In a recent Opinion in *Seismological Research Letters*, Jordan and Jones (2010) discussed the findings and recommendations of the International Commission on Earthquake Forecasting (ICEF) for operational earthquake forecasting convened by the Italian government following the 6 April 2009 L’Aquila Mw 6.3 earthquake, which killed 308 people in central Italy. "The goal of operational earthquake forecasting is to provide communities with information about seismic hazards that can be used to make decisions in advance of potentially destructive earthquakes" where "one of the outstanding challenges in the operational use of probabilistic forecasts is in translating them into decision-making in a low-probability environment" (Executive Summary, ICEF Report, Jordan et al. 2009).

An underlying assumption of the ICEF report is that earthquakes cannot yet be deterministically predicted, so that only probabilistic earthquake (low-probability) forecasts are possible. This "Second Opinion" discusses a new understanding of fluid-rock deformation that provides the opportunity for deterministic earthquake stress-forecasting. This removes one of the "outstanding challenges." Deterministic forecasts can be made in a high-probability environment, which changes the emphasis of the ICEF report.

**MONITORING FLUID–ROCK DEFORMATION AND EARTHQUAKE STRESS-FORECASTING**

Shear-wave splitting (seismic birefringence) monitors the stress-aligned fluid-saturated microcrack geometry along the ray path. Fluid-saturated microcracks are compliant to changing conditions so that rocks are weak to shear stress. Consequently, the necessary stress accumulation before all large earthquakes has to build up over enormous volumes of rock, possibly worldwide and certainly plate-wide (Crampin and Gao 2010). The new understanding of fluid-rock deformation (Crampin 2006; Crampin and Peacock 2005, 2008) is that stress accumulation before large earthquakes can be monitored by analyzing shear-wave splitting throughout large volumes surrounding the impending earthquake source zone. Using shear-waves recorded above persistent swarms of small earthquakes, stress changes before large (or larger) earthquakes have been observed, and the times, magnitudes, and in some cases locations of impending earthquakes “stress-forecast” retrospectively. There are 15 retrospective examples and one successful real-time stress-forecast when data were analyzed online. (The procedure is known as *earthquake stress-forecasting*, rather than earthquake prediction or earthquake forecasting, to emphasize the different formalism.) There are no exceptions: whenever appropriate shear-wave source-to-geophone recordings exist, widespread stress accumulation has always been observed before large earthquakes.

Table 1 summarizes the evidence for the new understanding of fluid-rock deformation. The two key phenomena for monitoring stress accumulation are:

1. The most compliant elements of *in situ* rock are the fluid-saturated stress-aligned microcracks throughout most rocks in the crust. Changes in stress modify the microcrack geometry, and these changes can be monitored by changes in shear-wave splitting. Widespread observations of shear-wave splitting show such stress-aligned microcracks are pervasive throughout almost all igneous, metamorphic, and sedimentary rocks in the crust.

2. Shear-wave splitting time-delays, Δτ, are sensitive to low-level changes in microcrack geometry along the ray path. Consequently, low-level stress changes before earthquakes can be monitored by analyzing changes in shear-wave splitting.

Table 2 summarizes the behavior of stress before earthquakes. As stress accumulates, microcrack geometry approaches levels of fracture criticality where shear strength is lost, and microcracks begin to coalesce onto the eventual fault break (Crampin and Peacock 2008). The increasing stress accumulation abruptly stops. There is stress relaxation and the time delays decrease until the impending earthquake occurs at characteristic low levels of 2 to 4 MPa stress, independent of the impending earthquake magnitude. As expected, logarithms of the duration in days of both stress-accumulation increases and crack-coalescent decreases are each proportional (self-similar) to the earthquake magnitude.

This new understanding of fluid-rock deformation (Table 1) has major implications for monitoring stress variations before earthquakes (Table 2) and hence for the operational earthquake forecasting of the ICEF report (Jordan and Jones 2010; Jordan et al. 2009). It should be noted that this new understanding is comparatively recent and has not yet won universal acceptance, although the evidence, summarized in Table 1, is indisputable. Unfortunately, many geoscientists are unwilling to accept the
Earth’s subsurface, and the vast majority of seismic investigation systems of microcracks. Shear-wave splitting (SWS) and critical systems of microcracks.

Seismology is the major investigative tool for examining the Earth’s subsurface, and the vast majority of seismic investiga-

1. Widespread observations of azimuthally varying stress-aligned shear-wave splitting (SWS) indicate that stress-aligned fluid-saturated microcracks are pervasive throughout almost all in situ igneous, metamorphic, and sedimentary rocks throughout the Earth’s crust.

2. The degree of SWS indicates that the microcracks are so closely spaced they verge on failure, and hence are critical systems. Critical systems are a new physics, hence a new geophysics, that imposes a range of fundamentally new properties on conventional subcritical geophysics.

3. All complex heterogeneous interactive phenomena are critical systems in a huge range of physical, biological, sociological, and other phenomena.

4. Consequently the Earth, an archetypal complex heterogeneous interactive phenomenon, is necessarily a critical system.

5. The evolution of fluid-saturated microcracks under changing conditions within the Earth can be modeled by anisotropic poro-elasticity (APE).

6. APE modeling matches some 20 different phenomena along innumerable shear-wave ray paths in exploration and earthquake seismology.

7. Since critical systems of microcracks are implicit in APE modeling, the match of APE to ~20 different phenomena is direct confirmation of pervasive distributions of critical systems of stress-aligned fluid-saturated microcracks in almost all in situ rocks.

8. There are no known exceptions: the effects of changing conditions are always matched by APE.

9. Fluid-saturated microcracks are the most compliant elements of in situ rock, and changes in SWS have been observed during CO$_2$ injection in seismic exploration, and in stress accumulation before earthquakes (15 in retrospect, with one successful real-time stress-forecast) and before and after volcanic eruptions.

10. Again, there are no known exceptions, whenever appropriate shear-wave data sets exist, larger earthquakes are always preceded by stress-accumulation changes in SWS.

*Evidence for these phenomena is reported in papers at: www.geos.ed.ac.uk/homes/scrampin/opinion.

implications of the evidence in Table 1 that the crust of the Earth is a compliant microcrack-induced critical system, with the fundamentally new properties that this implies.

### SHEAR-WAVE SPLITTING (SWS) AND CRITICAL SYSTEMS OF MICROCRACKS

Seismology is the major investigative tool for examining the Earth’s subsurface, and the vast majority of seismic investiga-

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<th>TABLE 2</th>
<th>Summary of the Behavior of Stress before Earthquakes</th>
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<tbody>
<tr>
<td>1.</td>
<td>Stress is typically generated by interactions at the margins of tectonic plates where the changes are independent of the impending earthquakes. Consequently the observed stress-accumulation increases are not precursory to particular earthquakes.</td>
</tr>
<tr>
<td>2.</td>
<td>As stress increases, microcrack geometry throughout the rock mass eventually approaches levels of fracture criticality (when microcracks are so closely spaced that shear strength is lost and rocks fail in earthquakes). At this stage, the stress accumulation stops, and there is stress relaxation as microcracks coalesce onto the eventual fault plane. The impending earthquake occurs at the typically low level of stress of 2 to 4 MPa, as observed. Consequently, stress-relaxation decreases are precursory to particular earthquakes.</td>
</tr>
<tr>
<td>3.</td>
<td>The Earth is heterogeneous and stress accumulates irregularly. If stress accumulates over small volumes, the build-up will be rapid but the eventual earthquake will be small. If stress accumulates over larger volumes, the build-up will be slower and the impending earthquakes will be larger. Logarithms of the durations of both increases and decreases are each observed to be proportional (self-similar) to impending earthquake magnitudes.</td>
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</table>

The reason why the pervasive distributions of stress-aligned fluid-saturated microcracks have not been recognized earlier is that P waves, although sensitive to a wide range of phenomena, are rather insensitive to aligned liquid-saturated microcracks. Shear-waves are sensitive to a similar range of phenomena, but in contrast, the time delays and polarizations of SWS are wholly controlled by microcrack geometry. Consequently, since microcrack geometry is sensitive to changes of in situ stress, shear-wave splitting monitors stress-induced changes to microcrack geometry before earthquakes (Table 2).

Table 3 summarizes the special conditions required for observing and measuring SWS. When these conditions are met, stress-aligned SWS is universally observed. (The difficulties in measuring SWS no doubt contribute to the slow acceptance of the new understanding of fluid-rock deformation.) The observed SWS indicates that the stress-aligned fluid-saturated microcracks in almost all igneous, metamorphic, and sedimentary rocks are so closely spaced that they verge on failure by fracturing, and hence are critical systems (Crampin and Peacock 2005, 2008). Critical systems (also known as complex systems, Davies 1989) are a new physics, hence a new geophysics (Crampin 2006), that impose a range of fundamentally new properties on the previous subcritical physics (and geophysics). These properties include: monitorability; calculability; predictability; in certain circumstances even controllability; universality; and extreme (“butterfly effect”) sensitivity to initial conditions (Davis 1989; Crampin et al. 2003). Examples of these...
TABLE 3  
Summary of conditions for observing and measuring shear-wave splitting

<table>
<thead>
<tr>
<th>Condition</th>
<th>Description</th>
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<tbody>
<tr>
<td>1.</td>
<td>Measurement of SWS at a free surface requires shear-wave arrivals incident within the shear-wave window (angle of incidence less than ~35°) so that shear-waves are not distorted by S-P conversions at the interface. Note that this is the free surface immediately at the source, not the average of a possibly topographically irregular free surface.</td>
</tr>
<tr>
<td>2.</td>
<td>Three-component recordings with the facility to rotate arrivals into preferred polarizations so that the split shear-wave arrivals can be separated into independent wave-trains.</td>
</tr>
<tr>
<td>3.</td>
<td>Shear-wave arrivals sufficiently separated from P-wave coda to isolate shear-wave signals.</td>
</tr>
<tr>
<td>4.</td>
<td>Appropriate frequencies of both signals and recordings to display measurable time delays.</td>
</tr>
<tr>
<td>5.</td>
<td>Although a reasonably successful semi-automatic measurement procedure has been developed for particular environments (above small earthquakes in Iceland), wholly automatic measurements of SWS are unlikely to be successful.</td>
</tr>
</tbody>
</table>

new properties have been identified in the crust (Crampin and Peacock 2005, 2008), where they have profound implications for the way stress accumulates, the behavior of the earthquake source, earthquake stress-forecasting, and the ICEF report.

A feature that contributes to the extreme sensitivity is that shear-wave splitting is a second-order phenomenon of marginal variations of shear-wave behavior with direction. However, when three-component seismograms are rotated into preferred shear-wave splitting polarizations, the shear-wave arrivals are separated and arrival times and hence time delays, $\Delta t$, between split shear-waves can frequently be read with first-order precision. A second-order quantity read with first-order precision yields an unprecedented level of accuracy, far greater than the majority of seismic observations.

**EVOLUTION OF MICROCRACKS UNDER CHANGING CONDITIONS**

The evolution of microcrack geometry under changes of stress can be modeled by the anisotropic poro-elasticity (APE) formulation of cracked rock evolution (reviewed by Crampin and Peacock 2008). APE modeling matches some 20 different phenomena and innumerable individual source-to-recorder ray paths in earthquake seismology and seismic exploration. Critical systems of fluid-saturated microcracks are implicit in the success of APE modeling.

Critical systems are extraordinarily common and include the weather, earthquake occurrence (demonstrated by the linearity of the Gutenberg-Richter relationship), the New York Stock Exchange, the life cycle of fruit flies, and a huge variety of physical phenomena ranging from quantum mechanics to stellar radiation. All complex heterogeneous interactive systems are critical systems, and the Earth, an archetypal complex heterogeneous interactive phenomenon, is necessarily a critical system with fundamentally new properties imposed on conventional subcritical geophysics.

**EARTHQUAKE PREPARATION**

Most analyses of earthquakes have focused, perhaps understandably, on the earthquake source zone. The linearity of the Gutenberg-Richter relationship demonstrates that earthquakes are critical phenomena. This means that although an earthquake mechanism can be modeled, perhaps very accurately by adjusting input parameters, the modeling is unrepeatable because it depends critically on minuscule differences in these input parameters. Consequently, earthquakes cannot be reliably or repeatedly modeled. However, the one characteristic phenomenon before all large earthquakes is that huge amounts of stress need to accumulate for release by the earthquake. Since rock is weak to shear-stress, this stress must accumulate over enormous volumes of *in situ* rock. Consequently, this stress accumulation can be monitored by changes in $\Delta t$ almost anywhere in a huge stressed volume surrounding the earthquake source (Crampin and Peacock 2008).

Apart from the twice daily variations of oceanic and solid-earth tides, changes in tectonic stress are generated primarily by interactive processes of subduction, magma-generation, and transform faulting at tectonic plate margins. Table 2 summarizes the evolution of stress before large earthquakes.

These stress-induced changes in SWS are not precursory to earthquakes in the usual sense of the word. The changes are monitoring the fundamental processes of stress accumulation and stress relaxation on *in situ* rock that are the underlying mechanism that causes the earthquakes to occur (Crampin and Peacock 2008).

**IMPLICATIONS FOR OPERATIVE EARTHQUAKE FORECASTING IN ITALY**

One of the underlying assumptions of the ICEF report is that operational earthquake forecasting will be made in a “low-probability environment” (Jordan et al. 2009). This Second Opinion indicates that if appropriate shear-wave stress stations are available, the time, magnitude, and in some cases location can be stress-forecast with high-probability. This could transform operational earthquake forecasting from a low-to a high-probability environment. In some cases, this would lessen alarm and the consequent expense of mitigating hazard, and in other cases, justify the alarm and expense of precautionary procedures.

Unfortunately, suitably persistent swarms of small earthquakes for use as stress-measuring-station sources of shear-waves are very uncommon. Only Iceland, where transform faults of the Mid-Atlantic Ridge uniquely run onshore, provides suitably persistent seismicity recorded by a first class seismic network. As a result, much of the recent understanding
of SWS has come from analysis of seismic data from Iceland (Crampin and Peacock 2005, 2008).

Routine stress-forecasting outside Iceland requires measurement of a controlled source of shear-waves below the near-surface weathering and stress-release anomalies in three-borehole stress-monitoring sites (SMSs) (Crampin 2001). An optimum SMS would consist of a stress-oriented isosceles triangle of boreholes, with offsets between 200 m and 300 m, and a borehole source at 1,000 m depth transmitting shear-waves at appropriate angles of incidence to strings of borehole geophones between 1,000 m and 1,700 m depths. SWS Δt along these ray paths is particularly sensitive to crack aspect-ratios and hence to changes of tectonic stress.

The prototype SMS in northern Iceland recorded SWS propagating horizontally at 500 m depth between two boreholes offset 350 m. The shear-wave source, the downhole orbital vibrator (DOV) (Leary and Walter 2005) was pulsed 40,000 times, two to four times each minute in a two weeks’ experiment, without changing the waveform or damaging the borehole wall (Crampin et al. 2003). The source-to-receiver geometry was non-optimal, but the recordings showed exceptional sensitivity to seismic-induced changes of stress associated with low-level seismicity at a distance of 70 km on a neighboring transform fault with equivalent energy to one \( M = \sim3.5 \) earthquake (Crampin et al. 2003). This sensitivity at distances of hundreds of times the conventional source dimensions confirms the extreme sensitivity expected of critical systems of stress-aligned fluid-saturated microcracks. Assuming similar observable stress-energy concentrations at the source of all earthquakes confirms that an SMS could stress-forecast an \( M = 5 \) earthquake up to 1,000 km from the SMS and larger earthquakes anywhere within the tectonic plate (Crampin and Gao 2010).

This means that a single three-borehole SMS in central Italy, near L’Aquila, say, would be within \(~600\) km of the whole of Italy (including Sicily), and in principle could identify stress accumulation and stress-forecast all \( M \geq 5 \) within Italy and smaller events nearer the SMS. At 600 km, SMS signals for an \( M = 5 \) earthquake might tend to be noisy, and the preferred option would be two or three equidistant three-borehole SMSs down the length of Italy.

Stress accumulation and crack coalescence observed at a single three-borehole SMS would indicate magnitude of the impending earthquake from the rates of increase and decrease of time delays, and the time of occurrence from the time the stress accumulation reaches levels of fracture criticality. In our present understanding of the phenomenon, observations at a single SMS would not indicate the location (fault break) of the impending event. Networks or arrays of SMSs (as suggested by Crampin et al. 2010) might provide some indication of epicenter or fault break. In any case, knowing a large earthquake was approaching would allow other precursory phenomena to be interpreted realistically. Thus the fault break of the successfully stress-forecast \( M = 5 \) earthquake in Iceland (Crampin et al. 1999, 2008) was estimated from the continuing seismic activity on the fault plane of an \( M = 5.1 \) earthquake six months earlier.

The conclusion is that one or more three-borehole stress-monitoring sites would stress-forecast the times and magnitudes, and possibly fault breaks, of all damaging earthquakes \( (M \geq 5, \text{say}) \) earthquakes in Italy, and provide operational earthquake forecasting in a high-probability rather than a low-probability environment.

**REFERENCES**


* Papers available at www.geos.ed.ac.uk/homes/scrampin/opinion.

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