Temporal variations of shear-wave splitting in field and laboratory studies in China

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Abstract

Observations of shear-wave splitting at seismic stations above a swarm of small earthquakes on Hainan Island, China, and other examples world-wide, suggest that the time-delays of split shear-waves monitor the build up of stress before earthquakes and the stress release as earthquakes occur. Rock physics experiments on marble specimens also show variations of shear-wave time-delays with uniaxial pressure analogous to the field observations. The rock experiments show an abrupt decrease in time-delays immediately before fracturing occurs. Similar precursory behaviour has been observed before earthquakes elsewhere, and is believed to be important for two reasons. Precursory changes in shear-wave splitting could be used for short-term forecasting, but of greater importance may be the information such behaviour provides about the source processes in earthquake preparation zones.

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1. Introduction

Seismic shear-waves split into two approximately orthogonal polarisations (seismic birefringence) when travelling through anisotropic media. Stress-aligned shear-wave splitting is widely observed in the Earth’s crust and appears to be caused by propagation through the fluid-saturated stress-aligned vertically oriented parallel grain-boundary cracks and intergranular pores present in almost all rocks (Crampin, 1994, 1999). For propagation within about 45° of the vertical, the polarisation directions of the faster split shear-waves are approximately parallel to the direction of maximum horizontal stress indicating fluid-saturated microcracks oriented, like hydraulic fractures, perpendicular to the direction of minimum compressional stress.

The polarisations and time-delays between the split shear-waves are sensitive to small changes in microcrack geometry. Both theory and observations suggest that small increases of stress cause crack aspect-ratios to increase (Zatsepin and Crampin, 1997; Crampin
and Zatsepin, 1997; Crampin, 1999). These changes can be monitored by observations of time-delays of split shear-waves along a specific range of solid-angle directions relative to the crack orientations (Crampin, 1999).

There are geometrical, technical and logistic problems in observing variations in three-dimensional patterns of time-delays of shear-wave splitting, before and after strong earthquakes. However, temporal changes in time-delays before earthquakes have been reported (with hindsight) from several places in America and Europe (Peacock et al., 1988; Crampin et al., 1990, 1991, 1999; Booth et al., 1990; Liu et al., 1997; V olti and Crampin, 2003 (a,b)). On one occasion, the time and magnitude of a \((M = 5)\) earthquake in SW Iceland was successfully stress-forecast in real time during an extensive study of shear-wave splitting in Iceland (Crampin et al., 1999; V olti and Crampin, 2003 (a,b)). Note that shear-wave splitting can lead to estimates of the time and magnitude of future earthquakes, but typically cannot directly predict time, magnitude and location of impending earthquakes. Consequently, we call the process earthquake stress-forecasting not earthquake prediction. However, if a large earthquake is known to be approaching, other precursory phenomena may indicate the location, as happened in the successful stress-forecast in SW Iceland, where small-scale seismic activity indicated the fault on which the forecast earthquake occurred.

The major problem in stress-forecasting is the need for persistent swarms of small earthquakes to provide shear-wave source signals for monitoring shear-wave splitting by local seismic networks, where there are stations within the shear-wave window of the seismic activity. (The shear-wave window is the cone of directions within \(\sim 45°\) of the vertical where shear waves at the free surface are not distorted by \(S\)-to-\(P\) conversions (Booth and Crampin, 1985).) Such persistent swarms are uncommon and sporadic. Consequently, it is difficult to set up and maintain local seismic arrays for extended periods of time above swarms of small earthquakes in zones where strong earthquakes are expected. There is only one example in China where temporal variations in shear-wave splitting have been observed by a local seismic network (Gao et al., 1998). We reproduce the results here with some additional data.

Strong earthquakes in China are often recorded by networks of strong-motion instruments which sometimes record data within the shear-wave window. Despite an extensive search (Gao et al., 2000), these strong-motion records have not been above persistent swarms and the data are too sparse to be analysed.

In an attempt to provide confirmatory evidence from laboratory data, we report changes in time-delays in a rock physics experiments which show changes in shear-wave splitting before the samples fracture. Even more importantly, they also show precursory changes in shear-wave splitting immediately before fracturing similar to precursory changes observed in the field.

2. Temporal changes of shear-wave splitting from observations in China

2.1. Data analysis technique

We use an automatic analysis method (SAM) using correlation function analysis for processing shear-wave splitting (Gao and Zheng, 1995). SAM calculates cross-correlation functions, eliminates time-delays, and analyses polarisation diagrams (Gao et al., 2000). SAM assumes shear-waves split into two polarisations, and that the waveforms correlate with each other with the lag of the time-delay. SAM seeks the best fit between rotated horizontal seismograms normalised to the maximum amplitude.

Fig. 1 shows a typical example. The two horizontal component records are rotated every \(1°\) of azimuth and the cross-correlation functions are calculated for relative time-delays and azimuths (Fig. 1a). The maximum value of the cross-correlation function, normalised to 1, indicates the polarisation azimuth of the fast shear-wave and the lag is the time-delay of the slow shear-wave. Fig. 1b shows two horizontal shear-wave seismograms and the polarisation diagram for the seismograms as recorded on NS and EW components. Fig. 1c shows rotated seismograms and rotated polarisation diagrams for the azimuth taken from the contour calculation. Fig. 1d shows the same plots where the time-delay has been eliminated from the seismograms. The shear waves arrive at the same time on both components, and the polarisation diagrams show approximately linear motion indicating
that the shear-wave splitting analysis is satisfactory (Gao and Zheng, 1995; Gao et al., 1998).

Note that this SAM technique assumes that the two split shear-waves are geometrically split and there is no frequency modification to the waveforms. This may be applicable to waveforms from earthquakes in limited source volumes, as in the field example in Section 2.2, which is almost an isolated swarm (Crampin, 1993) and the shear-wave travel are along very similar ray paths. In general, this is not the case. Shear waves split into two polarisations because the polarisations respond to different features of the rock structure, and the slower shear-wave is expected to be more attenuated (Hudson, 1981). Crampin et al. (1991) showed that at least some of the errors in the automated analysis of Aster et al. (1990) were the result of cross-correlating split shear-waves where the low frequencies of the fast wave were attenuated in the slow wave.

2.2. Temporal changes in shear-wave splitting in Hainan Island, southern China

Temporal changes of shear-wave splitting were observed for a small isolated swarm of earthquakes in Dongfang district, Hainan Island, southern China (Gao et al., 1998). Isolated swarms have tightly constrained focal zones (in this case, it was 2 or 3 km in
radius), which are particularly useful for earthquake source studies as they tend to have very repeatable source parameters (Crampin, 1993).

In January of 1992, two $M_L = 3.4$ and $M_L = 3.7$ earthquakes within 30 s of each other initiated a swarm of small earthquakes in the region of Dongfang, which continued for several months. Two stations, GAC and BAQ, of a temporary array recorded three-component data within the shear-wave window from May to August (Fig. 2). SAM analysis of the waveforms indicated temporal changes of time-delays between the split shear-waves at these two stations. Fig. 2b shows analysis of 16 events at station BAQ and 18 events at station GAC. This is 25% more observations than those reported by Gao et al. (1998), although the conclusions are similar. Based on the anisotropic poro-elasticity (APE) model for the evolution of stressed fluid-saturated rock (Crampin and Zatsepin, 1997; Zatsepin and Crampin, 1997), both theory and observations of fluid–rock interactions (Crampin, 1999) suggest that the shear-wave window should be divided into two bands for the analysis of shear-wave splitting. Band-1 is the double-leafed solid angle of ray paths with angles between $15^\circ$ and $45^\circ$ either side of the crack plane, where time-delays are sensitive to crack aspect-ratios. Band-2 is the solid angle, $15^\circ$ either side of the crack plane, where time-delays are sensitive principally to crack density. Station BAQ is largely within Band-2 and is expected to be sensitive principally to crack density which probably does not vary significantly with small changes of stress. APE shows that the immediate effect of small changes of stress is to modify crack aspect-ratios and station GAC, within the Band-1, does show more significant variations than BAQ.

Note that measured shear-wave time-delays typically display a scatter of up to $\pm 80\%$ about the mean. Crampin et al. (2002) show that the scatter is almost certainly caused by $90^\circ$ flips in shear-wave polarisations when shear waves propagate through the critically pressurised microcrack distributions, which are likely to be present on all seismically active fault planes. Isolated swarms with earthquake foci within a small focal volume typically display much less scatter in time-delays as in Fig. 2b. This is because persistent swarm activity indicates that high fluid-pressures are retained at the source, beneath impermeable layers for example, so that changes in high pore pressure distribution are minimised and the scatter in time-delays reduced. Stress and fluid-pressure are likely to be severely disturbed by stress changes following the more usual unconfined earthquake activity.
The pattern of variations of time-delays at station GAC shows scattered arrivals with two, possibly three, increases with one abrupt decrease, and a decrease which may be abrupt but the data is too sparse to be reliable. There are no records before the largest $M_L = 4.5$ event of the swarm, and the start of the recording coincides with the $M_L = 3.1$ event in early June 1992. Immediately before the first abrupt decrease in $\Delta t$ in mid-June 1992, there are a concentration of six events with magnitudes from $M_L = 1.8$ to $M_L = 2.5$ (approximately equivalent to the energy of 1 $M_L \sim 3.1$ event). Crampin et al. (2003), in this issue, show another example where the effects of a swarm of small earthquakes are similar to those of one earthquake releasing the sum of the energies released by the smaller earthquakes. The second $\Delta t$ decrease follows a $M_L = 3.6$ event in mid-July. Station BAQ is in Band-2, and being sensitive principally to changes in crack density shows only minor variations. At the beginning of $\Delta t$ time variations at BAQ, there is an increase, which does not appear to be related to earthquake occurrence. This phenomenon is believed to reflect the different effects of crack aspect-ratio and crack density at the two stations.

In order to allow comparison of time-delays, $\Delta t$ is normalised to focal distance, giving time-delays corresponding to milliseconds per kilometre. Correspondingly, these time-delays are marked ms/km, and may be considered (perhaps misleadingly) as slownesses.

3. Experimental study of response of shear-wave splitting to variations in differential stress

3.1. Experimental stress-cell

Stimulated by the observations at Hainan, a rock physics experiment was designed to study the response of shear-wave splitting to changes in differential uniaxial stress in a laboratory stress cell. Fig. 3 is a schematic illustration of the equipment. The experiment made use of a multi-channel waveform recorder (DZ95) and an engineering multiple-wave parameter analytical-controller (GC-100) (Gao et al., 1999). The recorder DZ95 has a maximum sampling rate of 20 MHz. The GC-100 controller transmitted single pulses at 3 s time intervals. Both transmitters and receivers were three-component transducers. The experimental samples were Laizhou marbles from Shandong, China. Three specimens ($115 \times 150 \times 115$ mm) were cut from the same unfractured rock with a dominant lamination parallel to one of the $115 \times 150$ mm faces (Gao et al., 1999). The transducers were positioned to

Fig. 3. Schematic diagram of the rock physics experiment.
record shear waves travelling parallel to the lamina-
tions. The uniaxial stress opened microcracks parallel
to the lamina-tions, and the records showed splitting
with the faster shear-wave polarised parallel and the
slower shear-wave orthogonal to the lamina-
tions.

In order to measure the shear-wave splitting time-
delays $\Delta t$ and its response to changing stress, each
specimen was gradually loaded, allowing the shear-
wave splitting to be monitored until the specimen lost
stability, and fracturing and fragmentation occurred.
Note that the time-delays are also normalised by path
length to ms/km so that their values can be compared
to field observations.

3.2. Analysis of results

Fig. 4 shows the stress history for the three
samples which allowed gradual changes to be
recorded before fracturing occurred. We measured
time-delay data at the critical stage, immediately
before fracturing, on two rock samples (Fig. 4a and
4c). Unfortunately, a third sample, sample B (Fig.
4b), fractured prematurely before we were ready to
record appropriate data. Fig. 4d and f shows the last
few seconds before fracturing in the boxed sections of
Fig. 4a and c, respectively. When loading sample C,
several measurements were made at a constant load-

Fig. 4. Variation of shear-wave splitting in uniaxial compression tests on three marble samples, A, B and C, in (a), (b) and (c), respectively. The
left-hand plots show shear-wave time-delays and loading pressures, where the time-delays are measured across the sample, perpendicular to the
direction of loading pressure, and normalised to ms/km. The solid triangles indicate critical points where the rock fragments. The right-hand
plots are the temporal changes in time-delays in the boxed intervals in the left-hand plots, where the pressure is held constant, immediately
before the sample fragments. (d) Refers to sample A; (e, f) refer to the behaviour at intermediate stress and at fracturing in sample C. The stress
at which fracturing occurs are 51.87, 51.80 and 42.98 MPa for samples A, B and C, respectively. Error bars of 0.2 ms/km or less are too small to
be visible (modified after Gao, 2001).
ing pressure (marked Tc1 in Fig. 4c), and shown in Fig. 4e. Fig. 4e shows a few seconds of sample C when the pressure was constant but where the splitting changed spontaneously.

Fig. 4a–c shows that the time-delays in shear-wave splitting increase with loading pressure until fracturing occurs. This was expected and suggests that cracking becomes more pronounced and time-delays increase as stress increases, so that $\Delta t$ is approximately proportional to the loading pressure. In samples A and C, fracturing occurs spontaneously after the stress had been held constant for several seconds, showing that the cracked rock responds to stress in a time-dependent process. It has been recognised previously that samples respond spontaneously while the stress is held constant (Gao, 2001; Gao et al., 1999). Fig. 4 suggests that the response is due to modifications of microcrack geometry.

An unexpected feature was that $\Delta t$ decreases immediately before fracturing in all three samples. This occurs even when the loaded pressure is held constant near the critical level for samples A and C (Fig. 4a and c). Sample A (Fig. 4a) shows a marked decrease from about 10.8 to 5.4 ms/km with the final increment of stress. With the stress held constant, there is a further decrease in time-delay to 3.6 ms/km before a final rise to about 9.9 ms/km when the sample fragments. Similarly, the last three stress increments for sample B (Fig. 4b) also show a decrease in $\Delta t$ from 10.8 to 5.2 ms/km and a rise to 6.5 ms/km, where the rock fractures without further $\Delta t$ measurements being taken. The behaviour of sample C shows varying $\Delta t$ as the stress increment was held constant, with approximate values of $\Delta t = 2.8$ ms/km, 3.2 ms/km, a small decrease to 2.8 ms/km, and a final rise to 4.0 ms/km when the sample fractures.

3.3. Limitations to the experiment

(1) The measurements are made parallel to the face of the cracks which were parallel to the laminations. This is in Band-2 directions, in the notation of field observations, where the effects are expected to be less sensitive to changes in aspect ratio. This suggests there is little sensitivity to small changes of stress, and the effects in Fig. 4 are principally due to changes in crack density.

(2) The state of fluid saturation is not controlled and saturation may vary throughout the sample. This may be a serious limitation.

(3) The samples A, B and C from the same rock mass had very different fracture strengths, 51.87, 51.80 and 42.98 MPa, respectively. As the samples were cut from the same rock and were superficially similar, the difference in fracture strength is probably due to differences both in increasing style of loading pressure and particularly in saturation.

(4) The equipment allowed measurements to be taken only at 3 s intervals. With continuously loading, such intermittent sampling may hide features that more frequent measurements would reveal. Details near critical points immediately before fracturing may be hidden in this way, and the apparent differences in behaviour between samples may be less severe than Fig. 4 suggests.

4. Discussion and conclusions

We have demonstrated similarities between laboratory and field observations of changes in shear-wave splitting before earthquakes. This tends to confirm that shear-wave splitting in the crust is caused principally by stress-aligned fluid-saturated grain-boundary cracks and low aspect-ratio pores. Note also that the shear-wave splitting in the laboratory experiments reported here is caused by stress-induced microcracking oriented by the intrinsic laminations of only partially saturated marble samples. These differences mean that the laboratory experiments do not strictly mimic the behaviour of cracking in crustal rocks. Nevertheless, they do reproduce several characteristics of crustal shear-wave splitting, including the sensitivity to comparatively small changes of stress, and the similar levels of normalised time-delays immediately before earthquakes.

In view of the various limitations listed in Section 3.3, it is perhaps remarkable that the laboratory measurements are so similar to field observations. This is thought to be because all fluid-saturated microcracked rocks are critical systems with similar underlying microcrack structures regardless of rock type, porosity, and tectonic history (Crampin and Chastin, 2001; Crampin et al., 2003). This paper
suggests the effects are also regardless of in situ and laboratory conditions.

A particularly interesting feature of the experiments is that although the shear-wave splitting time-delays are sensitive to loading pressure and increase with pressure, in all three samples the time-delays decrease immediately before fragmentation. This precursory decrease in time-delays immediately before fracturing is also observed before earthquakes in the field on those occasions when there is sufficient seismic activity immediately before the earthquakes for detailed monitoring. Before earthquakes the time of the precursory decrease appears to vary with the earthquake magnitude. The decrease is found to be ∼2 h before a $M = 3.8$ event (Booth et al., 1990), ∼4 days before a $M = 5$ event (Volti and Crampin, in press (b)), and (close inspection also shows a decrease) ∼25 days before the $M = 6$ North Palm Springs earthquake (Peacock et al., 1988; Crampin et al., 1990).

In the laboratory experiments, the decrease in time-delays occurs spontaneously sometimes at a constant level of stress. We suggest that these decreases may be important for two reasons. Such precursory decreases immediately before earthquakes suggest that shear-wave splitting could provide a short-term precursory signal that the earthquake was imminent. This would require rapid processing and analysis which is not easy to arrange in field conditions.

Perhaps more important is the information the decrease provides about earthquake source processes. We do not understand the cause of the precursory decrease. It appears that both in situ rock and laboratory specimens recognise the approach of fracturing, and suggest that the microcrack geometry begins some form of relaxation, where cracks begin to close, leading to lower levels of shear-wave splitting.

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References


