Shear-wave splitting and earthquake forecasting

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ABSTRACT

Seismic shear-wave splitting (SWS) monitors the low-level deformation of fluid-saturated microcracked rock. We report evidence of systematic SWS changes, recorded above small earthquakes, monitoring the accumulation of stress before earthquakes that allows the time and magnitude of impending large earthquakes to be stress-forecast. The effects have been seen with hindsight before some 15 earthquakes ranging in magnitude from an M1.7 seismic swarm event in Iceland to the M7.7 Chi-Chi Earthquake in Taiwan, including a successfully stress-forecast of a M5.0 earthquake in SW Iceland. Characteristic increases in SWS time-delays are observed before large earthquakes, which abruptly change to decreases shortly before the earthquake occurs. There is a linear relationship between magnitudes and logarithms of durations of both increases and decreases in SWS time-delays before large impending earthquakes. However, suitably persistent swarms of small earthquakes are too scarce for routine stress-forecasting. Reliable forecasting requires controlled-source cross-hole seismics between neighbouring boreholes in stress-monitoring sites (SMS). It would be possible to stress-forecast damaging earthquakes worldwide by a global network of SMS in real time.

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Introduction

Stress-aligned shear-wave splitting (SWS) (seismic birefringence) is widely observed throughout the Earth’s crust (Crampin et al., 1990; Gao et al., 1995; Zhang et al., 2000; Miller and Savage, 2001; Cochran et al., 2006; Margheriti et al., 2006), where these widespread observations of azimuthally-varying seismic SWS suggest an internal stress-aligned structure in almost all in situ rocks (Crampin, 1994, 1999). Most rocks in the crust are pervaded by stress-aligned fluid-saturated microcracks, which have been shown to be the cause for the SWS (Crampin and Zatsepin, 1997; Crampin and Peacock, 2005, 2008). Fluid-saturated microcracks are the most easily modified components of the rock mass, whereas larger cracks tend to be rigid and less compliant. It can be shown that changes in SWS monitor the small-scale stress-induced deformation of microcracks throughout the rock mass before a level of microcracking known as fracture criticality is reached when rocks are expected to fracture (Crampin and Chastin, 2003). Both theory and field observations of SWS show that the accumulation of stress before earthquakes and volcanic eruptions builds up until fracture criticality is reached when shear-stress can no longer be maintained so that rocks tend to fracture and earthquakes or eruptions occur (Crampin and Zatsepin, 1997; Zatsepin and Crampin, 1997; Crampin and Chastin, 2003; Volti and Crampin, 2003a,b). When there are appropriate observations, these phenomena allow earthquakes to be stress-forecasted (Crampin, 1999). This study presents the evidence and discusses the use of SWS for stress-forecasting the time and magnitude of impending earthquakes.

SWS and microcracks in rocks in the crust

On entering anisotropic rock, shear-waves split into two nearly-perpendicular polarizations with different velocities, which write characteristic signatures into three-component seismograms. The faster split shear-wave is generally polarized approximately parallel to the direction of maximum horizontal stress (Fig. 1). Such stress-aligned SWS is caused by the distributions of stress-aligned fluid-saturated parallel vertical microcracks pervading almost all in situ rocks (Crampin, 1994). The only anisotropic symmetry system that displays such parallel polarizations, within a large part of shear-wave window is transverse isotropy (hexagonal symmetry)
with a horizontal axis of symmetry (TIH-anisotropy) or a minor variation thereof (Crampin, 1981). Additionally, the only geological configuration with such symmetry phenomena, common to both crystalline and sedimentary rocks, is stress-aligned cracks or microcracks (Crampin, 1994). SWS can be observed within the shear-wave window above almost all small earthquakes (Fig. 2).

The cracks are predominately stress-aligned fluid-saturated grain-boundary cracks in crystalline rocks, and low-aspect-ratio pores and pore throats in porous sedimentary rocks. The mechanism for alignment is fluid movement along pressure gradients between neighbouring microcracks at different orientations to the crack plane. This model of deformation is known as Anisotropic Poro-Elasticity (APE) (Crampin and Zatsepin, 1997; Zatsepin and Crampin, 1997). Such microcracks make the rock intrinsically anisotropic for elastic propagation of seismic waves at the frequencies of most earthquake and exploration signals (Crampin and Zatsepin, 1997). The levels of shear-wave velocity anisotropy indicate that even in ostensibly-intact unfractured rock, the fluid-saturated microcracks are so closely spaced that they are critical systems verging on fracturing with very high sensitivity to small disturbances (Crampin, 1994, 1999; Crampin and Peacock, 2005).

Although numerous experiments in rock physics laboratories show that seismic anisotropy, rock types, stress, microcracks, permeability and texture are associated (Rai and Hanson, 1988; Siegesmund et al., 1989, 1991; Sayers and van Munster, 1991; Cruts et al., 1995; Mavko et al., 1995; Kern et al., 1997; Christensen et al., 2001; Gao, 2001; Popp et al., 2001; Ma et al., 2003), APE is difficult to calibrate directly at depth as in situ rocks are essentially inaccessible, without destroying the in situ microcrack geometry. However, APE modelling matches a large range of phenomena referring to cracks, stress, and SWS, along many millions of individual shear-wave ray paths in seismic exploration (Crampin, 1999; Crampin and Peacock, 2005). The best calibration of APE-modelling to date is modelling the seismic response to both high- and low-pressure CO$_2$-injections at depth in a carbonate reservoir by Angerer et al. (2002), where the changes in SWS were the dominant effect (Davis et al., 1997).

**Changes in SWS before earthquakes**

The polarizations and time-delays of SWS are sensitive to small changes in
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Receivers are less sensitive to increasing temperatures and the shallower DOV in (b) is an earlier geometry (Crampin, 2001), where the DOV was in the deeper well. Note that this is revised from /C176

directions are at 442/211 442

DOV is the highly-repeatable Downhole Orbital Vibrator (Leary and Walter, 1999). (b) SMS geometry, where directions are between 15° and 45° either side of the average crack plane and Band-2 are directions within 15° either side of the average crack plane (also see Crampin, 1999). (b) SMS geometry, where Xm is the depth below which the minimum compressional stress is horizontal so that cracks tend to be aligned vertically. The DOV is the highly-repeatable Downhole Orbital Vibrator (Leary and Walter, 2005a,b). The DOV source operates at Xm depth in the shallower well and receivers are at X + 1000 m depth in (at least two) vertical wells at 300-m offset. The azimuths of the offsets should be within ±45° of the direction of minimum horizontal stress, which for this illustration is taken to be North–South. Note that this is revised from an earlier geometry (Crampin, 2001), where the DOV was in the deeper well. Receivers are less sensitive to increasing temperatures and the shallower DOV in (b) is more robust.

microcrack geometry. APE modelling shows that the effect of increasing stress is to increase crack aspect-ratios and this can be monitored by increasing average time-delays in Band-1 of the shear-wave window (Crampin and Zatsepin, 1997). Band-1 and Band-2 ray-path geometry is illustrated in (Fig. 3a). Time-delays in Band-2 directions are sensitive to crack density and crack densities are not affected by small changes of stress below levels of fracture-criticality and fracturing (Crampin, 1999). Consequently, low-level changes of stress (pre-fracting deformation) can be monitored by changes in average time-delays along ray paths in Band-1 directions. However, suitable seismic swarms are extremely scarce and it is difficult to find appropriate swarm activity for routine stress forecasting (Crampin, 1993, 1999). A controlled-seismic source is required in a borehole stress-monitoring site (SMS) the geometry of which is given in (Fig. 3b).

Observations of time-delays above small earthquakes invariably display a ±80% scatter about the mean (Volit and Crampin, 2003a; Crampin and Peacock, 2005), whereas controlled-source observations typically display negligible scatter (for example, Li and Crampin, 1991). Crampin et al. (2004) have shown that the scatter is probably caused by the critically high pore-fluid pressures on all seismically active fault planes. The critically high pore-fluid pressures rearrange microcrack geometry and cause 90°-flips in shear-wave polarizations, where the fast and slow shear-waves exchange polarizations (Crampin et al., 2002). Each earthquake changes local stress and pore-fluid pressures. Small variations in the proportions of the high-pressure to normal pressurized path lengths at each earthquake modify the triaxial stress-field and the pore-fluid pressures can easily cause the observed ±80% scatter (Crampin et al., 2004).

Notwithstanding these difficulties and limitations, small earthquakes as a source of shear-waves provide valuable observations of temporal change in SWS before larger earthquakes. Average changes in time-delays in Band-1 directions have been observed, with hindsight, before the 15 earthquakes worldwide listed in (Table 1) with magnitudes ranging from M1.7 to M7.7 (Volit and Crampin, 2003b; Gao and Crampin, 2004, 2006). On one occasion (event 10, Table 1), the time and magnitude of a M5.0 was successfully stress forecast (Crampin et al., 1999). In that case, continuing seismicity on a neighbouring fault also allowed the impending fault plane to be identified (Crampin et al., 1999).

It had previously been assumed that the accumulation of stress before earthquakes continued until stress is released by faulting at the time of the earthquake. A recent study suggests that the stress begins to relax and microcracks close from tens of minutes to months before the earthquake actually occurs. The duration of the decrease indicated by time-delays (Table 1) is known as the ‘stress relaxation’ (Gao and Crampin, 2004). Similar stress relaxation has also been observed before a volcanic eruption (Bianco et al., 2006). This stress relaxation may have important implications for the process of fracturing in both earthquake and volcanic source processes. It almost certainly reflects the coalescing or clustering of small microcracks into larger through-going fractures as fracture criticality is approached. Such crack coalescence decreases both crack density (as cracks coalesce and get fewer in number), and average aspect-ratios (as the same fluid volume is distributed over larger cracks) resulting in a decrease in Band-1 time-delays. Figure 4 is an example of SWS temporal changes and measurements of durations of increases and decreases in time-delays. The durations of increases and decreases indicate the durations of stress accumulation and stress relaxation.

**Variations in SWS with magnitudes**

The relationship between the logarithm of duration of inferred stress accumulation and magnitude is shown

Fig. 3 (a) The geometry of Band-1 and Band-2 directions in the shear-wave window in a distributions of parallel vertical cracks (modified from Volit and Crampin, 2003a). The circle is a section of a vertical cone of ray-path directions within which source events are in the effective shear-wave window at a seismic horizontal free-surface, where there are typically low-velocity surface layers. Band-1 ray-path directions are between 15° and 45° either side of the average crack plane and Band-2 are directions within 15° either side of the average crack plane (also see Crampin, 1999). (b) SMS geometry, where Xm is the depth below which the minimum compressional stress is horizontal so that cracks tend to be aligned vertically. The DOV is the highly-repeatable Downhole Orbital Vibrator (Leary and Walter, 2005a,b). The DOV source operates at Xm depth in the shallower well and receivers are at X + 1000 m depth in (at least two) vertical wells at 300-m offset. The azimuths of the offsets should be within ±45° of the direction of minimum horizontal stress, which for this illustration is taken to be North–South. Note that this is revised from an earlier geometry (Crampin, 2001), where the DOV was in the deeper well. Receivers are less sensitive to increasing temperatures and the shallower DOV in (b) is more robust.
Table 1 Duration and epicentral distance of changes in SWS time-delays before earthquakes.

<table>
<thead>
<tr>
<th>No.</th>
<th>Location, Date</th>
<th>Approx. Epi. distance (km)/Station</th>
<th>Magnitude*</th>
<th>Approx. duration (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>( T_{\text{ACC}} )</td>
</tr>
<tr>
<td>1</td>
<td>Swarm, N Iceland, 31 Mar 2002</td>
<td>7/BRE</td>
<td>1.7 ( M_d )</td>
<td>( \geq 0.055 )</td>
</tr>
<tr>
<td>2</td>
<td>Swarm, N Iceland, 31 Mar 2002</td>
<td>7/BRE</td>
<td>2.5 ( M_d )</td>
<td>( \geq 0.210 )</td>
</tr>
<tr>
<td>3</td>
<td>SW Iceland, 29 Dec 1997</td>
<td>10/BIA</td>
<td>3.4 ( M_d )</td>
<td>47</td>
</tr>
<tr>
<td>5</td>
<td>Enola Swarm, Arkansas, 5 Jul 1982</td>
<td>3/MHC</td>
<td>3.8 ( M_d )</td>
<td>( \geq 4.5 )</td>
</tr>
<tr>
<td>6</td>
<td>SW Iceland, 12 Apr 1997</td>
<td>14/BIA</td>
<td>3.8 ( M_d )</td>
<td>40</td>
</tr>
<tr>
<td>7</td>
<td>Parkfield, California, 25 May 1989</td>
<td>14/VC</td>
<td>4.0 ( M_d )</td>
<td>478</td>
</tr>
<tr>
<td>8§</td>
<td>SW Iceland, 24 Aug 1997</td>
<td>10/BIA</td>
<td>4.4 ( M_d )</td>
<td>83</td>
</tr>
<tr>
<td>9§</td>
<td>SW Iceland, 4 Jun 1998</td>
<td>43/KRI</td>
<td>4.7 ( M_d )</td>
<td>77</td>
</tr>
<tr>
<td>10§</td>
<td>SW Iceland, 13 Nov 1998 (successfully stress-forecast)</td>
<td>2/BIA</td>
<td>4.9 ( M_d )</td>
<td>127</td>
</tr>
<tr>
<td>11§</td>
<td>Grimsey Lineament, N Iceland, 16 Sep 2002</td>
<td>50/GRI</td>
<td>4.9 ( M_d )</td>
<td>147</td>
</tr>
<tr>
<td>12</td>
<td>Shidian, Yunnan, China, 12 Apr 2001 (mainshock)</td>
<td>35/BS</td>
<td>5.9 Ms</td>
<td>404</td>
</tr>
<tr>
<td>12a</td>
<td>Shidian, Yunnan, China, 8 Jun 2001 (aftershock)</td>
<td>35/BS</td>
<td>5.3 Ms</td>
<td>–</td>
</tr>
<tr>
<td>13</td>
<td>N Palm Springs, California, 8 Jul 1986</td>
<td>33/KNW</td>
<td>6.0 Ms</td>
<td>1106</td>
</tr>
<tr>
<td>14§</td>
<td>SW Iceland, 17 Jun 2000</td>
<td>3/BIA</td>
<td>6.6 Ms/5.6 Ms</td>
<td>175</td>
</tr>
<tr>
<td>15</td>
<td>Chi-Chi earthquake, Taiwan, 21 Sep 1999</td>
<td>55/CHY</td>
<td>7.7 Ms</td>
<td>598</td>
</tr>
</tbody>
</table>

\( T_{\text{ACC}} \) and \( T_{\text{REL}} \) are respectively observation durations of inferred stress accumulation and stress relaxation, as formulae (1) and (2). The mark ‘–’ in column \( T_{\text{REL}} \) means N/A, i.e. not assessed, because of lack of source earthquakes.

* Icelandic Bulletin Magnitude, \( M = M_L \); Duration magnitude, \( M_d \approx M \) (Haar et al., 1984). Magnitudes of the Icelandic earthquake catalogue have recently been updated from \( M \) to \( M_d \) for events in Table 1. The original magnitudes, \( M \), have been retained in the text in this paper.

† For a variety of reasons, a number of time-delays are unreliable because of: earthquakes overlain by preceding earthquakes (events 1, and 5); duration owing to: lack of source earthquakes (14). The original magnitude is \( M \), i.e. not assessed, because of lack of source earthquakes.

‡ For a variety of reasons, a number of time-delays are unreliable because of: earthquakes overlain by preceding earthquakes (events 1, and 5); duration owing to: lack of source earthquakes (14). The magnitude scales and this may well contribute to the scatter.

If we define the durations of the increases in time-delays as \( T_{\text{ACC}} \), the magnitude of earthquake as \( M \), then a least-square fit line constrains \( T_{\text{ACC}} \) and \( M \) in the relation (Fig. 6), where:

\[
M = a \log_{10}(T_{\text{ACC}}) + b, \tag{1}
\]

where \( a \) and \( b \) are constants. Note that \( T_{\text{ACC}} \) is the duration from the start time of the stress accumulation to time of earthquake occurrence (Fig. 4). The heavy-dashed lines in (Figs 5 and 6) are the least-squares fit for reliable data in various magnitudes: \( a = 2.19 \pm 0.33; \quad \text{and} \quad b = 0.31 \pm 0.70 \) with a correlation coefficient of 0.88. Considering only earthquakes in Iceland, the least-squares fit leads to: \( a = 2.80 \pm 0.35 \) and \( b = -0.97 \pm 0.71 \); with a correlation coefficient of 0.93. Here, \( M \) is the Icelandic catalogue magnitude approximately equivalent to \( m_d \).

Figure 7 shows another self-similar relationship between the duration of stress relaxation and magnitude for ten earthquakes listed under column headed ‘\( T_{\text{REL}} \)’ in (Table 1). Such decreases in time-delays are found whenever there are sufficient shear-wave source data. The slope in (Fig. 7)
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 depend on the rate of coalescence of cracks, which may well be less dependent on rock type, and show less variability than the rate of stress accumulation in different tectonic regions.

Similarly, if we define the durations of the decreases in time-delays as $T_{\text{REL}}$, then a similar least-square fit is expected to constrain $T_{\text{REL}}$ and $M$ (Fig. 7). We have:

$$ M = a \log_{10}(T_{\text{REL}}) + b, \quad (2) $$

where $a$ and $b$ are two constants. Note that $T_{\text{REL}}$ is the duration from the start of the stress relaxation before the earthquake to time of earthquake occurrence (Fig. 4). The long-dashed line in (Fig. 7) is the least-squares fit for reliable data in various magnitudes scales. The least-squares fit results are: $a = 1.18 \pm 0.15$ and $b = 3.98 \pm 0.21$; with a correlation coefficient $= 0.94$. Considering only Icelandic earthquake data, the least-square fit (solid line) is similar: $a = 1.16 \pm 0.10$; and $b = 3.78 \pm 0.13$; with a correlation coefficient of 0.98.

The formulae (1) and (2) are fitted to the updated data in (Table 1), where higher values of the correlation coefficients suggest more reliable self-similar relationships from consistent datasets.

**Stress-forecasting earthquakes at SMSs**

It is difficult to investigate routinely temporal variations of SWS using small earthquakes as the source of shear-waves because of the scarcity of appropriate swarm activity and the lack of source-receiver geometry (Crampin, 1993). The cause of the typical $\pm 80\%$ scatter of SWS time-delays is understood, but its effects cannot be eliminated. Consequently, it requires extensive datasets to obtain meaningful estimates of the variations. Isolated swarms of small earthquakes, where the sources are restricted to a small volume, are particularly valuable for studies in SWS temporal variation and could reduce disturbances from spatial inhomogeneous tectonics (Booth et al., 1990; Crampin, 1993; Gao et al., 1998). Unfortunately, they are generally too scarce to be used for routine stress forecasting except in fortuitous circumstances as in SW Iceland where onshore transform faults of the Mid-Atlantic Ridge provide persistent seismicity (Volti and Crampin, 2003a). Controlled-source SMSs using cross-hole seismics between adjacent boreholes would resolve these difficulties.

The prototype SMS, the EC-funded SMSITES Project at Húsavík in northern Iceland, installed a DOV (Fig. 3b) and three-component geophones in existing wells drilled for geothermal purposes. Despite non-optimal geometry, the cross-well seismics showed spectacular sensitivity of SWS to a burst of low-level seismicity on a neighbouring transform fault at 70 km distance (Crampin et al., 2003). The energy released by the seismicity was equivalent to one (comparatively small) $M \sim 3.5$ earthquake, at a distance several hundred times the likely source dimensions. These records showed exceptional sensitivity well beyond that expected in the conventional brittle-elastic crust. With the examples in (Table 1), they bring a new understanding to earthquake forecasting (Crampin et al., 2008a).

The shear-waves need to be recorded below about 1 km to be below the scattering and attenuation inherent in near-surface recordings. The prototype SMS confirms both the science and technology of SMSs for forecasting impending earthquakes.

This sensitivity to low-levels of seismic energy release confirms that a single SMS, with three ($1\text{–}1.5$ km deep) wells, could recognize stress-
in time-delays, i.e. the $T_{ACC}$ in the fitting formula (1).

Fig. 5 Duration–magnitude relationship for the increases in time-delays (interpreted as stress accumulation). The numbers refer to earthquakes listed in (Table 1). Solid points are thought to be reliable data. Open points are less reliable (earthquakes numbered 1, 2, 5, 7 and 12) for the reasons listed in (Table 1). Double points (earthquakes numbered 8, 9, 10, 11 and 14) are range of durations for different seismic stations. The least-squares fit lines are shown as a thin-dashed line fitted through whole data and a heavy-dashed line fitted through the reliable data which is dominated by the Icelandic data. ‘Duration’ in figure means the duration of increases in time-delays, i.e. the $T_{ACC}$ in the fitting formula (1).

Fig. 6 Duration–magnitude relationship for the increases in time-delays. Solid points are thought to be reliable data. Only reliable data are adopted with the numbers referred to earthquakes listed in (Table 1). The least-squares fit lines are shown as a heavy-dashed line fitted through the reliable data for various magnitudes (same as Fig. 5), and as a solid line fitted through reliable data only for Icelandic data. ‘Duration’ here means the duration of increases in time-delays, i.e. the $T_{ACC}$ in the fitting formula (1).

accumulation several months before a $M5$ earthquake at a distance of up to $\sim 400$ km. $M5$ is approximately the minimum size for a damaging earthquake. Stress-accumulation before a $M6$ earthquake could be recognized up to $\sim 800$ km; $M7$ to $\sim 1500$ km; and $M8$ to plate-wide if not worldwide (Crampin et al., 2008b). The exceptional sensitivity is because fluid-saturated microcracks are so closely spaced they are critical systems. Crampin et al. (2008b) suggest that a global network of SMSs, on a 400 km grid, say, would be an effective tool to recognize the approach of large earthquakes.

Discussion

Earthquake prediction or earthquake forecasting has been discussed for 120 years with singular lack of success (Geller, 1997). The problem is not well understood and considerable research is still required (Silver, 1998).

Source zones are small for both earthquakes (Chen and Xu, 2000) and eruptions (Gudmundsson, 2006). However, the sensitivity of SWS to subtle deformation of stress-aligned microcracks in rock allows SWS monitoring far beyond the simple source zone (Crampin et al., 2008).

Temporal changes in SWS have already been observed many times in the field (Crampin et al., 1990; Gao et al., 1998; Miller and Savage, 2001; Teanby et al., 2004; Bianco et al., 2006; Wu et al., 2006). However, SWS is frequently misunderstood (Crampin and Peacock, 2008). The principal problem of investigating temporal variations in SWS is that seldom sufficient high-quality data are there before and after large earthquake in suitable station-to- earthquake recording geometries (Crampin and Chastin, 2003; Crampin and Gao, 2005). Many current analysis techniques for SWS are sufficiently effective for measuring polarizations of fast shear-waves, but are inadequate for measuring time-delays (Crampin and Gao, 2006; Gao et al., 2006), which are the key element in monitoring stress accumulation before earthquakes.

Stress relaxation immediately before rock rupture is found in rock experiments monitored by SWS (Gao, 2001; Gao and Crampin, 2003) and by direct measurements on differential stress (Ma et al., 2003), although theory on stress relaxation is not wholly understood.

The self-similar relationships between earthquake magnitudes and logarithmic durations of stress accumulation and crack coalescence analyzed in this study suggest that SWS could be adopted to monitor seismicity both in natural earthquake zones (Booth et al., 1990; Crampin et al., 1990, 1991; Gao et al., 1998; Tadokoro and Ando, 2002; Sase et al., 2003;...
Voll and Crampin, 2003b; Gao and Crampin, 2004, 2006) and in volcanic zones (Miller and Savage, 2001; Voll and Crampin, 2003b; Gerst and Savage, 2004; Bianco et al., 2006).

The hypothesis for stress accumulation here is that there is a uniform rate of strain increase because of the movement of tectonic plates. Consequently, if stress builds up over a small rock volume, the increase is rapid, but of short duration and the resulting earthquake is comparatively small. Whereas, if the stress builds up over a larger volume, the increase is slower, but of longer duration, and the final earthquake is larger. The self-similarity of (Figs 5 and 6) supports this hypothesis.

Note that it is suggested that the rate of tectonic strain increase, leading to the straight lines in (Figs 5 and 6), is dependent on the particular plate boundary. The subduction of the Pacific Plate under Japan and Taiwan appears to have a relatively rapid rate of strain increase leading to a short time for stress accumulation before the Chi-Chi Earthquake in Taiwan (event 15, Table 1). However, the stress accumulation before the strike-slip motion of the San Andreas Fault onshore in California is likely to be very much slower leading to much less seismic activity and a lower value of stress accumulation for the North Palm Springs Earthquake (event 13, Table 1).

There are two ways to monitor effectively seismicity by SWS to forecast large earthquakes. One way is to monitor closely spaced seismic arrays when there are suitably-persistent swarms of small earthquakes. The other way is to set up the controlled-source SMS in a network of SMSs, a Global Earthquake Monitoring System (Crampin et al., 2008b) for routine reliable stress-forecasting, which is expensive, but would place mankind in control of earthquake hazards as well as provide the intellectual stimulus of investigating a critical system on which we are all totally dependent. SWS is opening a new window in forecast earthquakes in real time.

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References


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


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