Stress-forecasting not predicting earthquakes: a paradigm shift

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After 120 years of unsuccessful endeavour, a paradigm shift is required before earthquakes can be predicted[1]. The suggested shift is to neglect the earthquake source zone, but monitor stress accumulation before earthquakes in the rock mass remote from the source. The most sensitive diagnostic of low-level stress changes in in situ rock, modifications to the geometry of the in situ fluid-saturated stress-aligned microcracks in most rocks in the crust, can be monitored by analysing shear-wave splitting (seismic birefringence) at substantial distances from the eventual source. Characteristic patterns in increasing shear-wave time-delays of have been observed in retrospect before some 15 earthquakes world-wide[2-12], and in one case, when changes were recognised early enough, time, magnitude, and fault break of a M=5 earthquake in SW Iceland were successfully stress-forecast in a comparatively narrow time-magnitude window[8]. When data is available, the increases also show abrupt decreases shortly before impending earthquakes[2,6-12], thought to be due to crack coalescence along the impending fault break. The new results confirming these results are that logarithms of the durations of both increase and decreases are proportional (self-similar) to the magnitudes of the eventual earthquakes over six orders of magnitude, similar to the well-known Gutenberg-Richter relationship[13].

Azimuthally varying shear-wave splitting is widely observed throughout the Earth's crust in almost all types of geological and tectonic regimes, where the polarisations of the faster split shear-waves are typically aligned parallel the direction of maximum horizontal stress[14-17]. Shear-wave splitting is diagnostic of some form of seismic anisotropy, and the only anisotropic symmetry system that has such stress-parallel polarisations for nearly-vertical propagation is hexagonal symmetry (transverse isotropy) with a horizontal axis of symmetry[18], sometimes known as TIH-anisotropy. There is only one configuration, common to almost all *in situ* igneous, metamorphic, and sedimentary rocks in the crust that has TIH symmetry, and that is distributions of fluid-saturated microcracks that are aligned, like hydraulic fractures in the oil industry, perpendicular to the direction of minimum horizontal stress[17].

Such fluid-saturated microcracks, the most compliant elements of *in situ* rock, are confirmed as the source of the shear-wave splitting as temporal variations in splitting are observed whenever there are changes in rock mass conditions. In particular, characteristic patterns of changes in time-delays between split shear-wave are observed before earthquakes[2-12] (parameters listed in Tables 1a and 1b); before volcanic eruptions[3,19-21] (Table 1c); during distant low-level seismicity[22] (equivalent energy to M ~3.5 at 70 km distance) (Table 1d); and during both high- and low-pressure CO_2-injections in a carbonate reservoir[23] (Table 1e).

With one exception, the changes in time-delays have been observed only in retrospect after a larger earthquake had stimulated the search for anomalies. The exception was in October 1999, when it was recognised that time-delays at two seismic stations in SW Iceland were increasing at similar rates to those of a previous increase before a M 5.1 earthquake some four months earlier. Consequently, we issued a preliminary forecast. On 10th November 1998, we made the final (successful) stress-forecast[7].

Text of exchange of email messages (in italics) between University of Edinburgh (EU) and Iceland Meteorological Office (IMO)[8]:

10th Nov. 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 ($M \geq 5$) and end of February ($M \geq 6$).*"

13th Nov. 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.*"

(Note that to improve comparisons over different path lengths, time-delays are normalised to ms/km.)

In response to a less-specific stress-forecast a few days earlier, Ragnar Stefánsson, IMO, had correctly inferred that the impending earthquake would be on the fault-plane of an earlier *M* 5.1 earthquake where low-level seismicity was still continuing. This allowed the time, magnitude, *and fault-plane* to be correctly stress-forecast[8].

Note that:

a) A further *M* 5.6/*Ms* 6.6 earthquake (No. 14 in Table 1a) would have been successfully stress-forecast with the current lower magnitude limits of the current Iceland Seismic Catalogue[11]. At that time, the higher magnitude limits imposed a seismic quiescence before the larger earthquake which hid the actual increase in time-delays[11].

b) To improve comparison over different path lengths, time-delays are usually normalised to ms/km[13].

c) 10ms/m was the level of *fracture criticality* estimated from previous earthquakes[3], where fracture-criticality is the level of cracking at which cracked rocks lose shear-strength, with consequent likelihood of fracturing and earthquakes if there is any disturbance[17]; and

d) We call this process stress-forecasting to distinguish it from earthquake-source-zone-based earthquake prediction.

The deformation of fluid-saturated microcracked rocks for small changes of stress, well below levels at which fracturing occurs, can be modelled by Anisotropic Poro-Elasticity[13,24,25] (APE). The mechanism for deformation is fluid movement by flow or dispersion along pressure-gradients between grain-boundary cracks in crystalline rocks, and aligned pores and pore-throats in granular rocks, at different orientations to the stress field. APE-modelling approximately matches over twenty different phenomena referring to stress, cracks, and shear-wave splitting and thousands to millions of individual source-to-recorder ray paths, at hundreds of different sites above small earthquakes and in seismic reflection profiles in hydrocarbon reservoirs by the oil industry[13,17,25-28].

The match can only be approximate because of the difficulty of getting accurate *in situ* measurements of sub-surface microcracks. The crack geometry of fluid-saturated microcracked rocks is highly compliant to changing conditions, so that drilling, and other means of direct access such as mining or quarrying, impose severe traumas of de-stressing, creating temperature contrasts, and fluid pressure perturbations that disrupt microcrack geometry. Such perturbations have been observed in the rock mass to at least six times the borehole diameter[29] and certainly occur much further. This makes it impossible to directly sample *in situ* undisturbed microcrack geometry by well-logs, borehole wall imaging, or other subsurface sampling.

The most successful calibration of APE to-date is where changes in shear-wave splitting in three-component seismic reflection surveys in a carbonate reservoir were matched almost exactly before and after both high-pressure and low-pressure CO_2-injections by inserting the exact injection pressures into the APE model[23]. (This also implies that the physical effects of changing stress and pressure during CO_2-sequestration, say, are dominated by modifications to microcrack geometry.)

Recently, it has been noticed that whenever there are sufficient source events, the (stress-accumulation) increase of time-delays starts to decrease abruptly, shortly before the impending earthquake actually occurs[2]. Table 1b lists the nine earthquakes where decreases have been observed out of the 15 earthquakes where increases have been observed.

APE-modelling 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 the vertical cracks striking parallel to the direction of maximum horizontal stress, and increases (or decreases) the average time-delays in 'Band-1' directions to the free surface[13,25]. Band-1 is the double-leafed solid angle of ray paths making angles ± (15º to 45º) to the plane of the cracks[13,25]. (Band-2 directions, ± 15º to the plane of the cracks, are sensitive principally to crack density, and crack density does not have a simple relationship to changes of stress[25].) It is the duration of increases and decreases in time-delays in Band-1 directions that are listed in Tables 1a and 1b, respectively.

The new result is that the durations of both increases and decreases in time-delays, in Table 1, are found to (separately) scale logarithmically with the magnitudes of the impending events to nearly six units of earthquake magnitude (Figures 1a and 1b). This self-similarity suggests that these durations are linked to the earthquake mechanisms, analogous to the well-known Gutenberg-Richter relationship between logarithm of the cumulative frequency and the earthquake magnitude, which is linear (self-similar) for a similar range of magnitude units[13].

Since APE shows that increasing stress causes increasing (average) Band-1 time-delays, the observed increase is interpreted as monitoring the effects of the accumulation of strain-energy (which we call *stress-accumulation*) on microcrack geometry at substantial distances from the impending earthquake. In any particular region, strain-energy can be expected to increase at a uniform rate from the movement of tectonic plates, which typically converge or separate at 0.02 to 0.10 metres per year. If stress accumulates over a small volume in the complex heterogeneous Earth, the rate of increase will be comparatively rapid until levels of fracture-criticality are reached with a comparatively short duration of increase, but the final stress-releasing earthquake will be small. (Fracture-criticality is the level of cracking at which cracked rocks lose shear-strength, with consequent likelihood of fracturing and earthquakes if there is any disturbance[16,17].) If stress accumulates over a larger volume, the rate of accumulation will be slower with a longer duration and the final earthquake will be larger, as observed in Figure 1a. The slope of the straight line in Figure 1a is thought to depend on the rate of increase of strain energy which appears to be similar for most regions in Figure 1a which plot earthquakes confined largely to the crust. Stress-accumulation before larger earthquakes, such as No. 15, the Ms 7.7 Chi-Chi Earthquake in Taiwan[12], involves the whole crust, and may accumulate over two-dimensions, rather than three-dimensions for smaller earthquakes, and the relationship may not be linear for larger earthquakes. Note that we have not attempted to homogenise the various magnitude scales, which is difficult over such a wide range of dissimilar data, and this no doubt contributes to the scatter in Figure 1a and 1b.

Figure 1b is interpreted as monitoring stress-relaxation as microcracks coalesce onto the eventual fault plane[13]. As suggested by APE, crack coalescence is probably a function of the crack distributions rather than the properties of the geology or tectonics of the rock matrix, and the least-squares line is a comparatively good fit to the data.

Figures 1a and 1b suggest that, if patterns of increasing and decreasing time–delays can be recognised before the impending earthquake has occurred, the time and magnitude of larger earthquake can be stress-forecast, as was the 1998 *M* 5 earthquake in SW Iceland[7]. Shear-wave splitting data does not appear to contain direct information about the location of the impending event, but knowing a larger earthquake is expected allows other information to be interpreted realistically[7]. The data in Table 1 show that these changes in time-delays can be recognised at substantial distances from the impending events.

We suggest this is a paradigm shift in earthquake prediction studies. Instead of trying to predict the earthquake source, which has been singularly unsuccessful, probably due to the critical sensitivity of earthquake source behaviour to initial conditions[1], the time and magnitude and in some circumstances location of the impending event can be stress-forecast by monitoring the approach to fracture-criticality of the stressed rock mass in an extensive volume surrounding the eventual epicentre[8]. There is an enormous amount and variety of evidence supporting this new understanding of fluid-rock deformation[17,25,26,28], with no contrary observations.

The difficulty in using stress-forecasting routinely to forecast earthquakes, using seismic swarms as the source of shear-waves, is the scarcity (and irregularity[11]) of suitable seismic swarms. Reliable routine stress-forecasting requires the controlled-source cross-hole seismics of a Stress-Monitoring Site[30] (SMS), where a borehole source transmits shear-waves in Band-1 directions to borehole recorders in adjacent boreholes below the near-surface stress and weathering anomalies. The prototype SMS at Húsavík, Northern Iceland, used existing boreholes drilled for geothermal purposes, adjacent and offsets parallel to a transform fault of the Mid-Atlantic Ridge[22]. The SMS was not in optimal source-stress geometry, yet recorded spectacular sensitivity to very low-level seismic swarm activity (energy equivalent to one *M* ~3.5 earthquake) at ~70 km distance[22] (Table 1d), confirming the science, technology, and sensitivity of SMSs for monitoring stress-accumulation and stress-forecast impending large earthquakes.

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

Table 1. Observations of changes in shear-wave splitting

No.	Location	Approx.dist. (km)	Magnitude	Approx.duration (days)	Ref.
a)	Observations of increasing shear-wave time-delays before earthquakes.				
1	Swarm at BRE, N Iceland	7	M* 1.7	≥ 0.055	2
2	Swarm at BRE, N Iceland	7	M 2.5	≥ 0.210	2
3	SW Iceland	10	M 3.4	47	3
4	Dongfang, Hainan, China	9	M_L 3.6	21	4
5	Enola Swarm, Arkansas	3	M_L 3.8	≥ 4.5	5
6	SW Iceland	14	M 3.8	40	3
7	Parkfield, California	14	M_L 4.0	≥ 220	6
8†	SW Iceland	10, 43	M 4.4	83, 77	3
9†	SW Iceland	10, 43	M 4.7	123, 106	3
10†	Grímsey Lineament, Iceland	50, 92, 96	M 4.9	147, 163, 0	7
11†	SW Iceland (successfully stress-forecast)	2, 36	M 5.0‡	127, 121	8
12	Shidian, Yunnan, China	35	Ms 5.9	400	2
13	N Palm Springs, California	33	Ms 6.0	1100	2, 9, 10
14†	SW Iceland	3, 46	M 5.6/Ms 6.6	175, 151	11
15	Chi-Chi earthquake, Taiwan	55	Ms 7.7	598	12
b)	Observations of decreasing shear-wave time-delays immediately before earthquakes.				
1	Swarm at BRE, N Iceland	7	M 1.7	0.0306	2
2	Swarm at BRE, N Iceland	7	M 2.5	0.0465	2
3	Enola Swarm, Arkansas	3	M_L 3.8	0.123	5
4	Grímsey Lineament, Iceland	50	M 4.9	24	7
5	SW Iceland (successfully stress-forecast)	2	M 5.0‡	4.4	8
6	Shidian, Yunnan, China	35	Ms 5.3	38	2
7	N Palm Springs, California	33	Ms 6.0	69	2, 9, 10
8†	SW Iceland	3, 46	Ms 6.6/M 5.6	38, 21	11
9	Chi-Chi earthquake, Taiwan	55	Ms 7.7	131	12
c)	Observations of changes before volcanic eruptions.				
1†	Gjàlp, Vatnajökull, Iceland (increasing time-delays)	230S, 240SW, 245WSW	Large fissure eruption	120	3
2†	Mount Etna, Sicily (increasing and decreasing time-delays, 90º-flips€)	1, 5	Minor eruption	66§	19
3†	Mount Ruapehu, New Zealand (90º-flips)	2-15	Minor eruption	-	20, 21
d)	Observations during swarm at prototype Stress-Monitoring Site, Húsavík, Iceland.				
	Húsavík, Iceland	~70	$M \equiv 3.5$	-	22
e)	Observations during high- and low-pressure CO_2-injections in carbonate reservoir.				
	Vacuum Field, New Mexico, USA	-	-	-	23

FOOTNOTES

*Iceland seismic catalogue magnitude $M \approx m_b$.

†Observed at more than one seismic station.

‡Older magnitude value, now changed to M 4.9 to be compatible with other listed values.

§As interpreted by in this study.

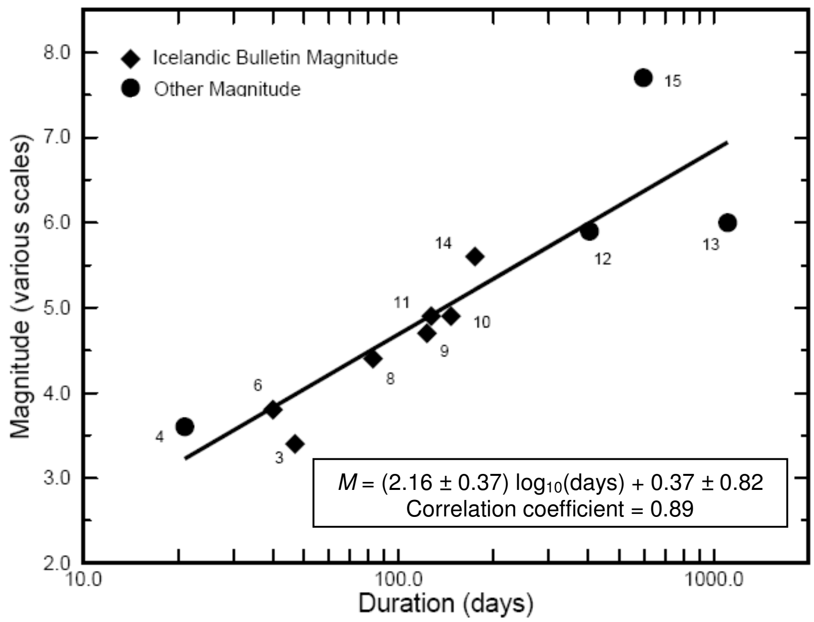
€90º-flips are where faster and slower split shear-waves exchange polarizations due to microcrack realignments in the presence of critically high pore-fluid pressures[13,24-26].

FIGURE CAPTION

Figure 1. Least-squares lines through impending earthquake magnitudes plotted against logarithms of the duration in days of (a) increasing, and (b) decreasing time-delays. Numbered data points refer to Tables 1a, and 1b, respectively. Where earthquakes have observations at more than one seismic station (earthquakes Nos. 8, 9, 10, 11, and 14, in Table 1a, and earthquake No. 8 in Table 1b), duration values from stations closest to the impending earthquakes are plotted. Note that onsets of increases of time-delays are sometimes uncertain because of overlays with other earthquakes in the seismograms (earthquakes Nos. 1, 2, 5, and 7 in Table 1a), and these data points are not plotted.

a)

Duration of increasing time−delays



b)

Duration of decreasing time−delays

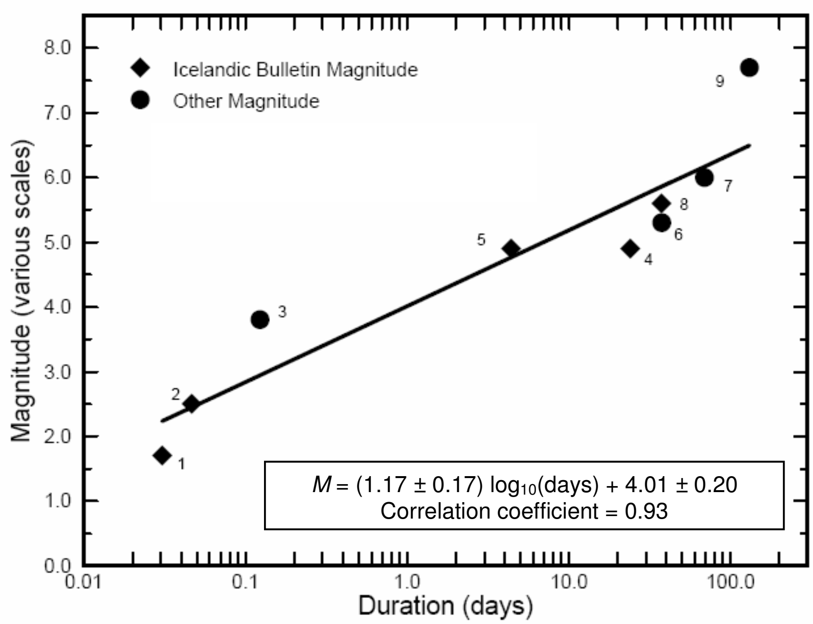


Figure 1