, the time and magnitude are unknown. The observed variations in SWS before Eyjafjallajökull eruption would have allowed the time of the flank eruption to be stress-forecast within one or two days (Fig. 2, No. 3), had SWS time-delays been monitored before the event. Eruptions are complicated and there is no agreed measure of the size of an eruption as there is with the magnitudes of earthquakes.

Note that claims of criticality in the occurrence of earthquakes are not new. Bak and Tang (1989) suggested self-organised criticality and Main (1995) linked criticality with earthquake b-values. However, the hypothesis of New Geophysics is the first time that criticality replaces conventional sub-critical geophysics.

Note also the preponderance of references to Crampin and colleagues. This is because changes in SWS can only be interpreted as implied changes of stress above small earthquakes for the very specific source-to-recorder Band-1-and-Band-2 geometry indicated in Fig. B1 suggested by Crampin (1999). Only Crampin and colleagues and Bianco et al. (2006) have used such geometry. SWS is a common crustal phenomenon and there are numerous papers reporting observations of SWS above small earthquakes by other researchers (from Buchbinder, 1989, to Giannopoulos et al., 2015), where some imply changes in SWS, but, without the specific Band-1 and Band-2 geometry on a comparatively horizontal free-surface, the results are merely phenomenological and cannot be interpreted in terms of changes of stress.

7. Conclusions

(1) SWS demonstrates that stress-induced variations to microcrack geometry before large or larger earthquakes is established so that the times, magnitudes, and in some circumstances fault-planes, of large earthquakes can be stress-forecast if suitable source-to-receiver monitoring geometry is available.

(2) Stress-induced variations before earthquakes and volcanic eruptions are similar so that the onset of eruptions can also be stress-forecast. If SWS had been monitored, the time of the onset of the 2010 disruptive ash-cloud eruption of Eyjafjallajökull volcano in Iceland could have been stress-forecast to within one or two days.

(3) The New Geophysics of a critical-system of stress-aligned fluid-saturated microcracks in the Earth is established with important applications and implications both to earthquake and volcanic eruption stress-forecasting (Crampin, 2004; Crampin and Gao, 2012) and to hydrocarbon seismics (Crampin, 2006).

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Appendix A. A brief outline of New Geophysics

Stress-aligned shear-wave splitting (SWS) (illustrated schematically in Fig. A1) is observed worldwide in the shear-wave window (Appendix B) above small earthquakes (Crampin, 1994; Crampin and Peacock, 2008) and in record sections in seismic exploration (Helbig and Thomsen, 2005). SWS shows that most rocks throughout the Earth’s crust (and uppermost ~400 km of the mantle, Savage, 1999) are pervaded by stress-aligned fluid-saturated microcracks (Crampin, 1994; Crampin and Peacock, 2008) [intergranular films of hydrated melt in the upper mantle, Crampin, 2003].
Fig. A1. Schematic illustration of shear-wave splitting in the distributions of stress-aligned fluid-saturated microcracks throughout the Earth’s crust.

Fig. A2 shows that the degree of observed SWS (the percentage of shear-wave velocity anisotropy, SWVA), ~1.5% to ~4.5%, means that the microcracks in the Earth are so closely-spaced they verge on failure at fracture criticality leading to fracturing and earthquakes (Crampin, 1994). Phenomena that verge on failure in this way are a New Physics (Davies, 1989) (hence a New Geophysics, Crampin, 1999, 2006) of critical-systems that imposes a range of fundamentally-new properties on conventional sub-critical physics (and geophysics, Crampin and Gao, 2013). Table A1 lists some of these fundamentally-new properties. The references in Crampin and Gao (2013) demonstrate that these properties have been observed many times over thousands-to-millions of source-to-receiver ray paths [only property P6 Controllability has not been tested]. We suggest this provides irrefutable proof that New Geophysics is valid proposition.

These properties answer several conundrums (Crampin et al., 2013; Crampin and Gao, 2013). In particular, the well-established Gutenberg–Richter (1956) relationship demonstrates that some aspects of earthquakes are controlled by non-linear elasticity. The properties of New Geophysics explain how conventional sub-critical purely-elastic geophysics can satisfy tens of thousands of theoretical, analytical, and observational investigations of earthquakes and seismic-wave propagation in the Earth, despite Gutenberg–Richter demonstrating that non-linear elasticity applies to fundamental aspects of geophysical behaviour (Crampin and Gao, 2015).

Note that one cannot understand the new properties in Table A1 from experience based solely on conventional sub-critical geophysics. A paradigm shift in understanding is required (Crampin and Gao, 2013, 2015).

Appendix B. Ray-path geometry for monitoring stress-accumulation and SWS time-delays within the shear-wave window at the free-surface

Shear-waves have strong interactions at the free-surface (Booth and Crampin, 1985). In an isotropic half-space with a horizontal free-surface, SH-waves have complete internal reflection at a horizontal free-surface at all incidence angles. In an isotropic half-space with a horizontal free-surface, SV-waves have complete internal reflection only for incidence angles less than the critical angle for P-wave reflections, sin^-1(β/2z), which is ~35° for a Poisson’s ratio of 0.25, where z and β are the P- and S-wave velocities, respectively. Since an arbitrary shear-wave has components of both SV- and SH-motion, this critical angle defines the radius of the shear-wave window for observing undisturbed shear-waves and SWS at a free-surface. For larger angles of incidence, P-waves are generated, and the amplitude and wave-forms of shear-waves observed at a free-surface are severely distorted (Evans, 1984). Since SWS, in an anisotropic half-space, is typically a mixture of SH- and SV-motion, the waveforms,
polarisations, and SWS time-delays are uninterpretable outside the shear-wave window (Booth and Crampin, 1985).

The geometry of SWS in stress-aligned vertical microcracks imposes further restrictions on observations of SWS at a free-surface. Fig. B1, Appendix B, is the ray-path geometry for observing undisturbed waveforms of shear-waves and SWS in stress-aligned fluid-saturated microcracks at a horizontal free-surface. ABScD is a crack-plane in a half-space with a uniform distribution of parallel-vertical microcracks, where S is a three-component recorder on the horizontal free-surface. Band-1 directions to the free-surface, where SWS time-delays are sensitive to crack aspect-ratio (Crampin, 1999), are within the solid angle EFGH-to-S subending 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, 1999), 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.

Note that the effects of the shear-wave window for observations of SWS (as well as isotropic observations of shear waves), are determined by the topography within about a wavelength of the recorder. Consequently, irregular surface topography places severe constraints on measuring SWS time-delays and polarisations on recorders in mountainous localities. SWS may be observed, but will be impossible to interpret realistically unless the criteria in Fig. B1, can be met. Several of the 17 common fallacies about SWS listed by Crampin and Peacock (2008) are the result of neglecting the effects of the free-surface on observations and measurements of SWS.

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