Stress-forecasting (not predicting) earthquakes: A paradigm shift?

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ABSTRACT
After 120 years of unsuccessful endeavor, a paradigm shift is required before earthquakes can be predicted. The most sensitive diagnostic of low-level changes of stress in in situ rock, variations in microcrack geometry, can be monitored by analyzing shear-wave splitting. The suggested paradigm shift is that, instead of investigating the source zone, we monitor stress accumulation before earthquakes at, possibly, substantial distances from the source. Characteristic temporal variations of shear-wave time delays have been observed in retrospect before 14 earthquakes worldwide. On one occasion, when changes were recognized early enough, the time, magnitude, and fault break of an M = 5 earthquake in southwest Iceland were successfully stress-forecast in a narrow time-magnitude window. Such stress accumulation can be theoretically modeled and is believed to be at least partially understood. When sufficient shear-wave source earthquakes are available, increasing time delays also show an abrupt decrease shortly before the impending earthquake occurs. This is not fully understood but is thought to be caused by stress relaxation as microcracks coalesce onto the eventual fault break. The new result confirming these ideas, and justifying the paradigm shift, is that logarithms of the durations of both increases and decreases in time delays are found to be proportional (self-similar) to the magnitudes of impending earthquakes.

Keywords: stress accumulation, paradigm shift, shear-wave splitting, stress-forecasting earthquakes.

INTRODUCTION
In a comprehensive review of earthquake prediction, Geller (1997) concludes that a paradigm shift is required before times, magnitudes, and epicenters of large earthquakes can be predicted. Previous attempts at earthquake prediction investigated the earthquake source (and associated precursors) with singular lack of success. We suggest that the paradigm shift is to neglect the earthquake source zone, which is locally heterogeneous and probably overly complicated by initial conditions (Geller, 1997). Instead, with a new understanding of fluid-rock deformation (Crampin, 1999, 2006; Crampin and Peacock, 2005), seismic shear-wave splitting is used to monitor the buildup of strain energy in the rock mass remote from the source. We refer to increasing strain energy as "stress accumulation." Since rock is weak to shear stress, stress must accumulate over enormous volumes of rock in order to amass sufficient energy for release by large earthquakes. This allows stress accumulation to be recognized at substantial distances from the eventual source zone. We report new results showing that the time, magnitude, and in some cases location of earthquakes can be stress-forecast by monitoring swarm activity with shear-wave splitting.

MONITORING IN SITU STRESS WITH SHEAR-WAVE SPLITTING
Azimuthally aligned shear-wave splitting (seismic birefringence) is widely observed throughout Earth’s crust in almost all geological and tectonic regimes. The polarizations of the faster split shear waves are typically parallel to the direction of maximum horizontal stress (Crampin, 1981, 1994, 2006; Alford, 1986). Shear-wave splitting is diagnostic of some form of seismic anisotropy, and the only anisotropic symmetry system that has such parallel polarizations for propagation within ~30° of the vertical is hexagonal symmetry (transverse isotropy) with a horizontal axis of symmetry (Crampin, 1981). Moreover, the only geological configurations common to almost all in situ igneous, metamorphic, and sedimentary rocks that have such symmetry are distributions of fluid-saturated microcracks that are aligned, like hydraulic fractures in the oil industry (Hubbert and Rubey, 1959), perpendicular to the direction of minimum horizontal stress (Crampin, 1981, 1994, 2006).

Figure 1 gives a schematic illustration of shear-wave splitting in stress-aligned microcracked rock. Fluid-saturated microcracks are the most compliant elements of in situ rocks and are the only geological phenomenon that can display the occasionally rapid temporal changes in time delays listed in Table 1. No other source of anisotropy has such sensitivity, and characteristic patterns of temporal changes in time delays between split shear waves are observed before earthquakes (15 examples listed in Table 1A, nine in Table 1B), before volcanic eruptions (three examples in Table 1C), during distant low-level seismicity at 70 km distance (with energy equivalent to an M = 3.5 earthquake) (Table 1D), and during both high- and low-pressure CO₂ injections in a carbonate reservoir (Table 1E).

Generally, changes in time delays before earthquakes have been observed only in retrospect. However, in October 1999, it was recognized that time delays at two seismic stations in southwest Iceland were increasing at rates similar to those before an M = 5.1 earthquake some four months earlier. Consequently, we issued a preliminary forecast and, on 10 November 1998, made the final (successful) stress forecast (Crampin et al., 1999).

Texts of e-mail messages between the University of Edinburgh (EU) and the Iceland Meteorological Office (IMO) (Crampin et al., 1999):

10 November 1998—EU to IMO: "...the last plot...of shear-wave time delays...is already very close to 10 ms/km. This means that an event could occur any time between now (M ≥ 5) and end of February (M ≥ 6)."

13 November 1998—IMO to EU: "...there was a magnitude 5 earthquake just near BJA, preliminary epicenter 2 km west of BJA this morning 10 38 GMT."

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In response to an initial less-specific stress forecast a few days earlier, Ragnar Stefánsson, IMO, correctly inferred that the impending earthquake would be associated with the fault of an earlier M ≥ 5.1 earthquake where low-level seismicity was still continuing. This allowed time, magnitude, and fault plane to be accurately stress-forecast (Crampin et al., 1999). The earthquake was 2 km from station BJA, but similar effects have been observed with hindsight up to 70 km from small-scale seismicity, and 245 km from volcanic eruptions (Table 1).

Note the following:
1. Time delays are normalized to ms/km (Crampin, 1999).
2. A time delay of 10 ms/km corresponds to levels of fracture criticality estimated from previous earthquakes (Volti and Crampin, 2003). Fracture criticality is the level of cracking when cracks lose shear strength and earthquakes occur (Crampin and Peacock, 2005).
3. This procedure is called “stress forecasting” to distinguish it from source-zone-based earthquake prediction.
4. There are few examples in Table 1 because combinations of persistent swarms of small earthquakes, seismic three-component recorders immediately above the swarms, and suitable large earthquakes nearby, are extremely scarce (Crampin, 1993).

**MODELING FLUID-ROCK DEFORMATION**

The deformation of fluid-saturated microcracked rocks for small changes of stress can be modeled by anisotropic poro-elasticity (APE) (Zatsepin and Crampin, 1997; Crampin and Zatsepin, 1997; Crampin, 2006). Fluid-saturated microcracks are the most compliant elements of in situ rocks, and APE models the mechanism for low-level deformation before fracturing occurs. Deformation is by fluid movement along pressure gradients between neighboring microcracks at different orientations to the stress field. These microcracks are grain-boundary cracks in crystalline rocks and aligned pores and pore throats in higher-permeability sedimentary rocks. APE approximately matches a large range of phenomena involving cracks, stress, and shear-wave splitting (Crampin and Chastin, 2003; Crampin and Peacock, 2005). Note that the match is only approximate because of the difficulty of getting accurate in situ measurements of subsurface microcracks.

APE shows that the most diagnostic effect of small increases (or decreases) of stress on microcrack geometry is to increase (or decrease) the aspect ratio of vertical cracks striking parallel to the direction of maximum horizontal stress. These increase (or decrease) the average time delays in Band-1 directions to the free surface (Crampin, 1999). Band-1 is the double-leaved solid angle of ray-path directions with an incidence 15°–45° either side of the plane of vertical cracks (geometry in Fig. DR1 of the GSA Data Repository1). Band-2 directions, 15° to either side of the plane of the cracks, are sensitive principally to crack density, and crack density does not have a simple relationship with changes of stress (Crampin, 1999).

Recently, it has been noticed that whenever there are enough shear-wave ray paths in Band-1, the increase of time delays abruptly starts to decrease shortly before the time of the impending earthquake (Gao and Crampin, 2004). Figure 2 shows a typical example (see also Fig. DR2). Table 1B lists nine earthquakes where such decreases have been observed in the 15 earthquakes showing increases.

The new result is that durations of both increases and decreases are found to scale logarithmically with magnitudes of the impending events for three to four units of earthquake magnitude in Figures 3A and 3B. This self-similarity directly links variations in time delays with earthquake magnitudes, analogous to the well-known Gutenberg-Richter relationship.

Since APE modeling shows that increasing stress causes increases in average Band-1 time delays.

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**Table 1. Observations of Changes in Shear-Wave Splitting**

<table>
<thead>
<tr>
<th>No.</th>
<th>Earthquake (or volcano)</th>
<th>Approximate distance (km)</th>
<th>Magnitude</th>
<th>Approximate duration (days)</th>
<th>Reference*</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Observations of increasing shear-wave time delays before earthquakes</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Swarm at BRE, northern Iceland</td>
<td>7</td>
<td>M 1.7</td>
<td>≥0.055</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Swarm at BRE, northern Iceland</td>
<td>7</td>
<td>M 2.5</td>
<td>≥0.210</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>Southwest Iceland</td>
<td>10</td>
<td>M 3.4</td>
<td>47</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>Dongfeng, Hainan, China</td>
<td>9</td>
<td>M 3.6</td>
<td>21</td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td>Enola Swirl, Arkansas</td>
<td>3</td>
<td>M 3.8</td>
<td>≥4.5</td>
<td>4</td>
</tr>
<tr>
<td>6</td>
<td>Southwest Iceland</td>
<td>14</td>
<td>M 3.8</td>
<td>40</td>
<td>2</td>
</tr>
<tr>
<td>7</td>
<td>Parkfield, California</td>
<td>14</td>
<td>M 4.0</td>
<td>≥220</td>
<td>5</td>
</tr>
<tr>
<td>8</td>
<td>Southwest Iceland</td>
<td>10, 43</td>
<td>M 4.4</td>
<td>83, 77</td>
<td>2</td>
</tr>
<tr>
<td>9</td>
<td>Southwest Iceland</td>
<td>10, 43</td>
<td>M 4.7</td>
<td>123, 106</td>
<td>2</td>
</tr>
<tr>
<td>10</td>
<td>Grimsey Lineament, Iceland</td>
<td>50, 92, 96</td>
<td>M 4.9</td>
<td>147, 163</td>
<td>6</td>
</tr>
<tr>
<td>11</td>
<td>Southwest Iceland</td>
<td>2, 36</td>
<td>M 5.0</td>
<td>127, 121</td>
<td>1, 2, 7</td>
</tr>
<tr>
<td>B</td>
<td>Observations of decreasing shear-wave time delays immediately before earthquakes in (A)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Swarm at BRE, northern Iceland</td>
<td>7</td>
<td>M 1.7</td>
<td>0.0306</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Swarm at BRE, northern Iceland</td>
<td>7</td>
<td>M 2.5</td>
<td>0.0465</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>Enola Swirl, Arkansas</td>
<td>3</td>
<td>M 3.8</td>
<td>0.123</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td>Grimsey Lineament, Iceland</td>
<td>50</td>
<td>M 4.9</td>
<td>24</td>
<td>6</td>
</tr>
<tr>
<td>5</td>
<td>Southwest Iceland</td>
<td>2</td>
<td>M 5.0</td>
<td>4.4</td>
<td>1, 2, 7</td>
</tr>
<tr>
<td>C</td>
<td>Observations of changes before volcanic eruptions</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Gjálp, Vatnajökull, Iceland</td>
<td>230 S, 240 SW</td>
<td>Large fissure</td>
<td>120</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>Mount Etna, Sicily (increasing time delays)</td>
<td>1, 5</td>
<td>Minor</td>
<td>66**</td>
<td>11</td>
</tr>
<tr>
<td>3</td>
<td>Mount Ruapehu, New Zealand</td>
<td>2–15</td>
<td>Minor</td>
<td>–</td>
<td>12</td>
</tr>
<tr>
<td>D</td>
<td>Observations during seismic swarm at prototype stress-monitoring site, Húsavík, Iceland</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Grimsey Lineament, Iceland</td>
<td>–70</td>
<td>M = 3.5</td>
<td>–</td>
<td>13</td>
</tr>
<tr>
<td>E</td>
<td>Observations during high- and low-pressure CO2 injections in carbonate reservoir</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Vacuum Field, New Mexico</td>
<td>0 (vertical)</td>
<td>–</td>
<td>–</td>
<td>14</td>
</tr>
</tbody>
</table>

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1GSA Data Repository item 2005102, geometry for Band-1 and Band-2 directions, and further examples of characteristic changes in time delays before earthquakes, is available online at www.geosociety.org/pubs/ft2008.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.
delays, the observed increase is interpreted as monitoring the effects of stress accumulation on microcrack geometry at large distances from impending earthquakes. In any particular region, the overall stress can be expected to increase at a comparatively uniform rate over the recurrence cycles of large earthquakes (decades to thousands of years), driven by the movement of tectonic plates, which typically converge or diverge at some 2–10 cm/yr. If stress accumulates over a small volume in a heterogeneous Earth, the rate of increase will be rapid, and the level of fracture criticality at which earthquakes occur will be reached within the small volume after a short time, so that the total energy accumulated and the impending stress-releasing earthquake will be small. If stress accumulates over a larger volume, the rate of accumulation will be slower and the duration longer, but the impending earthquake will be larger, as in Table 1A and Figure 3A. The slope of the straight line in Figure 3A depends on the rate of increase of stress. This rate appears to be similar for most data in Figure 3A, which, except for earthquake 15 (Ms 7.7), plots smaller earthquakes where stress accumulation is presumed to be wholly within the crust. Stress accumulation before larger earthquakes, such as earthquake 15, involves the whole crust, and the increase will be over two dimensions, rather than the accumulation over three dimensions for smaller earthquakes. Consequently, the relationship may not be linear for larger earthquakes. Note that we have not attempted to unify the various magnitude scales, which are typically unreliable over such a range of dissimilar data, and this no doubt contributes to the scatter in Figure 3A.

The decrease shown in Figure 3B is not wholly understood but is interpreted as monitoring stress relaxation as microcracks coalesce onto the eventual fault plane (similar phenomena occur in laboratory stress cells; see Figs. DR2F and DR2G). As APE suggests, “crack coalescence” is probably a function of crack geometry rather than the properties of the geology or tectonics of the rock matrix.

Figures 3A and 3B suggest that, if patterns of increasing and decreasing time delays can be recognized before impending earthquakes, the times and magnitudes of larger earthquakes can be stress-forecast, as the M = 5 earthquake in southwest Iceland was successfully stress-forecast three days before it occurred (Crampin et al., 1999). Shear-wave splitting does not appear to contain direct information about the location of the impending event, but knowing a larger earthquake is approaching allows other information to be interpreted realistically, as occurred with the successfully forecast earthquake (Crampin et al., 1999). The data in Table 1 show that these changes in time delays can be recognized at considerable distances from the impending epicenters.

THE PARADIGM SHIFT

The suggested paradigm shift is that instead of attempting to predict earthquakes by investigating source zones and source-zone precursors, the time and magnitude and in some circumstances location of impending larger earthquakes can be stress-forecast by monitoring the approach to fracture criticality anywhere within an extensive volume surrounding the eventual epicenter. This bypasses the essential deterministic unpredictability of the earthquake source. Rock is so weak to shear stress that the strain energy released by large earthquakes necessarily accumulates over very large volumes of rock, as indicated by distances at which changes in shear-wave splitting are observed (Table 1). There is an enormous variety and quantity of evidence supporting this new understanding of fluid-rock deformation (Crampin and Chastin, 2003; Crampin and Peacock, 2005) with no contrary observations. Consequently, we suggest that...
large earthquakes can be stress-forecast by using shear-wave splitting to monitor stress-induced changes to microcrack geometry remote from impending epicenters. Unfortunately, variations in shear-wave splitting above small earthquakes cannot be used to routinely stress-forecast earthquakes, because of the scarcity (Crampin, 1993) and irregularity (Wu et al., 2006) of suitable swarms of small earthquakes. Reliable routine stress forecasting requires the controlled-source cross-hole seismics of a stress-monitoring site (SMS) (Crampin, 2001), where a borehole source transmits shear waves in Band-1 directions to recorders in adjacent boreholes at depths below the level of the near-surface stress release and weathering anomalies. The prototype SMS at Húsavík, northern Iceland, used existing boreholes drilled for geothermal purposes adjacent to a transform fault of the Mid-Atlantic Ridge. The SMS was not in optimal source-stress geometry, but showed spectral sensitivity to very low-level seismic swarm activity (seismic energy equivalent to one M = 3.5 earthquake at ~70 km distance; Crampin et al., 2003) (Table 1D), confirming the science, technology, and sensitivity of SMSs for monitoring stress accumulation and stress-forecasting impending large earthquakes. SMSs would allow variations in tectonic strain rates between different regions to be cataloged routinely, so that the accuracy of forecast magnitudes would be improved.

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