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FAST TRACK PAPER

Observations of stress relaxation before earthquakes

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

[1] *Centre for Analysis and Prediction, China Seismological Bureau,* 63 *Fuxing Avenue,* 100036 *Beijing, China. E-mail: gaoyuan@seis.ac.cn*
[2] *Shear-Wave Analysis Group, School of GeoSciences, University of Edinburgh, Grant Institute, West Mains, Edinburgh* EH9 3JW, *UK.*
E-mails: ygao@staffmail.ed.ac.uk; scrampin@ed.ac.uk
[3] *Edinburgh Anisotropy Project, British Geological Survey, Murchison House, West Mains Road, Edinburgh* EH9 3LA, *UK*

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SUMMARY

Theory and observations suggest that seismic shear wave splitting, caused by fluid-saturated stress-aligned microcracks, directly monitors low-level deformation before fracturing, faulting and earthquakes occur. In the past, it had been assumed that the accumulation of stress before earthquakes continued until stress was released by faulting at the time of the earthquake. However, new data and reappraisal of existing data sets now suggests that the stress begins to relax and cracks close from tens of minutes to months before the earthquake actually occurs, with the logarithm of the duration of the relaxation proportional to the magnitude of the impending earthquake. The duration of the relaxation appears to be directly correlated with earthquake magnitude, and may have implications for the earthquake source process and the ability to predict earthquakes.

Key words: precursory stress relaxation, shear wave splitting, stress-forecasting earthquakes, stress relaxation.

1 INTRODUCTION

There is increasing evidence to suggest that the almost universally observed stress-aligned splitting of seismic shear waves is caused by the anisotropy of stress-aligned fluid-saturated microcracks. These are stress-aligned grain boundary cracks in crystalline rocks, and thin pores and pore throats in porous sedimentary rocks. Changes in shear wave splitting appear to monitor the effects on the microcrack geometry of the stress accumulation before earthquakes. The effects have been seen, with hindsight, before some dozen earthquakes worldwide. On one occasion the phenomenon was recognized in real time and the time and magnitude of an $M = 5$ earthquake in southwest Iceland was successfully stress-forecast (Crampin *et al.* 1999). The theory and observations of these various phenomena have been comprehensively reviewed in a recent issue of this journal (Crampin & Chastin 2003, hereafter referred to as Paper 1), and the discussions will not be repeated here.

Low-level deformation (before fracturing occurs) can be modelled by anisotropic poro-elasticity (APE) which shows that shear wave splitting directly monitors stress-induced modifications to microcrack geometry. APE modelling demonstrates that, as had been previously recognized intuitively (Peacock *et al.* 1988; Crampin *et al.* 1990, 1991), accumulating horizontal (tectonic) stress increases the average aspect ratio of crack distributions of approximately parallel, approximately vertical stress-aligned microcracks. (Physically, this can be visualized as parallel fluid-saturated cracks swelling (bowing) when squeezed parallel to the plane of the cracks.) This increase in aspect ratio affects shear wave splitting by increasing the *average* time delay between the split shear waves in Band-1 directions. Band 1 is the double-leafed solid angle of ray path directions making angles between 15° and 45° either side of the average crack plane. Ray paths in Band-2 directions within the solid angle 15° either side of the average crack plane are sensitive principally to changes in crack density. Average crack planes are determined from rose diagrams of observed shear wave polarizations as in Fig. 1 for example. These various phenomena are fully discussed in Paper 1.

Note that increases in time delays of shear wave splitting monitoring stress accumulation before earthquakes are not precursory to earthquakes. They monitor *any* stress accumulation, and may be caused by movements of magma before volcanic eruptions as well as by stress accumulations before earthquakes (Paper 1).

Although few people have published work on these phenomena, APE modelling may be considered as comparatively well-established. Paper 1 lists some 15 different effects which are modelled by and are compatible with APE, including millions of individual source-to-receiver observations in industrial seismology. Usually the match of APE to observations can only be approximate, because of the difficulty of obtaining accurate subsurface measurements, where high temperatures and pressures inhibit direct instrumental access. However, when highly accurate observations are obtained, as in Angerer *et al.* (2002), the match of APE modelling to observations is nearly perfect. In particular, there is no contrary

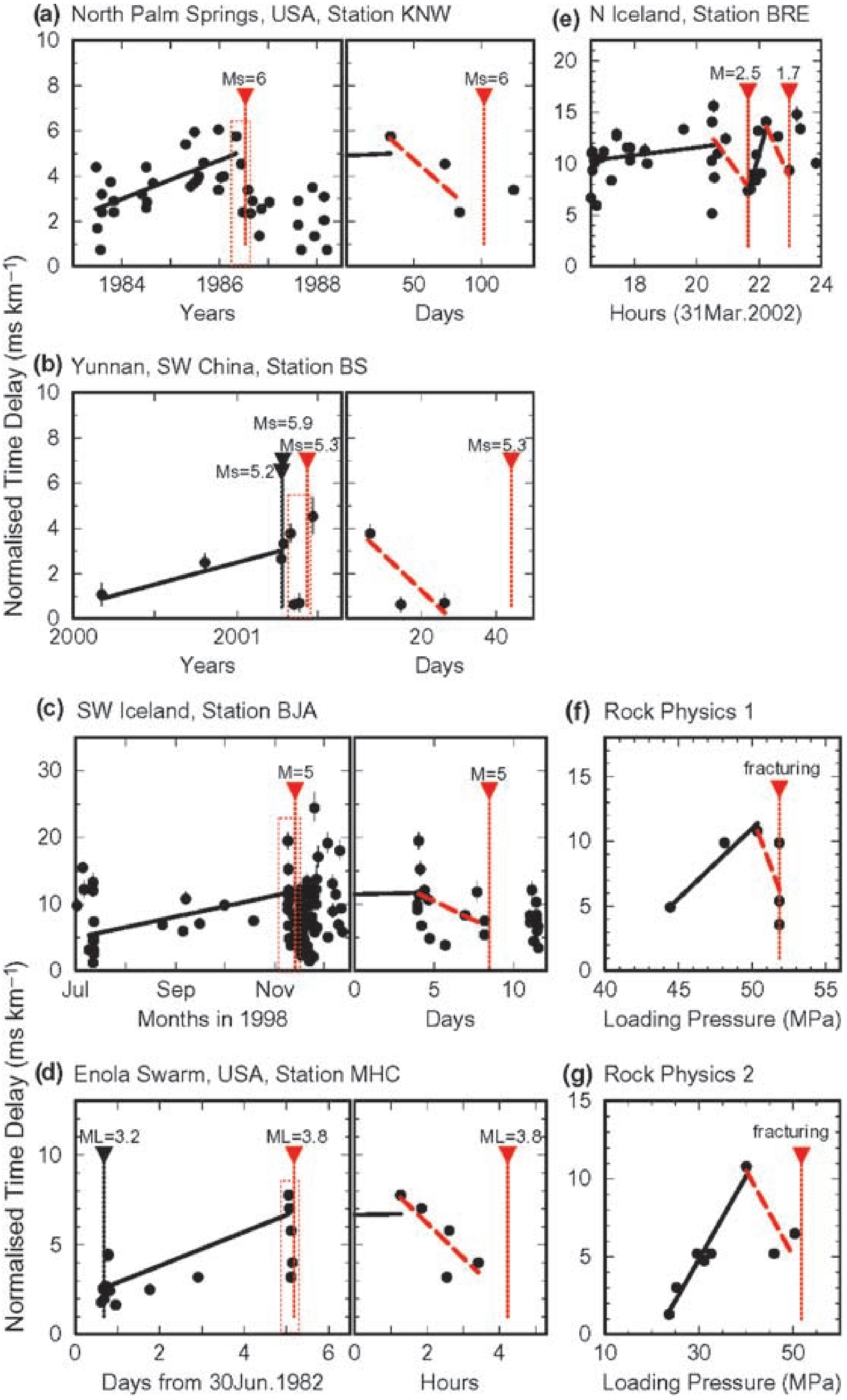

Figure 1. Precursory delays in field and laboratory. Shear wave time delays normalized to ms km^{-1} before earthquakes and experiments listed in Table 1 plotted against time for earthquakes and increments of applied stress for laboratory data. (a) $M_s = 6$ North Palm Springs earthquake (Crampin *et al.* 1990, 1991). Left-hand side: time delays with a least-squares line showing increase for 3 yr before the (red) earthquake. Right-hand side: enlarged timescale for the red dotted box in the left-hand-side, with the red dashed line showing the precursory decrease in time delays starting 68 days before the earthquake. (b) $M_s = 5.3$ earthquake (marked in red, the last of three closely spaced earthquakes with M_s greater than 5) in Shidian, Yunnan, China (Gao & Crampin 2003). Notation as above with poorly resolved increase before the black earthquake, but a precursory decrease of 38 days before the red $M_s = 5.3$ earthquake. (c) $M = 5$ earthquake in southwest Iceland (Volti & Crampin 2003b): with an increase for 5 months and a precursory decrease of 4.4 days. (d) $M_L = 3.8$ Enola Swarm event (Booth *et al.* 1990): Notation as in (a) with an increase for 4.1 days and a precursory decrease of 3.5 hr. (e) $M = 2.5$ and 1.7 in a swarm beneath Flatey Island in northern Iceland (Crampin & Chastin 2002; Crampin *et al.* 2004) with increases for 5.0 and 1.3 hr respectively, and precursory decreases of 1.12 and 0.73 hr respectively. (f), (g) Variation in time-delays in two marble samples, subjected to uniaxial stress increments until fracturing and fragmentation, for ray paths perpendicular to uniaxial stress (after Gao & Crampin 2003). At the final stress increment in Rock Physics 1, the time delays varied with time before spontaneous fracturing.

evidence refuting APE modelling, and Paper 1 reviews wholly consistent phenomena.

This paper reports new data and reappraisal of existing data sets that show changes in shear wave splitting suggesting precursory relaxation of stress *before* earthquakes occur. Since the duration of the precursory changes vary with the magnitude of the impending earthquake, these can be considered as true precursors.

2 PRECURSORY STRESS RELAXATION

Although there were exceptions, it had been previously assumed that the increase of time delays in Band 1 continued until stress was released at the time of the earthquake. The two exceptions were: (1) time delays in the Enola swarm, Arkansas began decreasing abruptly about 3.5 hr before a $M_L = 3.8$ earthquake (Booth *et al.* 1990); and (2) time-delays started decreasing abruptly about 4.4 days before a $M = 5$ earthquake in southwest Iceland (Crampin *et al.* 1999; Volti & Crampin 2003b). Reappraisal of existing data, new data from Yunnan, China (Gao *et al.* 2004) and previously unpublished data from Flatey Island, Iceland, suggest that such decreases are *always* present whenever there are sufficient source signals to monitor the phenomena: that is, when there are sufficient small earthquakes in the shear wave window below the recording stations. There are no contrary results. Similar precursory behaviour in shear wave splitting is also seen in laboratory experiments, where marble blocks were fractured under uniaxial stress (Gao & Crampin 2003).

Fig. 1 shows precursory decreases in shear wave splitting before six earthquakes with magnitudes ranging from $M_s = 6$ to $M = 1.7$, and before fracturing in the laboratory experiments. Note the different timescales, ranging from tens of minutes to years. Note also the different magnitude scales specified in the footnotes to Table 1. Table 1 lists the earthquakes and the durations of the precursory decreases, together with the distances at which the anomalies were observed, and likely fault dimensions. The table shows that the durations of the precursory decreases correlate with earthquake magnitudes (and with increments of stress in laboratory experiments).

The ordinate axes in Fig. 1 are normalized time delays in ms km^{-1}. Time delays in crustal rocks are usually less than 10 ms km^{-1}, but time delays in Iceland are approximately twice as large as those measured elsewhere (Volti & Crampin 2003b). We do not know the reason for this, but time delays in shear wave splitting are very sensitive to details of crack and pore-fluid geometry (Crampin 1993), and the larger time delays in Iceland are probably associated with the high heat flow modifying pore-fluid elasticity in layered basalt (Volti & Crampin 2003a,b).

Relying on small earthquakes for source signals means that many of the data sets are sparse, as the occurrence of small earthquakes is often sporadic. Despite the very different timescales, the precursory decreases (the dashed lines in Fig. 1) are superficially similar. The duration of the decrease varies with earthquake magnitude, where Fig. 2 plots the logarithm of the durations of the precursory decreases against earthquake magnitude. As with other earthquake phenomena, such logarithm to magnitude plots are essentially linear, indicating the self-similarity of critical systems verging on criticality and failure (Paper 1; Crampin & Chastin 2002; Crampin *et al.* 2003). The slopes of such plots are typically close to 1:1, as in Fig. 2. This supports our suggestion that the precursory decreases are phenomena associated with the earthquake source and may be considered as true earthquake precursors.

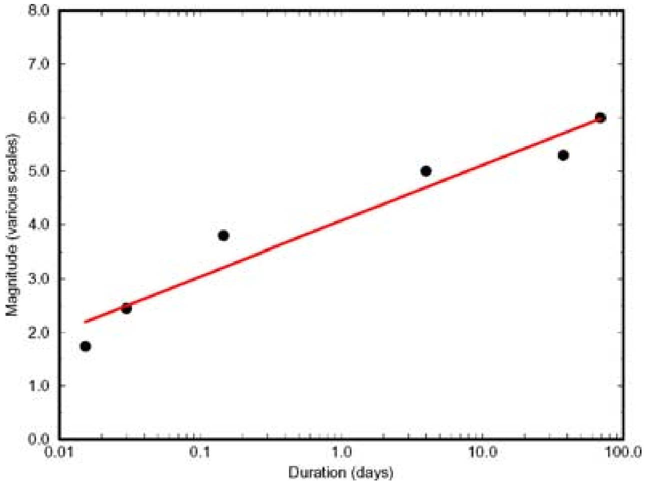

Figure 2. Duration of precursory decreases. Least-squares line through logarithm of duration in days plotted against earthquake magnitude for earthquakes listed in Table 1. Note that magnitudes are in different but similar scales specified in footnotes to Table 1.

Rikitake (1979) plotted a substantial number (391) of logarithmic precursor times against magnitude for a wide variety of phenomena. (Later papers by Rikitake reproduced similar data.) The four phenomena with most data are tilt and strain, foreshock activity, V_P/V_S anomalies, and resistivity anomalies. The plot in Rikitake (1979) is very scattered but gives an average slope of about 0.8:1, well-separated from the 1:1 slope in Fig. 2. The reason for the different slopes is not understood, but may be related to the sensitivity of shear wave splitting to microcrack geometry so that time delays pick up stress reorganizations early than other phenomena. Main & Meredith (1989) plot *b* values for foreshocks of the Western Nagano earthquake Imoto & Ishiguro (1986). These show a precursory drop both in seismic *b* values (defined by log $N = a - bM$, where N is

Table 1. Examples of precursory decreases in shear wave time delays.

Date	Earthquake location	Seismic station	Magn.	Duration of precursory decrease (days)	Distance to epicentre	Approx. fault diameter	Ref.
1988	North Palms Springs, CA, USA	KNW	$M_s = 6.0$	68	~30 km	~20 km	1
2001	Shidian, Yunnan Prov., China	BS	$M_s = 5.3$	38	~35 km	~7 km	2
1998	Southwest Iceland	BJA	$M\dagger = 5.0$	4.4	~2 km	~2 km	3
1982	Enola Swarm, Arkansas, USA	MHC	$M_d\ddagger = 3.8$	0.15	~2 km	~200 m	4
2002	Flatey Swarm, north Iceland	BRE	$M\dagger = 2.5$	0.05	~7 km	~20 m	5
2002	Flatey Swarm, north Iceland	BRE	$M\dagger = 1.7$	0.03	~7 km	~10 m	5
–	2 × Laboratory fracturing	–	–	–	–	~10 cm	6

† *Icelandic Bulletin* magnitude, $M \approx mb$

‡Duration magnitude, $M_d \approx ML$ (Haar *et al.* 1984)

References: 1, Crampin *et al.* (1990, 1991); 2, Gao & Crampin (2003); 3, Crampin *et al.* (1999); 4, Booth *et al.* (1990); 5, Crampin & Chastin (2002); Crampin *et al.* (2004); 6, Gao & Crampin (2003).

number of earthquakes larger than M and a and b are constants), and in stress and acoustic emissions in a stress-to-failure sandstone sample. They attribute both precursors to quasi-static fault slip immediately before failure. In laboratory uniaxial stress-to-failure tests, Lockner *et al.* (1991) also show precursory drops in b values, which again they attribute to fault nucleation.

The least-squares lines through the sparse scattered data of the precursory decreases (dashed lines) in Fig. 1 (in some cases through as few as three points) have poor statistical significance. Error bars, proportional to location errors, are shown for the time delay points (normalized to ms km^{-1}) for all figures except the early data (Figs 1a and d), and the laboratory data (Figs 1f and g) where they are too small to be visible.

The main support for the identification of the precursory relaxation phenomenon is the visual similarity of the plots of the dashed lines in the expanded timescales in Fig. 1, and the self-similarity of the almost exact 1:1 slope of the least-squares line in Fig. 2. This visual similarity is independent of the statistical significance (and independent of our attempt to explain the behaviour of shear wave splitting). The similarity and the 1:1 slope are strong indications that we are observing meaningful precursory phenomena.

Just as increasing time delays are thought to be universally present before all earthquakes and some volcanic eruptions, precursory decreases appear to be present before all earthquakes when there are adequate data, as in Fig. 1. The behaviour when data are less adequate is compatible with the possibility of precursory decreases.

3 THE SCATTER OF TIME DELAYS

Fig. 1 shows a pronounced scatter in measured time delays. Measurements of time delays of shear wave splitting, using small earthquakes as shear wave source signals, typically display a scatter of up to ±80 per cent about the mean. In contrast, measurements using controlled sources in exploration seismic surveys away from seismic faults do not show significant scatter. The scatter above earthquakes cannot be easily explained by conventional anomalies in earthquake location, measurement, analysis or interpretation (Volti & Crampin 2003a).

The apparent cause has recently been identified. Both theory and observations suggest that there are 90° flips in shear wave polarizations (faster and slower split shear waves exchange polarizations) on propagation through microcracked rocks with critically high pore-fluid pressures (Crampin *et al.* 2004). The behaviour of 90° flips is extremely sensitive to pore-fluid pressures in relation to the triaxial stress field. If we assume that all seismically active faults are pervaded by high pore-fluid pressures, APE modelling shows that minor alterations in pressure and triaxial stress, associated with the stress released at every earthquake, can easily cause the observed ±80 per cent scatter in the time delays (Paper 1; Crampin *et al.* 2004). Thus the scatter in shear wave time delays, which cannot be explained by conventional geophysics, can be explained by critically high pore-fluid pressures on all seismically active fault planes. The scatter is fully discussed in Paper 1 and Crampin *et al.* (2002, 2004).

4 IMPLICATIONS OF PRECURSORY DECREASES

There are three reasons why precursory stress relaxation may be important.

(1) The shear wave anomalies can be used as short-term precursors to earthquake occurrence, particularly in combination with the longer-term increases in Band-1 time delays, as indicators that an earthquake is about to occur. The duration of the decrease in time-delays can give some estimate of the magnitude of the impending event (Crampin *et al.* 1999).

(2) These precursory time delays are probably the only precursory phenomena that can be directly modelled and interpreted (Crampin *et al.* 2002, 2004), in terms of a relaxation of stress immediately before the earthquake occurs.

(3) Perhaps more importantly, the precursory decreases imply a relaxation of local compressional stress in the preparation zone of an earthquake well before the earthquake occurs. If this is correct, it suggests that the complex heterogeneous rock mass is responding to an imminent larger earthquake tens of minutes to months before the earthquake occurs, where the duration is related to the magnitude of the impending event. This has implications for the behaviour of earthquake source zones, and suggests that appropriate measurements can reveal deterministic short-term earthquake precursors months before large earthquakes. This is specifically denied by many who claim that the self-similarity of distributions, such as the Gutenberg–Richter relationship and the 1:1 line in Fig. 2, implies that small earthquakes cascade into larger earthquakes so that earthquakes are deterministically unpredictable.

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