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Review

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 fundamentally-new properties on conventional 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 (Svitek 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 M_w 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 Tables 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 polarisations along different but adjacent 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).