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The New Geophysics: similarities in forecasting earthquakes and eruptions

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Observations of shear-wave splitting above small earthquakes in Iceland and elsewhere have shown three types of phenomena.

1) Increases in shear-wave time-delays in Band-1 of the shear-wave window indicative of increasing crack aspect-ratios caused by the accumulation of stress before impending larger earthquakes. The increases continue until levels of cracking reach fracture-criticality when shear-strength so there is fracturing and the impending earthquake occurs. The rate and/or duration of the increase and the magnitude of the impending earthquake are self-similar so that the time and magnitude can be estimated. This phenomena has been recognised (with hindsight) before some 15 earthquakes worldwide and on one occasion the time, magnitude, and fault break of a M 5 earthquake in SW Iceland was successfully stress-forecast.

2) When there are sufficient observations immediately before impending larger earthquakes, the increases in Band-1 time-delays are observed to decrease, where the rate and/or duration of the decrease and the magnitude of the impending earthquake are again self-similar. This phenomenon is not wholly understood but appears to be some form of local stress relaxation immediately preceding the impending earthquake.

3) Observations of shear-wave splitting immediately above very large faults such as the San Andreas in California and the Húsavík-Flatey Fault, a transform fault of the North Atlantic Ridge in Iceland, show 90º-flips in shear-wave polarisations, where the polarisations are parallel to the minimum horizontal stress, σ_h, rather than the typical maximum horizontal stress, σ_H, directions. This occurs when the pore-fluid pressure exceeds the local σ_H-stress so that local stress directions around the fault also show 90º-flips as the directions of σ_H and σ_h are exchanged. Similar behaviour is believed

to occur, due to critically high pore-fluid pressures, on all seismically-active faults, but the effect on smaller faults which do not extend to the surface is to induce the $\pm 80\%$ scatter in shear-wave time-delays typically observed above all small earthquakes: the delay at the surface is the sum of positive time-delays (from normally-pressurised paths) and negative delays (along the 90º-flipped high-pressurised paths in the fault zone), and small differences in lengths of ray paths can easily cause the large scatter.

Mechanism (1), the increase in stress, has been observed with hindsight, before some 15 earthquakes ranging from a M 1.7 swarm event in Iceland to the *Ms* 7.7 Chi-Chi earthquake in Taiwan. The mechanisms for effects 1 and 3 are believed to be understood and can be calculated/ modelled by the Anisotropic Poro-Elasticity (APE) model for the evolution of fluid-saturated cracks to changing conditions.

The fundamental fracturing mechanisms of earthquakes and eruptions is believed to be similar: the fracturing of the earth so that slippage can occur in earthquakes; and the fracturing of the earth in a '*magma-frac*' (similar to oil-company hydro-fracs), which opens vertical fractures so that highly-pressurised magma can escape to the surface in eruptions. A major difference in fracturing between volcanic eruptions and earthquakes, is that most earthquakes occur at depth, whereas volcanic eruptions are at the surface. This means in particular that 90º-flips in shear-wave polarisations are likely to be observed at the surface.

When there is sufficient data (sufficient small earthquakes and adequate seismic monitoring network), all three phenomena have also been observed before volcanic eruptions. Numerous authors have noted 90º-flips (Item 3) sometimes as shear-wave polarisations, sometimes as earthquake focal mechanisms, and sometimes as implied dyke directions (they are all the same mechanism). Recently, one of us has noted all three phenomena (Items 1, 2, 3) before the 2001 flank eruption on Mount Etna.

It is suggested that the demonstration of similarities in the behaviour of stresses and fractures before earthquakes and eruptions is remarkable. It is important for the inferences that one mechanism can throw on another. Note that any use of these phenomena for forecasting either earthquakes or eruptions is severely limited by the scarcity and unreliability of swarms of small earthquakes as sources of shear waves. Consequently, controlled source seismology is required (see USC presentation). It is suggested that all eruptions require magma-fracs at the surface to break-through surface rocks and release magma to the surface, so that the suggested controlled-source seismics could universally forecast all volcanic eruptions.