Geophys. J. Int. (1999) **138,** F1–F5

FAST-TRACK PAPER

A successfully stress-forecast earthquake

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Accepted 1999 April 8. Received 1999 April 6; in original form 1999 January 28

SUMMARY

A $M=5$ earthquake in Iceland has been successfully 'stress forecast' by using variations in time delays of seismic shear wave splitting to assess the time and magnitude at which stress-modified microcracking reaches fracture criticality within the stressed volume where strain is released. Local investigations suggested the approximate location of the forecast earthquake. We report the criteria on which this stress forecast was based.

Key words: fracture criticality, shear wave splitting, stress forecasting.

1 INTRODUCTION

Stress-aligned shear wave splitting (seismic birefringence) is observed with very similar characteristics in almost all igneous, metamorphic and sedimentary rocks, below about 1 km depth in the Earth's crust (Crampin 1994). The polarizations of the faster split shear waves are approximately parallel to the direction of maximum compressional stress. Geometrical constraints indicate that the splitting is controlled by the densities and aspect ratios of distributions of the stress-aligned fluid-saturated grain boundary cracks and low-aspect-ratio pores present in almost all rocks. Consequently, shear wave splitting can be used to monitor the effects of the stress build-up before earthquakes and *stress forecast* future large earthquakes (Zatsepin & Crampin 1997; Crampin & Zatsepin 1997; Crampin 1998).

This paper reports the evidence on which a successful stress forecast was based. Possible optimizations, including synthetic modelling and statistical analyses, are beyond the scope of this paper.

2 MONITORING CHANGES BEFORE EARTHQUAKES

Fluid-saturated stress-aligned microcracks are the most compliant elements of the rock mass. Shear waves are sensitive to crack geometry, and variations in the build-up of stress before earthquakes can be monitored by changes in shear wave splitting (Crampin 1978). Observations suggest that cracking increases until a fracture criticality limit is reached, shear strength is lost, and the earthquake occurs (Crampin 1994). As rocks are weak, crack alignments and proximity to criticality are pervasive over very large volumes of the crust around the eventual source zone.

Monitoring the approach of fracture criticality using earthquakes as the source requires: (i) swarms of small earthquakes in order to provide a more or less continuous source of shear waves; (ii) these earthquakes need to be within the shear wave window of a three-component seismic recorder; and (iii) these earthquakes also need to be near to the epicentre of an impending large earthquake. These requirements are severe and until recently changes in shear wave splitting before earthquakes had only been observed with hindsight on four occasions: $M=6$, 1986, North Palm Springs, CA, USA; $M=4$, 1988, Parkfield, CA, USA; $M=3.8$, 1982, Enola, AR, USA; and $M=3.6$, 1992, Hainan Island, China. References are listed in Crampin (1999).

Initially, it was assumed that increasing stress would increase the aspect ratios of microcrack distributions (make cracks swell or dilate), which could be monitored by specific changes in the 3-D pattern of shear wave splitting (Crampin 1999). Recently, a tightly constrained theoretical anisotropic poro-elasticity (APE) model for pre-fracturing deformation has been developed, where the driving mechanism is fluid migration along pressure gradients between neighbouring grain boundary cracks and low-aspect-ratio pores at different orientations to the stress field (Zatsepin & Crampin 1997). APE matches or is compatible with a large range of seismic and crack phenomena (Crampin 1999), including the effects on shear wave splitting of the build-up of stress before earthquakes (Crampin & Zatsepin 1997).

3 EFFECTS OF INCREASING STRESS ON SHEAR WAVE SPLITTING

APE modelling confirms (Crampin & Zatsepin 1997) that the immediate effect of increasing (horizontal) stress on rocks is to increase average aspect ratios in distributions of (approximately) parallel vertical microcracks (Crampin 1994). This increases the average time delays in the double band, Band 1 (ray paths between 15° and 45° to the crack plane), of directions across the shear wave window. Such increases in Band 1 were observed before the four earthquakes cited above. APE also confirms that aspect ratios increase until a level of fracture criticality is reached and earthquakes occur (Crampin 1994; Crampin & Zatsepin 1997).

Time delays in the remainder of the shear wave window (Band 2), the solid angle with ray path directions within $\pm 15°$ of the crack plane, are controlled primarily by the crack density of the crack distribution (see Crampin 1999). The data in Band 2 show no simple correlations with earthquakes.

4 HYPOTHESES FOR STRESS FORECASTING

Stress forecasting uses changes in shear wave splitting in Band 1 of the shear wave window to monitor crack aspect ratios and estimate the time and magnitude that crack distributions reach fracture criticality. There are three principal hypotheses:

(1) the build-up of stress before earthquakes causes progressive changes in aspect ratios until a level of cracking, known as fracture criticality, is reached and the earthquake occurs;

(2) rock is weak to tensile stress, so the effects of the stress build-up before earthquakes are pervasive over large volumes of the crust, and the approach to fracture criticality can be monitored by analysing shear wave splitting at substantial distances from impending epicentres (Crampin 1998; Zatsepin & Crampin 1997);

(3) for a steady stress/strain input, from a moving plate, say, the magnitude of the impending earthquake is a function of the rapidity and duration of the stress build-up before fracture criticality is reached: if stress accumulates in a small volume, the build-up is fast but the resulting earthquake is comparatively small, whereas if stress accumulates over a larger volume, the increase is slower but the eventual earthquake is larger.

5 EFFECTS OF NOISE

Measured values of time delays are subject to two major sources of scatter, in addition to geological and geophysical heterogeneities. The first is that errors in earthquake location may be several kilometres, so that for 5–12 km deep earthquakes, say, equivalent errors in time delays normalized by path length may be 30 or 40 per cent. In the following figures, we only use earthquakes with small (1 km) location errors in order to minimize scatter.

The second source of scatter is more serious. Time delays within Band 1 of the shear wave window vary theoretically with azimuth and incidence angle from zero to a maximum. Consequently, although the average value within Band 1 increases with increasing stress, sampling with individual values may be severely scattered.

It is clear from Fig. 2 that variations in shear wave splitting are extremely sensitive to small changes in conditions. Consequently, a third source of scatter that will be investigated is variations in stress resulting from Earth and oceanic tides.

6 CHANGES IN TIME DELAYS IN ICELAND

The high seismicity of the transform zone of the Mid-Atlantic Ridge and the seismic network developed during the SIL Project (Stefánsson *et al.* 1993) provides good conditions for stress forecasting, and changes in shear wave splitting are now recognized routinely (with hindsight) before larger ($M \geq 3.5$) earthquakes close to seismic stations in SW Iceland. (Magnitudes in Iceland referred to as M are the local magnitude scale, M_L). Fig. 1 shows a map of SW Iceland with earthquakes from July 1 to November 7 1998, and equal-area projections of the polarizations and rose diagrams of the two seismic stations with sufficient earthquakes within Band 1 of the shear wave window. (Shear wave splitting at station KRO is irregular and believed to be the effect of local rifting. Station SAU, although very regular in 1996, now also shows somewhat irregular behaviour.) The average polarizations in Band 1 of the shear wave windows in Fig. 1 are in the direction of the maximum horizontal stress, approximately NE–SW.

Fig. 2 shows variations since 1997 of normalized time delays in both bands of the shear wave window at Stations (a) BJA and (b) KRI. The time delay data show the expected large scatter, making inferences subject to misleading recognized or unrecognized location-induced trends if the data are sparse; consequently, the interpretation below is based principally on Station BJA, which has the most adequate data.

The middle cartoons in Fig. 2 show nine-point moving averages through the time delays in Band 1 (15°–45°). BJA has a series of five pronounced minima. A series of least-squares lines through the data are drawn, where each line

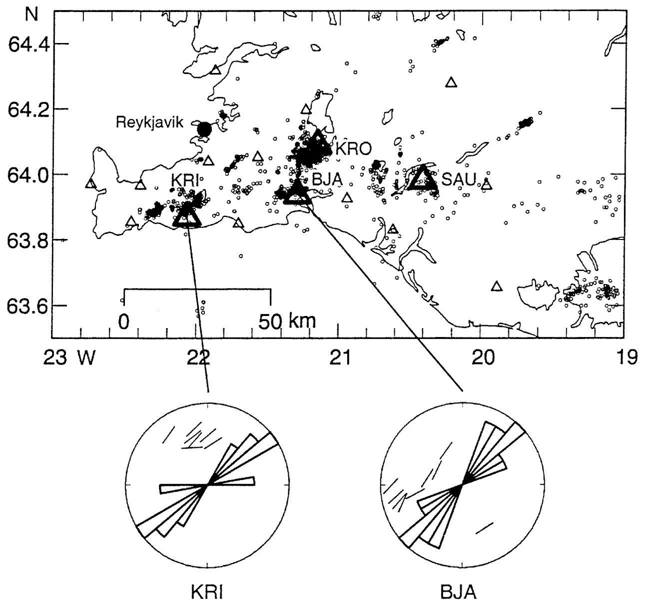

Figure 1. Map of SW Iceland with earthquake epicentres ($M \geq 1.5$) July 1–November 7 1998. Triangles are the Icelandic seismic network. Large triangles are stations BJA, KRI, KRO and SAU, where changes in shear wave splitting have been identified. Circles are equal-area polar maps of the shear wave window (out to 45°) with horizontal projections of polarizations and equal-area rose diagrams of shear wave arrivals in Band 1 of the shear wave window for the final least-squares lines in Fig. 2.

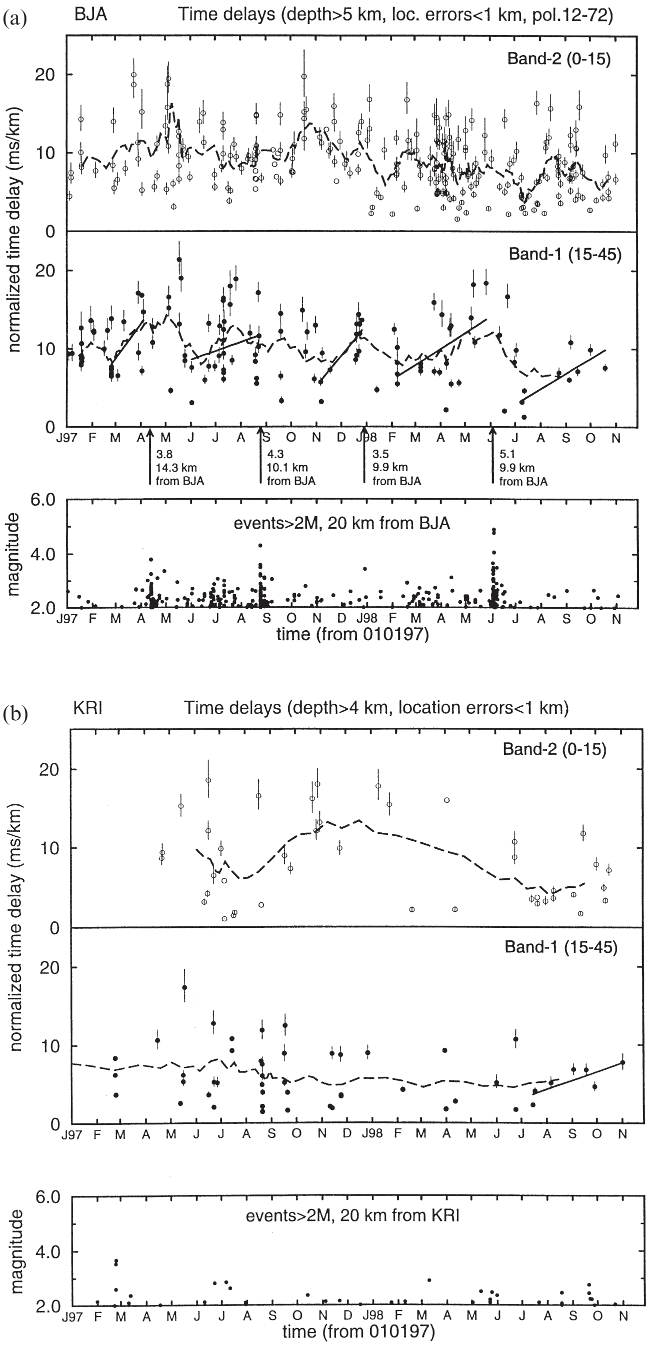

Figure 2. Time delays between split shear waves in Band 1 (middle diagrams) and Band 2 (upper diagrams) of the shear wave window at Stations (a) BJA and (b) KRI for earthquakes below 5 km depth from 1967 January 1 to 1998 November 7, normalized to ms km^{-1} and plotted against time. There are nine-point moving averages through the time delays in both bands. Middle diagrams (Band 1) show least-squares straight lines beginning near a minima of the nine-point average and ending at a larger earthquake. Only reliable time delays (errors less than 0.5 ms km^{-1}) are plotted, and error bars are derived from location errors when less than 1 km. Lower diagrams are earthquakes ($M \geq 2$) within 20 km of the recording stations.

begins just before the time of a minimum of the moving average (there is some subjectivity here) and ends at the time of a larger earthquake, when there is a comparatively abrupt decrease in time delays. (The lower cartoons show the magnitudes of all $M \geq 2$ earthquakes within 20 km of each station.) The straight lines show increasing time delays, implying increasing crack aspect ratios. The data at BJA show no false alarms, although the variations before the $M = 4.3$ earthquake show unexplained irregularities and are henceforth neglected. The upper cartoons show nine-point moving averages through the time delays in Band 2 (0°–15°) with irregular behaviour, and we have been unable to find any correlation with the earthquakes.

Behaviour at BJA: Prior to July 1998, the middle cartoons for BJA shows increases in time delays in Band 1 for all four larger earthquakes within 20 km of the station with magnitudes ranging from $M = 3.5$ to $M = 5.1$ (see note on $M = 4.3$ earthquake above). The duration and rate of increase vary with the magnitude of the eventual earthquake, and the greatest normalized time delay, the presumed level of fracture criticality, varies between about 12 and 14 ms km^{-1}.

Behaviour at KRI: Data are sparse and, apart from the changes after July 1998, there are no discernible variations of splitting in Band 1. The largest earthquake within 20 km of KRI is only $M = 3.7$ in February 1997, and there were no earthquakes within the shear wave window before this event.

Behaviour at SAU (not shown): Apart from the changes after July 1998, there are two increases of time delays in Band 1 associated with the same $M = 4.3$ and 5.1 earthquakes which showed changes at BJA at distances of 42 and 43 km, respectively, from SAU.

Note that both bands of the shear wave windows at BJA and KRI show a decreasing trend over the 2 yr period (also shown by SAU). This is believed to be caused by the relaxation of stress following the Vatnajökull eruption of 1996 September 30.

7 THE STRESS FORECAST

It was recognized on 1998 October 27 that the time delays in Band 1 were increasing from about July 1998 at stations BJA and KRI (Fig. 2). Five features were thought to be significant: (i) the increase had persisted for nearly four months; (ii) it had approximately the same duration and slope as the increases before the $M = 5.1$ earthquake which occurred previously at BJA; (iii) the increase at BJA started at about the lowest level ($\sim$4 ms km^{-1}) of any of the increases associated with previous earthquakes; (iv) there was less scatter about the line than for previous earthquakes; and (v) the increase at BJA was already nearly 10 ms km^{-1} and close to the inferred level of fracture criticality. Many of these features appeared simultaneously at stations BJA and KRI, which are about 38 km apart.

These features suggested that the crust was approaching fracture criticality before an impending larger earthquake. Consequently, stress forecasts were e-mailed (27 and 29 October) to the Icelandic Meteorological Office (IMO) in Reykjavik warning of an approaching (but unspecified) earthquake. Table 1 lists the timetable of e-mails and facsimiles associated with the stress forecast. IMO suggested (Table 1, Item 2) that the increase in stress might be associated with the $M = 5.1$ 1998 June 4 earthquake, 10 km from BJA, which was believed to have initiated movement on a previously dormant fault.

Table 1. Timetable.

1998	E-mails, facsimiles and actions
(1) 27 Oct.	Edinburgh University (EU) e-mails Iceland Meteorological Office (IMO) reporting shear wave time delays in Band 1 increasing from July at stations BJA and KRI and suggests '*… there was an 80% chance of something significant happening somewhere between BJA and KRI within three months.*'*
(2) 28 Oct.	EU faxes data for BJA and KRI to IMO. IMO suggests $M = 5.1$ earthquake near BJA in June 1998 may be linked to current increase in time delays.
(3) 29 Oct.	EU updates current interpretation and suggests '*Shear-wave splitting at both BJA and KRI indicate something is going to happen soon, probably within a month …*'*
(4) 30 Oct.	IMO sends notice to National Civil Defence Committee (NCDC) in Reykjavik suggesting a meeting.
(5) 31 Oct.–4 Nov.	Faxes and e-mails updating information. EU refines data and interpretation. IMO increases local geophysical and geological investigations.
(6) 5 Nov.	IMO presents stress forecast and other data from surrounding area to scientific advisors of NCDC, who conclude no further action is required of them (see comment in the Discussion).
(7) 6–9 Nov.	Exchange of various faxes and e-mails updating information and interpretation.
(8) 10 Nov.	EU concludes '*… the last plot … 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 ($M \geq 6$).*'*
(9) 11 Nov.	EU faxes updated data for KRI and BJA, with SAU now also suggesting increasing time delays from September (but see note in text, Section 7).
(10) 13 Nov.	IMO reports '*… there was a magnitude 5 earthquake just near to BJA (prel. epicenter 2 km west of BJA) this morning 10 38 GMT.*'*

* Quotations (in italics) are exact texts from e-mails.

In the next 10 days, time-delay data were checked and updated and scatter was reduced by plotting only the most reliable data. A meeting of the Scientific Advisors of the National Civil Defence Committee of Iceland (NCDC) was held on November 5. The stress forecasts of 27 and 29 October (Table 1, Items 1 and 3) were discussed, together with information about their possible association with the $M = 5.1$ June 4 earthquake. These forecasts were not specific and magnitudes were not suggested. Moreover, the concept of stress forecasting is new and optimal responses had not been established. Consequently, NCDC were faced with new criteria, and the scientific advisors to the NCDC decided with justification that no further action need be taken on their behalf. However, IMO and others initiated and intensified investigations of local geophysics and geology in an attempt to identify the potential location.

A further examination of new and updated data showed that from September station SAU also displayed a possible increase of time delays in Band 1 (later analysis suggested more irregular behaviour at SAU than was initially indicated and the data are not shown). Consequently, an e-mail to IMO was sent on 1998 November 10, with a *specific stress forecast* (Table 1, Item 8) that an earthquake could occur any time between now (with magnitude $M \geq 5$) and the end of February ($M \geq 6$) if stress kept increasing. These values were estimated from the middle cartoons of Fig. 2(a), with an earlier smaller-magnitude to later larger-magnitude window to allow for inaccuracies in the estimated increase and level of fracture criticality.

Three days later, on 1998 November 13, IMO reported (Table 1, Item 10) that there had been an $M = 5$ earthquake with an epicentre 2 km from BJA at 10:38 that morning (parameters: time 10.38.34, date 1998 November 13, depth 5.3 km, epicentre 63.949N, 21.344W, and magnitude now estimated as $M = 4.9$). As suggested by IMO (Table 1, Item 2), the earthquake appears to be on the same fault as the $M = 5.1$, 1998 June 4 event. We claim this is a successful stress forecast within a comparatively narrow time–magnitude window.

7.1 Definition of the time–magnitude window

Based on the above hypotheses for stress forecasting, there are three factors that allow the time–magnitude window for future larger earthquakes to be defined. These are: (1) the inferred levels of fracture criticality from the range in levels in ms km^{-1} at which previous earthquakes occurred; (2) the slope of the increase in time delays, which is inversely proportional to magnitude; and (3) the duration of the increase, which is proportional to magnitude. The earliest the earthquake could occur is (a) when the slope (from 2) reaches the lower limit of fracture criticality (from 1), where the duration of the increase (from 3) gives an approximate magnitude. The latest time of occurrence is (b) when the slope (from 2) reaches the upper limit of fracture criticality (from 1), where the duration again gives an approximate magnitude. Taken together, (a) and (b) define an earlier smaller-magnitude to later larger-magnitude window. The slope (from 2) can be used to give an optimum magnitude value. These are based on linear interpolations from the four variations before earthquakes in Band 1 at BJA in Fig. 2.

8 DISCUSSION

Since all previous earthquake warnings have been shown to be highly suspect or spurious (Geller 1997), all predictions and forecasts must be subject to severe scrutiny. There are several reasons why this stress forecast might be thought to be spurious.

(1) Larger events within 20 km of BJA repeat every four to six months, and an event could be expected within five months of the $M = 5.1$ June 4 event. However, these repeated events vary in magnitude between $M = 3.5$ and $M = 5.1$, with two orders of magnitude energy differences, and the forecast $M \geq 5$ earthquake would not be expected immediately after the previous large $M = 5.1$ event.

(2) Increased seismicity near BJA following the 1998 June 4 event, Table 1, Item 2, might suggest further activity near BJA. However, stress forecasting, as currently understood, cannot forecast location, and as similar changes in shear wave splitting were observed at both BJA and KRI, the eventual epicentre near BJA was not indicated by shear wave splitting.

(3) The coincidence that the November 13 forecast event was 2 km from BJA. However, since similar changes were seen at KRI, the proximity to BJA is believed not to have strongly influenced or affected either the data or the forecast.

(4) There was foreshock activity (not shown) starting on 1998 November 8 close to the eventual focus. However, there is currently delay of a day or two before data are placed on the web site, and a day or two before data are processed. The stress forecast on the November 10 (Table 1, Item 8) was based on the data in Fig. 2 up to November 7 and was independent of the foreshock activity.

There are two main reasons why we consider this stress forecast to be valid. Increases of time delays within Band 1 of the shear wave window before earthquakes have been observed elsewhere (Section 2) and are now observed routinely with hindsight in SW Iceland (Fig. 2). Thus, the identification of an increase before an earthquake in real time was expected and sought. Second, the APE model for the response of fluid-saturated microcracked rock to changes in stress matches observations before earthquakes (Crampin & Zatsepin 1997) and matches a substantial number of other observations of shear wave splitting and cracks, including both static quantities and dynamic changes (Crampin 1999). This suggests that the underlying assumptions and mechanisms cited here are physically valid.

However, there is no experience of either issuing or responding to stress forecasts, but we are learning. In particular, future episodes should not begin with unspecified forecasts (Table 1, Items 1 and 3), which place responsive authorities, such as the NCDC, in an awkward position when they are expected to make recommendations based on inadequate information.

9 CONCLUSIONS

An $M=5$ earthquake in SW Iceland has been successfully stress forecast in the sense that estimates of magnitude and time were correct and defined within a comparatively narrow time–magnitude window. These warnings stimulated local studies, which identified the approximate location.

There are important implications.

(1) Earthquakes can be stress forecast. However, without the pronounced seismicity of the Mid-Atlantic Ridge transform zone, routine stress forecasting elsewhere would require controlled-source seismology in stress monitoring sites using cross-hole seismology (Crampin 1998).

(2) Fluid-saturated cracks within the Earth's crust, even in the low-porosity igneous and metamorphic rocks in Iceland, are compliant to comparatively small changes in stress so that the proximity to fracture criticality is pervasive over large volumes of rock.

(3) Details of pre-fracturing deformation can be monitored with shear wave splitting.

(4) The behaviour of such stressed fluid-saturated cracked rock can be modelled by anisotropic poroelasticity (APE). This offers a new understanding and insight that is important for investigating all natural and artificial deformation processes.

Again we emphasize that the techniques presented here have not been optimized. This paper merely reports the data and criteria on which a successful stress forecast was based.

ACKNOWLEDGMENTS

We are grateful for the support of the EC in the PRENLAB Project. We thank David C. Booth, Peter Leary, Xiang-Yang Li and Ian Main for constructive comments on the manuscript. We also thank Páll Einarsson and an anonymous reviewer for their comments, which helped to improve the manuscript.

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