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EXPRESS LETTER

Earthquakes can be stress-forecast

Stuart Crampin[1,2] and Yuan Gao[3]

[1]*British Geological Survey, Edinburgh* EH9 3LA, *Scotland UK. E-mail: scrampin@ed.ac.uk*
[2]*School of GeoSciences, University of Edinburgh, Edinburgh* EH9 3JW *Scotland, UK*
[3]*Institute of Earthquake Science, China Earthquake Administration,* 1000036 *Beijing, China*

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SUMMARY

In 1997, Geller *et al.* wrote 'Earthquakes Cannot Be Predicted' because scale invariance is ubiquitous in self-organized critical systems, and the Earth is in a state of self-organized criticality where small earthquakes have some probability of cascading into a large event. Physically however, large earthquakes can only occur if there is sufficient stress-energy available for release by the specific earthquake magnitude. This stress dependence can be exploited for stress-forecasting by using shear wave splitting to monitor stress-accumulation in the rock mass surrounding impending earthquakes. The technique is arguably successful but, because of the assumed unpredictability, requires explicit justification before it can be generally accepted. Avalanches are also phenomena with self-organized criticality. Recent experimental observations of avalanches in 2-D piles of spherical beads show that natural physical phenomena with self-organized criticality, such as avalanches, and earthquakes, can be predicted. The key to predicting both earthquakes and avalanches is monitoring the matrix material, not monitoring impending source zones.

Key words: Self-organization; Earthquake dynamics; Earthquake interaction, forecasting, and prediction; Seismic anisotropy; Wave propagation; Dynamics: seismotectonics.

1 INTRODUCTION

It is a long-established assumption in geophysics that earthquakes are inherently unpredictable (Bak & Tang 1989; Geller *et al.* 1997). As a result of such assumptions, using shear-wave splitting (seismic birefringence) to monitor stress-accumulation by changes in microcrack geometry in order to 'stress-forecast' earthquakes, although apparently successful (Crampin *et al.* 1999, 2008), is controversial and difficult to get accepted. The technique uses seismic shear wave splitting to monitor stress-induced changes to microcrack geometry and estimate the approach of fracture-criticality (and earthquakes) at possibly substantial distances from the impending source zones (Crampin & Peacock 2005, 2008).

New experimental evidence on avalanches (Ramos *et al.* 2009) confirms that systems with self-organized criticality (SOC) can be predicted by monitoring overall behaviour of the matrix rock remote from the impending source zone. We show strong similarities between behaviour before avalanches and earthquakes that confirm that earthquakes can also be predicted/stress-forecast.

2 PREDICTING AVALANCHES

Avalanches in sand (or bead) piles are expected to display classic SOC (Bak 1996). Ramos *et al.* (2009) report laboratory measurements of avalanches in a 2-D pile of (~3300) spherical steel beads between vertical glass plates stimulated by successive single bead-drops in the centre of the pile. The position of each bead was analysed with single-bead resolution in photographs of the bead pile following every bead-drop. The linearity of logarithms of avalanche size (the number of beads moved) and cumulative numbers of avalanches confirm that the avalanches have SOC. The analyses of Ramos *et al.* (2009) were based on varying pile size, and on the average local-disorder of the system measured by a 'shape factor' ζ, which for a 2-D structure can be written

$$\zeta = A^2/(4\pi B), \tag{1}$$

where A is the circumference and B is the area of Voronoi Cells around each bead (Moučka & Nezbeda 2005). Low values of ζ correspond to well-ordered close packing, where the minimum is $\zeta = 1.08$ for a hexagonal Voronoi Cell.

Ramos *et al.* (2009) plot (reproduced in Fig. 1) the variation with time of temporal correlation functions, C, before and after large avalanches (100–1000 beads) for the time-series of bead-pile sizes. The correlation show an incremental increase, which peaks, and then decreases, over some 50 bead-drops, until the instantaneous decrease as large avalanches occur. The 50-point delay was interpreted as foreshocks (Ramos *et al.* 2009).

Fig. 1(b) shows temporal correlation functions of average shape-factors ζ. There is a gradual increase in disorder until, coinciding

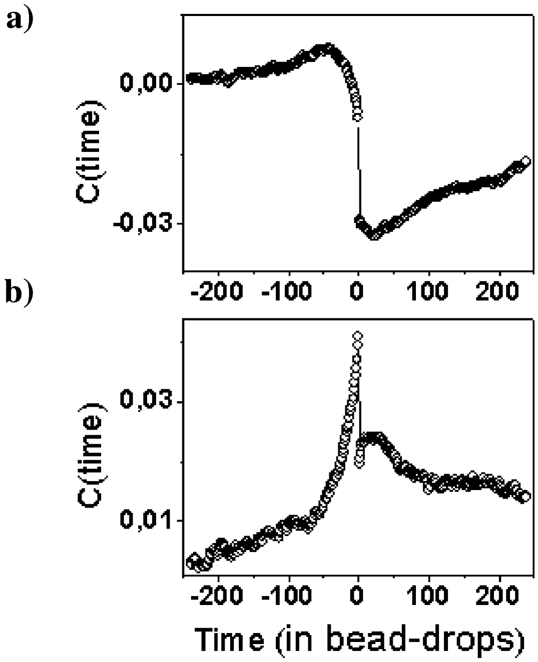

Figure 1. Temporal correlations, *C*, between avalanches and matrix of bead piles. (a) Correlation between large avalanches and sizes of bead piles. (b) Correlation between large avalanches and average shape factors ζ (modified after Ramos *et al.* 2009).

with the peak in pile-size in (a), there is an accelerating increase in disorder culminating (50 bead-drops later) in an instantaneous decrease as large avalanches occur (Ramos *et al.* 2009).

Analysing Fig. 1, Ramos *et al.* (2009) made retrospective predictions of 'large' avalanches which were correct 62 $\pm$ 4 per cent of the time (in a random process, such alarms would be 50 per cent correct). They claimed that this 'not very impressive percent' is significant as it demonstrates that by 'correlation between large avalanches and global structural variables in the system' (i.e. properties of the matrix material), 'it is possible to achieve some predictability' for phenomena with SOC (Ramos *et al.* 2009). These laboratory experiments on avalanches are important as demonstrating that phenomena with SOC can show precursory phenomena and can be predicted.

3 STRESS-FORECASTING EARTHQUAKES

The new understanding of fluid-rock deformation is that the almost universally-observed seismic shear wave splitting, aligned with the stress field, shows that almost all *in situ* rocks throughout the crust are pervaded by stress-aligned fluid-saturated microcracks (Crampin 1994, 1999, 2006; Crampin & Zatsepin 1997; Crampin & Peacock 2008). These microcracks are the most compliant elements of *in situ* rock, where the degree of observed shear wave splitting indicates that microcracks are so closely spaced that they verge on failure (by fracturing and earthquakes), and hence are critical-systems. Such critical-systems impose a range of fundamentally new properties on conventional subcritical geophysics (Crampin 1994, 1999, 2006; Crampin & Zatsepin 1997; Crampin & Peacock 2005). One of the effects of such criticality is that the evolution of microcracked rock under changing conditions can be modelled by anisotropic poro-elasticity (APE) (Crampin & Zatsepin 1997). The level of cracking, when cracking is so extensive that shear-strength is lost and fracturing and earthquakes necessarily occur if there is any disturbance, is known as fracture-criticality. Using APE, we have shown that the evolution of stress-accumulation can be monitored by variations in shear wave time-delays at the free-surface in specific stress-related directions (Crampin 1994, 1999, 2006; Crampin & Zatsepin 1997).

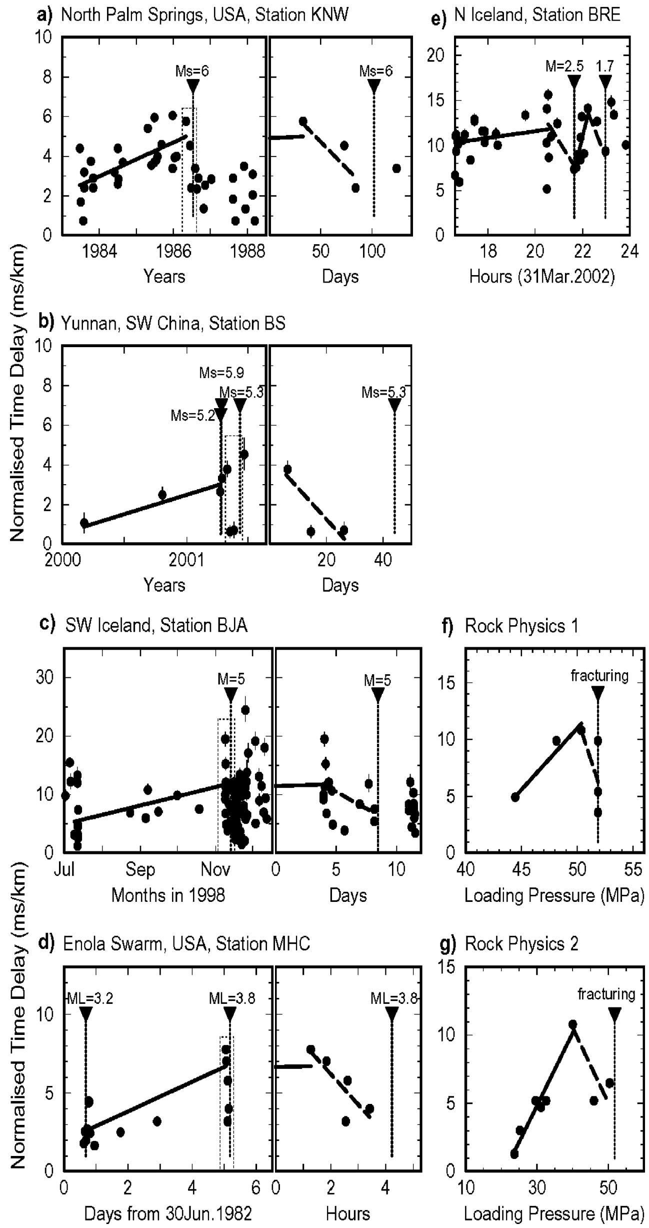

Figure 2. Variations in time-delays (normalized to ms km^{-1}) before earthquakes (triangles). LHS: least-square fits to increasing time-delays normalized to the same length of 5 yr, 3 yr, 6 months and 6 d, respectively. RHS: normalized timescales for dotted boxes in LHS with least-squares fits (dashed line) to decreasing time-delays (modified after Gao & Crampin 2004).

Fig. 2 shows examples of variations in time-delays between split shear waves before and after four earthquakes (Gao & Crampin 2004): (1) $M = 6$, 1986, North Palm Springs, California; (2) $M =$ 5.9/5.3, 2001, Yunnan Province, China [the left-hand side (LHS) increase is before a $M = 5.9$ event; the right-hand side (RHS) decrease is before a $M = 5.3$ event]; (3) $M = 5$, 1998, SW Iceland (the successfully stress-forecast earthquake) and (4) $M = 3.5$, 1982, Enola Swarm, Arkansas. The changes in time-delays, normalized to ms km^{-1}, are measured along shear wave ray paths above swarms of small earthquakes.

Fig. 2 shows two types of change (Crampin *et al.* 2008).

(1) The LHS increase in normalized time-delays over normalized timescales can be interpreted (and modelled) as stress accumulating from increasing strain at the boundaries of tectonic plates. Initially, stress increases are distributed widely over adjacent plates and are unrelated to incipient faults. However, the crust is highly heterogeneous. If stress accumulates over a small rock volume, it will accumulate fast and the resulting earthquake will be small. If stress accumulates over a larger rock volume, the accumulation will be slower but the resulting earthquake larger. Hence the similarities in the normalized LHS diagrams in Fig. 2, and the linearity (self-similarity) of plots of logarithms of duration against impending magnitudes (Crampin *et al.* 2008). These increases are not precursory, in the usual sense, as the impending fault-planes have not yet been identified.

(2) The RHS decrease in normalized time-delays over normalized timescales is stress-relaxation as the accumulating stress-field identifies a weakness and microcracks coalesce into the impending fault-plane. Again there are similarities in the normalized RHS diagrams in Fig. 2, and plots of magnitude against logarithm of duration are again self-similar (Crampin *et al.* 2008). These RHS decreases are precursory as the microcracks are coalescing on the impending fault-plane.

Stress-accumulation changes have been observed in retrospect before some 14 $M = 1.7$ to 7.7 earthquakes worldwide (nine of which showed stress relaxation) (Crampin & Peacock 2008; Crampin *et al.* 2008). On one occasion, when effects were recognized before the event, the time, magnitude and fault plane of a $M = 5$ earthquake in SW Iceland were successfully stress-forecast in real time (Crampin *et al.* 1999, 2008).

Earthquake magnitudes are logarithms of energy released, and self-similarity between logarithmic quantities is characteristic of critical systems with SOC (Davies 1989). It has been generally assumed that phenomena with SOC such as avalanches and earthquakes are unpredictable, because at any time, small events may cascade into larger unpredictable events (Bak & Tang 1989; Bak 1996; Geller *et al.* 1997). This is what even the low-level of predictability in avalanches (Ramos *et al.* 2009) specifically denies.

4 SIMILARITIES BETWEEN EARTHQUAKES AND AVALANCHES

We suggest that the observed increases and decreases before earthquakes in Fig. 2 are directly analogous to the experimental increases and decreases before avalanches in Fig. 1. Crampin *et al.* (2004) explains the scatter in Fig. 2. The increases in time-delays in the LHSs of Fig. 2 correspond to the increase in bead-pile size before the peak values in Fig. 1(a) (and the increase in disorder in Fig. 1b). Similarly, decreases in time-delays in the RHSs of Fig. 2 correspond to the 50-point decrease in pile sizes in Fig. 1(a) (and the accelerating increase in disorder in Fig. 1b).

These similarities have implications for the interpretation of both stress-forecasting earthquakes and predicting avalanches in piles of beads. As stress-accumulation in the LHSs of Fig. 2 approaches fracture-criticality, the increase abruptly stops and time-delays begin to decrease as plotted in the RHS diagrams. Such increases and decreases of time-delays have been observed whenever there have been suitable swarms of small (shear wave source) events with suitable recording networks before larger neighbouring earthquakes (Gao & Crampin 2004). These decreases cannot be modelled, as again we know insufficient details of the earthquake source volume, but can be plausibly interpreted as stress-relaxation as microcracks begin to coalesce onto the eventual fault-plane.

We suggest it is not surprising that, when the internal structure of every element of a system is known and can be at least partially specified as in the simple 2-D geometry of the bead pile, the result of a bead-drop can be predicted (if only to 12 ± 4 per cent accuracy above the randomness of 50 per cent). Since the increases and decrease in time-delays in Fig. 2 can be interpreted physically as stress-accumulation and crack coalescence, this suggests that the variations in pile-sizes and disorder in Fig. 1 should also have a physical explanation. This is likely to be associated with spatial variations of the directional anisotropy of the interbead gaps illustrated in fig. 3 of Ramos *et al.* (2009).

5 DISCUSSION

A reviewer asked a fundamental question. How much is SOC predictability a property of the matrix material? Is 'true' SOC unpredictable?

Bak *et al.* (1987) model SOC with random data where scale-invariance is implicit so that all elements have exactly the same probability of failure. Consequently, there can be no possibility of precursory phenomena, which demonstrates that the matrix material is crucial. This indicates that the predictability of both (natural) earthquakes and (bead pile) avalanches, as demonstrated above, depends on the material of the matrix, where the similarities between Figs 1 and 2 confirm that earthquakes can be stress-forecast.

We speculate that all genuine physical systems with SOC, as opposed to artificial constructs of random data, will display precursory phenomena in appropriate circumstances.

6 CONCLUSIONS

We have shown (Crampin *et al.* 2008; Ramos *et al.* 2009); that at least in some circumstances phenomena with SOC can be predicted, thus removing a major criticism of the technique for stress-forecasting earthquakes (Crampin *et al.* 1999, 2008).

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