Geophys. J. Int. (2006) **166,** 1293–1298 doi: 10.1111/j.1365-246X.2006.03054.x

Smaller source earthquakes and improved measuring techniques allow the largest earthquakes in Iceland to be stress forecast (with hindsight)

Jing Wu,[1,2] Stuart Crampin,[2,3]* Yuan Gao,[1,2] Ping Hao,[2] Theodora Volti[4] and Yun-Tai Chen[1]

[1]*Institute of Geophysics, China Earthquake Administration,* 100081 *Beijing, China*
[2]*Institute of Earthquake Science, China Earthquake Administration,* 100036 *Beijing, China*
[3]*Shear-Wave Analysis Group, School of GeoSciences, University of Edinburgh, West Mains Road, Edinburgh* EH9 3JW, *Scotland UK. E-mail: scrampin@ed.ac.uk*
[4]*IFREE, JAMSTEC, Yokohama* 236-0001, *Japan*

Accepted 2006 April 27. Received 2006 April 27; in original form 2005 July 8

SUMMARY

A group of three earthquakes in 2000 June in SW Iceland included the two largest earthquakes in Iceland in the past 30 yr. Previously, temporal changes in shear-wave splitting had not been recognized before these earthquakes as there were too few small earthquakes to provide adequate shear-wave data, and they were not stress forecast, even with hindsight. These large earthquakes were subject to a special investigation by the European Community funded PREPARED Project during which the seismic catalogue was extended to include smaller magnitude earthquakes. This more detailed data set, together with a semi-automatic programme for measuring the parameters of shear-wave splitting greatly increased the number of time-delay measurements.

The new measurements displayed the typical temporal variations before larger earthquakes as seen elsewhere: a long-term increase in time delays, interpreted as stress accumulation before the earthquake; and a decrease, interpreted as crack coalescence, immediately prior to the earthquake. The logarithms of the durations of both the implied accumulation of stress and the crack coalescence have the same self-similar relationships to earthquake magnitude as found elsewhere in Iceland. This means that, in principle, the time and magnitude of the larger earthquakes could have been stress forecast in real time had the smaller source earthquakes of the extended catalogue and the improved measuring procedures been available at the time.

Key words: extended seismic catalogue, forecasting earthquakes, improved measuring technique, polarizations, self-similarity, shear-wave splitting time delays.

1 INTRODUCTION

Theory and observations suggest that the accumulation of stress before earthquakes can be monitored by changes in the time delays between split shear waves along a particular range of ray-path directions in the shear-wave window (Crampin & Zatsepin 1997; Volti & Crampin 2003a,b; Gao & Crampin 2004). Self-similar relationships between the earthquake magnitude and the implied stress accumulations have now been identified, with hindsight, before some 15 earthquakes ranging from a *M* 1.7 swarm event in Iceland (Gao & Crampin 2004, 2006) to the 1999 *Ms* 7.7 Chi-Chi earthquake in Taiwan (Crampin & Gao 2005). On one occasion, the time, magnitude, and fault break of a *M* 5 earthquake in SW Iceland was successfully forecast in real time (Crampin *et al.* 1999). (Magnitude '*M*' in this paper refers to the Iceland seismic catalogue magnitude equivalent to *mb*).

Note that in eight cases, where there was sufficient shear-wave-source data, these earthquakes also showed precursory decreases immediately before the earthquake. Again the magnitude and the duration of the crack decreases were self-similar. Previously these decreases were interpreted as some (unidentified) stress relaxation (Gao & Crampin 2004), it is now suggested that crack coalescence is the most likely cause of the stress relaxation (Gao & Crampin 2006).

However, a series of three large earthquakes (referred to as 3LEQ), two of which were the largest earthquakes in the past 30 yr in Iceland, were not stress forecast, even with hindsight, because there were insufficient shear-wave source earthquakes to provide the necessary shear-wave ray-path data (Volti & Crampin 2003b). 3LEQ consisted

*Also at: Edinburgh Anisotropy Project, British Geological Survey, Murchison House, West Mains Road, Edinburgh EH9 3LA, UK of two *Ms* 6.6 earthquakes on 2000 June 17 and 21, and an *Ms* 5.7 event 2 min after the first *Ms* 6.6 earthquake.

Iceland has enhanced seismicity where transform faults of the Mid-Atlantic Ridge run onshore in SW and North Central Iceland. Seismic hazard is potentially severe and earthquake prediction studies in Iceland have been supported by the Nordic SIL Project (1988–1995) (Stefánsson *et al.* 1973) and European Commission-funded projects: PRENLAB (1996–1997 and 1998–1999), and SMSITES (2000–2003). When 3LEQ, the largest earthquakes in the past 30 yr were not predicted, the EC-funded project PREPARED was set up to investigate geophysical phenomena before, during and after 3LEQ. One of these investigations was to fine comb the data for small magnitude earthquakes to yield many subzero events. This present study of temporal changes before 3LEQ made use of this new extended catalogue from the PREPARED Project.

2 PREVIOUS FAILURE TO STRESS FORECAST

Fig. 1 shows variations in normalized shear-wave splitting time delays before 3LEQ (reproduced from Volti & Crampin 2003b). Theory (Crampin & Zatsepin 1997) suggests that the effect of low-level increases of stress, as in the accumulation of shear-wave propagation is to increase the average normalized time delay between the split shear stress before earthquakes, is to increase crack aspect ratios, and the effect of increasing aspect ratios on waves in Band-1 of the shear-wave window. This phenomenon was suggested intuitively by Peacock *et al.* (1988) and confirmed theoretically by Crampin & Zatsepin (1997). Band-1 is the double-leafed solid angle of ray paths between 15° and 45° either side of the average crack plane (Crampin 1999). Time delays in Band-2, ray paths within the solid angle 15° either side of the average crack plane, are sensitive principally to crack density, and crack density does not appear to change significantly for low-level increases of stress (Crampin 1999). Increases of time delays in Band-1 are the phenomena seen with hindsight before some 15 earthquakes worldwide (Crampin 1999; Volti & Crampin 2003b; Gao & Crampin 2004, 2006) and in one successful real-time stress forecast (Crampin *et al.* 1999).

When the behaviour of the normalized time delays before 3LEQ in Band-1 was first studied (Volti & Crampin 2003b), the time variation in Band-1 in Fig. 1 was dominated by a ∼6-weeks' absence of data from the end of 1999 December to the middle of 2000 February, and by the swarms at the ends of 2000 February and March. A least-squares line from the February swarm to just before 3LEQ does display an increase due to the accumulation of stress before the 3LEQ. However, the slope depends critically on earthquakes immediately before 3LEQ, and the duration was too short for the impending earthquake magnitude. Consequently, the increase was not identified at the time, and 3LEQ was not stress forecast. However, had we had the confidence to span the ∼6-weeks' absence of data and fitted the least-squares line from the end of 1999 December, the increase is the appropriate duration for the magnitude of the 3LEQ, and the time and magnitude of the 3LEQ might well have been successfully stress forecast. We were certainly searching for such phenomena at that time.

At least part of the reason for the ∼6-weeks' absence of data is the seismic quiescence before 3LEQ. Fig. 2 shows monthly histograms of the number of earthquakes $M \geq 0.0$ in the extended SIL seismic catalogue from 1996 to 2005. The 6 months immediately before the *Ms* 6.6 3LEQ earthquakes is the smallest 6 months' total in the whole 9 yr, and the month (May) immediately before 3LEQ is the lowest monthly total in the whole 9 yr. Had the extended catalogue been available at the time, this quiescence could have predicted an imminent large earthquake (but without any indication of magnitude or location).

Note that the large scatter of time delays in these swarms in Fig. 1 can be modelled as the result of 90°-flips in shear-wave polarizations caused by the modifications in microcrack geometry by critically high pore-fluid pressures on all seismically active faults (Crampin *et al.* 2004a). However, although we believe we understand what

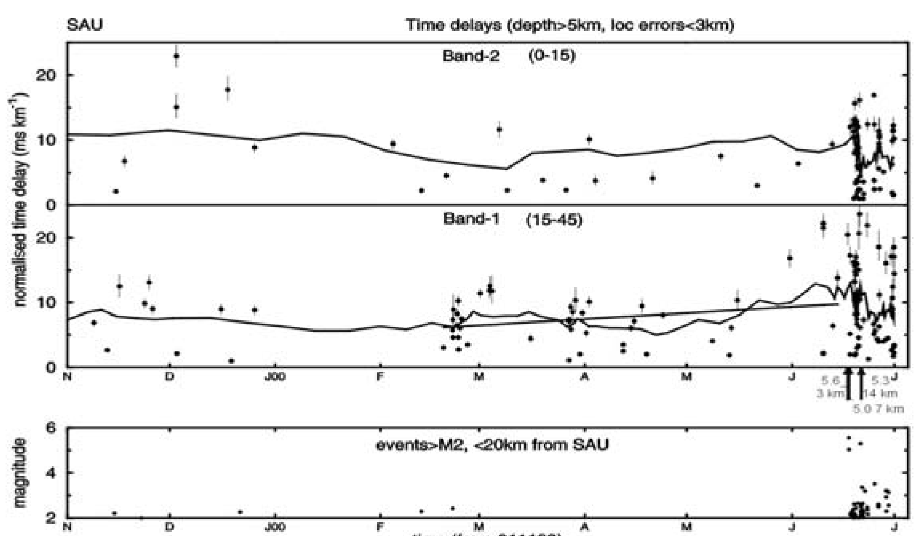

Figure 1. Variations of time delays between split shear waves for earthquakes in the period 1999 November to 2000 June at Station SAU. Earthquakes are below 5 km depth and have location errors less than 3 km. Middle and upper diagrams show the variation of time delays, normalized to ms km^{-1}, for ray paths in Band-1 and Band-2, respectively, of the shear-wave window. Error bars are time delays divided by the ray paths from the extremes of the hypocentral error ellipsoid. The irregular lines are nine-point moving averages drawn to show overall variations. The straight lines in Band-1 are least-squares lines fitted from just before a minimum of the nine-point moving average and ending at a larger earthquake. The arrows below the middle diagram indicate the times of the cluster of large events. The bottom diagram shows times and magnitudes of all earthquakes greater than M 2 within 20 km of SAU. (After Volti & Crampin 2003b).

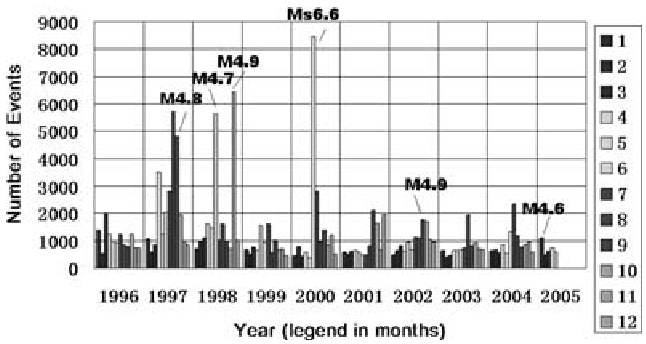

Figure 2. Monthly histogram of numbers of earthquakes from 1996 January to 2005 May in the Iceland 'PREPARED' seismic catalogue (within 100 km of the coast line) for earthquakes $M \geq 0.0$.

causes the scatter, critically high pore-fluid pressures, and can model the behaviour, the scatter cannot be eliminated.

Note also that, except for time delays before the 1986 North Palm Springs Earthquake (where there was statistically meaningful data, Peacock *et al.*, 1988), data points before the 15 earthquakes, where typical temporal variations have been recognized with hindsight, are too sparse and too scattered for meaningful statistical analyses. The analysis procedures are justified by the repetition of similar increases and decreases in time-delay variations observed worldwide (with no contrary results), and by the self-similarity of the magnitude-duration plots in Fig. 4, below.

3 ADVANCES IN DATA AND ANALYSIS

There have been three advances in data and data analysis since Fig. 1 was drawn.

(1) The Iceland seismic catalogue was extended (courtesy of the PREPARED project) to lower magnitude events down to M 0.0 and below. This greatly increased the number of time-delay data available for 2000.

Note that one of the distinguishing features of seismic recording in Iceland is that the seismic SIL network was designed to record and locate *all* possible earthquakes above the noise level (Stefánsson *et al.* 1973). Since small magnitude earthquakes typically provide high-quality shear-wave arrivals, with little disturbance from *P*-wave-generated noise, the Iceland seismic network provides excellent records for shear-wave splitting analysis.

(2) We used a new shear-wave analysis system (SWAS) developed for semi-automatic measuring of time delays and polarizations (Gao *et al.* 2006). SWAS uses an Expert System to determine preliminary values of time delays and polarizations. Typically, these automatic picks are within a few sample points of the best visual estimates. The advantage of SWAS is that it has a user-friendly format for rapidly adjusting and updating time delays and polarizations by comparing three screen images. These images are:

(i) Seismograms of EW, NS, vertical and horizontal-radial and horizontal-transverse orientations.

(ii) Seismograms of EW, NS, vertical and horizontal-fast and horizontal-slow orientations rotated parallel and perpendicular to the selected polarization, where picked sample points can be 'stepped' along the record by 'click buttons' until effects are optimized.

(iii) Polarization diagrams (hodograms) of horizontal particle motion, where again picked points can be adjusted by click buttons.

The ease of evaluating, updating, and adjusting screen images, where all adjustments are correlated across all images, and plotting diagrams, makes optimization of shear-wave splitting measurements rapid and comparatively effortless.

(3) The third advance lessens the impact of data clustering in the plots of time-delay variations. Earthquakes frequently cluster in time and space and, if such swarms occur within the shear-wave window, as at the ends of February and March 2000, in Fig. 1, the swarm activity tends to dominate the fitting of least squares to the data. We now lessen the impact of clustering by plotting only the daily average of (normalized) time delays.

4 CURRENT STRESS FORECAST (WITH HINDSIGHT)

Fig. 3 shows temporal variations in shear-wave splitting at Stations (a) SAU and (b) BJA using the PREPARED seismic catalogue increasing data availability, and using the semi-automated SWAS measurement technique to optimize time-delay picks, and plotting daily averages to lessen the impact of earthquake clustering. These techniques and the improved catalogue have eliminated (Fig. 3a) the $\sim$6-weeks' gap in data in Band-1 of SAU in Fig. 1. There is a comparatively well-defined increase in time delays starting at the end of 1999 December, 167 days before 3LEQ, which continues until a decrease starts about 30 days before 3LEQ.

Previously there were insufficient data to show temporal variations at Station BJA. The Band-1 data in Fig. 3(b) for BJA using the PREPARED seismic catalogue show a large scatter, and the start of the Band-1 increase is not well defined, but a least squares starting from the middle of 2000 January, 147 days before 3LEQ, continues until a well-defined decrease begins 17 days before 3LEQ.

Evidence suggests that the build-up takes place over a very large volume and it would be expected that the effects would be similar at SAU and BJA. The different measurements at BJA and SAU can be attributed to measurement and interpretation differences as a result of the sparseness and scatter in time delays (there is a 4-week gap in data at the start of the increase at BJA). However, since it is the logarithm of the duration, which is analysed in Fig. 4, below, the effects of the different measurements are minimized.

Fig. 4(a) plots the variation of the logarithm of the duration of the *increase* in Band-1 time delays (interpreted as stress accumulation) against the magnitude of the impending earthquake for earthquakes listed in Table 1(a) of Gao & Crampin (2006). Four earthquakes with questionable durations where the start of the increases are poorly constrained are omitted. The slope of the least-squares line is relatively well constrained at $M = 2.18\ (\pm 0.32)\ \log_{10}(\text{days}) + 0.33\ (\pm 0.70)$ but, due to inclusion of the North Palm Springs and Chi-Chi Taiwan earthquakes which are more than a magnitude away from the line, the errors on the constant term are comparatively large (see Discussion). The values for 3LEQ at SAU and BJA are comparatively close (within half a magnitude) from the least-squares line.

Fig. 4(b) plots the variation of the logarithm of the duration of the *decrease* in time delays (interpreted as crack coalescence) against the magnitude of the impending earthquake for earthquakes listed in Table 1(b) of Gao & Crampin (2006). The least-squares line is well constrained at $M = 1.19\ (\pm 0.15)\ \log_{10}(\text{days}) + 4.02\ (\pm 0.22)$, and the values for the 3LEQ at SAU and BJA are very close to the line.

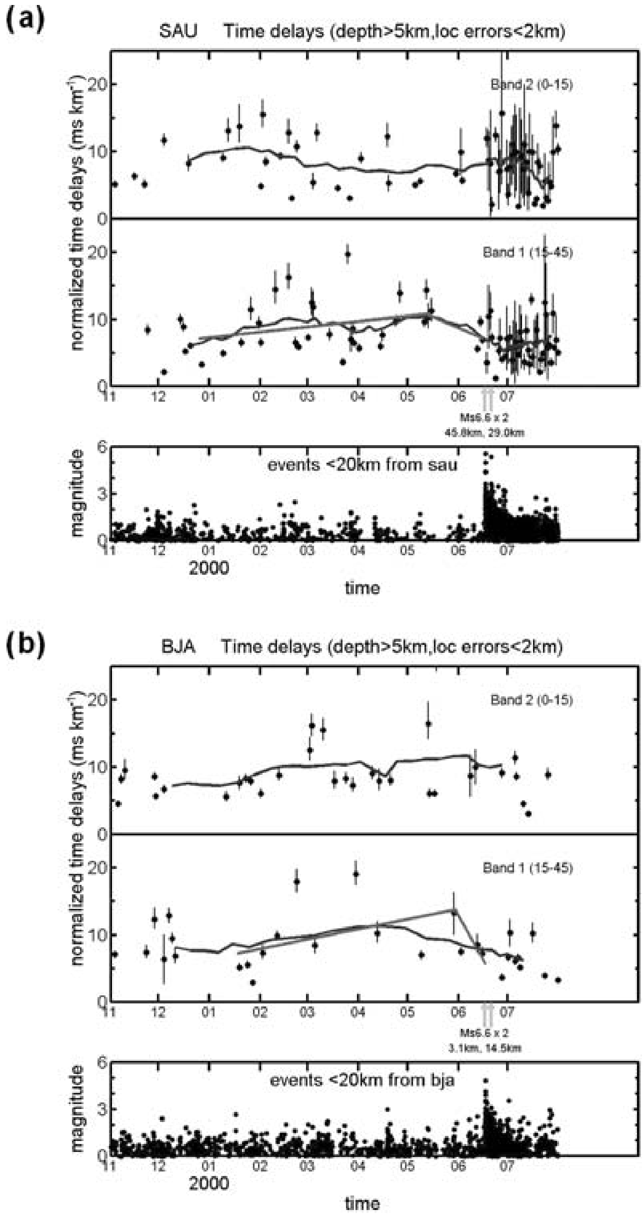

Figure 3. Variations of time delays at (a) Station SAU and (b) Station BJA for earthquakes in the extended seismic catalogue. Notation as in Fig. 1, except that only daily averages of normalized time delays are plotted, and the bottom diagrams show times and magnitudes of all earthquakes greater that *M* 0.0 within 20 km of (a) SAU and (b) BJA.

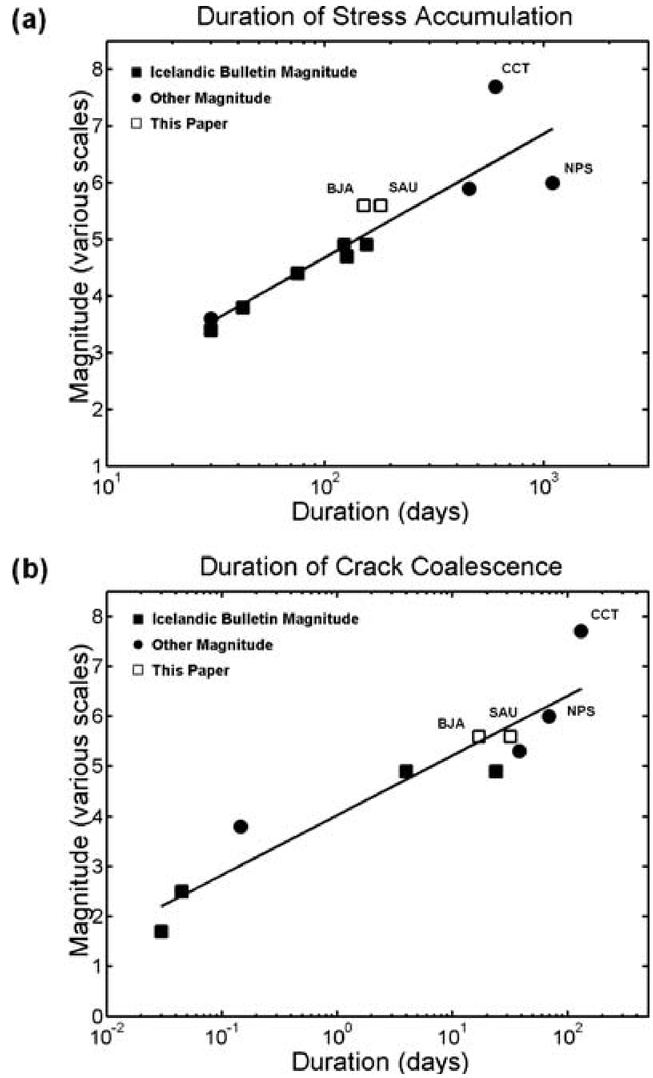

Figure 4. (a) Duration-magnitude relationship for the increases in time delays (interpreted as stress accumulation) for the earthquakes in Table 1(a) of Gao & Crampin (2006), omitting four earthquakes with questionable durations. (b) Duration-magnitude relationship for the decrease in time delays (interpreted as crack coalescence) for earthquakes listed in Table 1(b) of Gao & Crampin (2006). Note that the 3LEQ magnitude is plotted at the Iceland Catalogue value, *M* 5.8, for consistency with the other Iceland magnitudes. The earthquake labelled NPS and CCT refer to the 1988 *Ms* 6 North Palm Springs earthquake, California, and the 1999 *Ms* 7.7 Chi-Chi earthquake, Taiwan, respectively.

The closeness of 3LEQ to the least-squares lines in Figs 4(a) and (b) imply that the time and magnitude of 3LEQ could have been successfully stress forecast in real time if the catalogue of earthquakes including earthquakes down to *M* 0.0 and the improved measuring techniques had been available.

5 TEMPORAL CHANGES OR SPATIAL CHANGES IN SOURCE EARTHQUAKES

The time delays between split shear waves above small earthquakes are the sum of the delays along each particular ray path and carry no information about whether the anisotropy is uniformly distributed along the whole path length or due to a smaller section of stronger anisotropy. Stress-aligned seismic anisotropy has been observed at all depths in the crust (Crampin *et al.* 1986; Graham & Crampin 1993), which suggests that comparatively uniform anisotropy is distributed throughout most rocks in the crust (Crampin 1993). Consequently, the time delays that show temporal variations before earthquakes (Crampin 1999; Gao *et al.* 1998; Volti & Crampin 2003b; Gao & Crampin 2004, and others) have been normalized to hypocentral distance in ms km^{-1}. These variations provide relatively consistent patterns of behaviour showing increase in Band-1 time delays for some time before the earthquake with shorter-term (precursory) decreases immediately before the earthquake. In both cases, the logarithms of the durations of both the increases and decreases are proportional to the magnitude of the impending earthquake (we refer to this as self-similarity). If the assumption that anisotropy is approximately uniformly distributed were not substantially correct, these comparatively regular patterns of behaviour would be very unlikely.

Note that the only papers, which have directly questioned these temporal changes, Aster *et al.* (1990) and Seher & Main (2004), have been answered: Crampin *et al.* (1991) showed that the automatic measurements of Aster *et al.* (1990) were suspect and could be substantially in error by up to 300 per cent; and Crampin *et al.* (2004b) showed that the statistical analysis of Seher & Main (2004) analysing the time delays as a continuous time-series was inappropriate for analysis of discrete individual increases before each impending earthquake.

6 DISCUSSION

Time delays in earthquakes from the extended seismic catalogue of the PREPARED Project, listing earthquakes down to *M* 0.0, have shown consistent temporal variations before the 3LEQ earthquakes at Stations SAU and BJA, similar to those observed elsewhere. This means that the time and magnitude of 3LEQ could have been successfully stress forecast, and knowledge of the approach of a large earthquake might have the allowed the approximate location to be identified from other precursory phenomena, as it did before the successfully stress-forecast *M* 5 earthquake, where the impending fault-break was correctly identified by local seismic activity (Crampin *et al.* 1999). The increase at SAU in Fig. 3(a) would certainly have been recognized in 2000 May, at least 1 month before 3LEQ, and probably recognized at BJA. Note that we cannot distinguish between the effects of multiple and single earthquakes and we have treated the multiple 3LEQ as a single event of magnitude *Ms* 6.6.

It is thought that the slope of the duration-magnitude plots for stress accumulation depends on the rate of strain accumulation in the particular region. Thus the values from Iceland, square symbols in Fig. 4(a), reflect the strain associated with movement of the transform faults of the Mid-Atlantic Ridge. The two most anomalous points in Fig. 4(a), both *Ms* values, cannot be made compatible with the other data. They are the 1999 *Ms* 7.7 Chi-Chi earthquake in Taiwan associated with the subduction of the Philippine Plate and the 1986 *Ms* 6 North Palm Springs earthquake associated with right-lateral movement of the San Andreas Fault in California. It would not be expected that the rates of strain would be the same in these three very different tectonic environments.

In contrast, the duration-magnitude plots of crack coalescence in Fig. 4(b) are remarkably self-similar despite the different magnitudes scales. The anisotropic poro-elasticity (APE) model of rock mass evolution (Crampin & Zatsepin 1997; Crampin 1999) suggests that with increasing stress microcracks coalesce as the impending fault plane is beginning to be identified. This is thought to be the natural response of distributions of fluid-saturated stress-aligned microcracks as they approach fracture-criticality that APE suggests may be largely independent of the local rock type and tectonics. Such universality is expected in the assumptions of APE where the crust is pervaded by critical-systems of fluid-saturated stress-aligned microcracks (Crampin & Chastin 2003).

The increase of time delays in Fig. 2(a) is thought to be imaging the effect of increasing stress on the rock mass at considerable distance from the earthquake source zone, and is not precursory. In contrast, the decrease, imaging crack coalescence identifying the fault plane, appears to be a direct precursor to an earthquake (or an eruption—a similar decrease in time delays is observed before a volcanic eruption on Mount Etna, Bianco *et al.* 2006). That the precursory decrease is associated with the source zone is also suggested by Gao & Crampin (2006), who showed that a *M* 4.9 earthquake on the Grímsey Lineament caused a decrease at the nearest station at 50 km distance but not on a more distant station at 92 km.

ACKNOWLEDGMENTS

We thank Bergþóra S. Þorbjarnardóttir and Gunnar B. Guðmundsson for information about the Iceland Earthquake Catalogue. JW, YG & PH were partially supported by NSFC Project 40274011, China MOST Contract: 2004BA601B01, and a Royal Society Joint-Project with China. SC was partially supported by the European Commission PREPARED Project, Contract No. EVG1-CT2002-00073. We again thank our colleagues in Iceland for making the Icelandic data available.

REFERENCES

Aster, R., Shearer, P. & Berger, J., 1990. Quantitative measurements of shear-wave polarizations at the Anza seismic network, southern California: implications for shear-wave splitting and earthquake prediction, *J. geophys. Res.,* **95,** 12 449–12 473.

Bianco, F., Scarfì, L., Del Pezzo, E. & Patanè, D., 2006. Shear wave splitting time variation by stress-induced magma uprising at Mt. Etna volcano, http://www.earth-prints.org/handle/2122/1162.

Crampin, S., 1993. Arguments for EDA, *Can. J. Expl. Geophys.,* **29,** 18–30.

*Crampin, S., 1999. Calculable fluid-rock interactions, *J. Geol. Soc.,* **156,** 501–514.

*Crampin, S. & Chastin, S., 2003. A review of shear-wave splitting in the crack-critical crust, *Geophys. J. Int.,* **155,** 221–240.

*Crampin, S. & Gao, Y., 2005. Comment on 'systematic analysis of shear-wave splitting in the aftershock zone of the 1999 Chi-Chi, Taiwan, earthquake: shallow crustal anisotropy and lack of precursory changes,' by Liu, Teng, and Ben-Zion: temporal variations confirmed, *Bull. seism. Soc. Am.,* **95,** 354–360.

Crampin, S. & Zatsepin, S.V., 1997. Modelling the compliance of crustal rock: II—response to temporal changes before earthquakes, *Geophys. J. Int.,* **129,** 495–506.

Crampin, S., McGonigle, R. & Ando, M., 1986. Extensive-dilatancy anisotropy beneath Mount Hood, Oregon, and the effect of aspect ratio on seismic velocities through aligned cracks, *J. geophys. Res.,* **91,** 12 703–12 710.

Crampin, S., Booth, D.B., Evans, R., Peacock, S. & Fletcher, J.B., 1991. Comment on 'quantitative measurements of shear wave polarizations at the Anza Seismic Network, Southern California: implications for shear wave splitting and earthquake prediction' by R.C. Aster, P.M. Shearer & J. Berger, *J. geophys. Res.,* **96,** 6403–6414.

*Crampin, S., Volti, T. & Stefánsson, R., 1999. A successfully stress-forecast earthquake, *Geophys. J. Int.,* **138,** F1–F5.

*Crampin, S., Peacock, S., Gao, Y. & Chastin, S., 2004a. The scatter of time-delays in shear-wave splitting above small earthquakes, *Geophys. J. Int.,* **156,** 39–44.

*Crampin, S., Volti, T. & Stefánsson, R., 2004b. Response to 'A statistical evaluation of a 'stress-forecast' earthquake' by T. Seher & I. G. Main, *Geophys. J. Int.,* **157,** 194–199.

*Gao, Y. & Crampin, S., 2004. Observations of stress relaxation before earthquakes, *Geophys. J. Int.,* **157,** 578–582.

*Gao, Y. & Crampin, S., 2006. A further stress-forecast earthquake (with hindsight), where migration of source earthquakes causes anomalies in shear-wave polarisations, http://www.geos.ed.ac.uk/homes/scrampin/opinion.

Gao, Y., Wang, P., Zheng, S., Wang, M., Chen, Y.-T. & Zhou, H.-L., 1998. Temporal changes in shear-wave splitting at an isolated swarm of small earthquakes in 1992 near Dongfang, Hainan Island, Southern China, *Geophys. J. Int.,* **135,** 102–112.

*Gao, Y., Hao, P. & Crampin, S., 2006. SWAS: a Shear-Wave Analysis System for semi-automatic measurement of shear-wave splitting above small earthquakes, *Phys. Earth. planet. Inter.*, in press.

Graham, G. & Crampin, S., 1993. Shear-wave splitting from regional earthquakes in Turkey, *Can. J. Expl. Geophys.,* **29,** 371–379.

Peacock, S., Crampin, S., Booth, D.C. & Fletcher, J.B., 1988. Shear-wave splitting in the Anza seismic gap, Southern California: temporal variations as possible precursors, *J. geophys. Res.,* **93,** 3339–3356.

Seher, T. & Main, I.G., 2004. A statistical evaluation of a 'stress-forecast' earthquake, *Geophys. J. Int.,* **157,** 187–193.

Stefánsson, R. et al., 1973. Earthquake prediction research in the South Iceland Seismic Zone and the SIL Project, *Bull. seism. Soc. Am.,* **83,** 696–716.

*Volti, T. & Crampin, S., 2003a. A four-year study of shear-wave splitting in Iceland: 1. Background and preliminary analysis, in *New insights into structural interpretation and modelling*, Vol. 212, pp. 117–133, ed. Nieuwland, D.A., Geol. Soc. Lond., Spec. Publ.

*Volti, T. & Crampin, S., 2003b. A four-year study of shear-wave splitting in Iceland: 2. Temporal changes before earthquakes and volcanic eruptions, in *New insights into structural interpretation and modelling*, Vol. 212, pp. 135–149, ed. Nieuwland, D.A., Geol. Soc. Lond., Spec. Publ.

*Papers available at <http://www.geos.ed.ac.uk/homes/scrampin/opinion/>