Shear-wave polarizations near the North Anatolian Fault – I. Evidence for anisotropy-induced shear-wave splitting

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Summary. The Turkish Dilatancy Projects (TDP1 in 1979 and TDP2 in 1980) recorded small earthquakes near the North Anatolian Fault with closely-spaced networks of three-component seismometers in order to investigate the possibility of diagnosing dilatancy from its effects on shear-wave propagation. This paper examines the polarizations of shear wavetrains recorded in the shear-wave window immediately above the earthquake foci. Abrupt changes in the orientation and/or ellipticity of the shear-wave polarizations are almost always observed during the first few cycles following the initial shear-wave arrival on each seismogram. The horizontal projections of the polarizations of the first shear-wave arrivals at any given station show nearly parallel alignments with approximately the same orientations at each of the recording sites (with one exception). It is difficult to explain this uniform alignment over a wide area in terms of scattering at the irregular surface topography or by earthquake focal mechanisms. We demonstrate that the shear-wave splitting is likely to be the result of anisotropy in the region above the earthquake foci, which could produce polarizations displaying the observed alignments. The temporal change of the azimuth of alignment, observed at one locality between 1979 and 1980, may be due to the release of a local stress anomaly by a very near earthquake.

1 Introduction

The shear wavetrain typically carries over three times more information than the P-wavetrain about the behaviour of the source and the propagation path (Crampin 1985). If the raypath of the shear waves passes through anisotropic, or effectively-anisotropic media such as that resulting from aligned cracks (Crampin 1978), the shear waves will split into two or more arrivals with different velocities and different polarizations. This shear-wave splitting is probably the most

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diagnostic effect of anisotropy on seismic-wave propagation (Crampin 1981) and can be used to evaluate the orientation and geometry of the anisotropy (Crampin & McGonigle 1981).

Crampin (1978) suggested that it might be possible to monitor dilatancy by shear-wave splitting, since all stress-induced cracks are likely to be aligned and hence effectively anisotropic. Following this suggestion, the Turkish Dilatancy projects, TDP1 in 1979 and TDP2 in 1980, were set up to investigate shear-wave splitting above a swarm of small earthquakes near the North Anatolian Fault in Turkey (Crampin et al. 1980; Crampin, Evans & Üçer 1985). This paper analyses the shear-wave polarizations in the TDP recordings. We shall show that the polarizations of the faster split shear wave, on several hundred wavetrains recorded within the shear-wave window, arrive with alignments typical of anisotropy-induced splitting. The following paper (Crampin & Booth 1985) interprets this anisotropy in terms of a regional stress-field producing extensive dilatancy anisotropy (Crampin, Evans & Atkinson 1984) and shows that crack-induced anisotropy can account for the observed polarization anomalies.

2 Shear-wave propagation

2.1 SHEAR WAVES AT THE FREE SURFACE

It has been recognized for some time (Nuttli 1961; Meissner 1965) that plane shear waves may be substantially modified by interaction with the free surface. The incident shear waves are free from distortion only when the angle of incidence at the free surface is less than a critical angle $\sin^{-1}\left(\frac{V_s}{V_p}\right)$, which is equal to about 35° for a Poisson’s ratio of 0.25 (Booth & Crampin 1985; Evans 1984). This region, where the shear wave can be recorded at the surface without distortion, is known as the shear-wave window. Synthetic seismogram for curved wavefronts have similar behaviour (Booth & Crampin 1985), except that the critical angle is now also dependent on the curvature relative to the seismic wavelength, and the aperture of the effective shear-wave window is increased by the curvature of the wavefront and possibly by the presence of low-velocity surface layers.

The activity monitored by the TDP networks was at focal depths between 6 and 12 km. However, it must be noted that the focal depths of earthquakes located mainly by P-wave arrivals from the upper focal sphere are not well controlled as there is a trade-off between origin time and focal depth. In addition, Doyle, McGonigle & Crampin (1982) show that the focal depths of local earthquakes in effective anisotropic structures appropriate to the TDP events can be in error by up to 2 km if they are calculated under the assumption that the structure is isotropic. Such mislocations in depth (epicentres are better controlled) will have little effect on measurements of the split shear waves, but they will affect the estimated angle of incidence (Crampin & Booth 1985). For this reason and because of the enlargement of the effective shear-wave window due to the curved wavefront, we shall consider shear-wave polarizations for incidence angles up to 40°. The consistency of the observations (see Fig. 2) suggests that this is a realistic estimate of the aperture of the effective shear-wave window.

Further notes on shear waves at a free surface

(i) The particle motion of shear waves becomes elliptical for incidence near the critical angle, and the initial polarization may become indeterminate (Booth & Crampin 1985). Such elliptical polarizations may also indicate shear-wave splitting between shear waves with almost the same velocity so that there is a small phase difference between them. Consequently, to avoid misinterpretation or over-interpretations, we do not analyse shear-wave polarizations when the ratio of the minor to the major axis is greater than 1:2. However, Crampin (1985) has shown that the anisotropy-induced orientation of the initial onset may be recognized even for very elliptical
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(ii) A refracted mode-converted P-wave, the local SP-phase (Evans 1984; Booth & Crampin 1985), may be generated when the incidence angle of a shear wave is locally equal to the critical angle. This local SP-wave is a P headwave propagating parallel to the surface with nearly radial polarization. This SP-wave has a considerable theoretical background (see Evans 1984), but the observations in the TDP records by Evans (private communication) appear to be the first time that the phase has been positively identified on seismograms. If there is rough topography, as in the TDP area, the critical angle may be exceeded locally and the SP phase can appear within the shear-wave window defined for a horizontal interface. Occasionally, it may be the largest arrival on the seismogram, if focused by the curvature of the surface. Seismograms on which the local SP phase could be positively identified by the large radial horizontal component were discarded in this present study.

(iii) Outside the shear-wave window, the SV component of the incident shear wave is diminished and the horizontally-recorded shear wave on the free surface has predominantly SH polarization. SH-polarized shear waves observed near the edge of the shear-wave window cannot be discarded, since they may well represent the true polarization of the incident wave, but they must be interpreted with caution.

2.2 SHEAR-WAVE SPLITTING

Almost all of the several hundred shear wavetrains recorded within the shear-wave window at the various TDP stations display the abrupt changes in polarization typical of shear-wave splitting in synthetic seismograms calculated for anisotropic raypaths (Crampin 1978; Crampin et al. 1985). The particle motion of the first shear-wave arrival is nearly always linear. Evans (1984) and Booth & Crampin (1985) have shown that the interaction of the incident shear wave with the free surface can produce an SH polarized shear wave immediately preceded by a radially-polarized SP arrival which can be misinterpreted as a split shear wave. Crampin (1985) has shown that topographic irregularities can lead to the local SP phase being observed well within the shear-wave window. The polarization of about half of these linear onsets are within 20° of SV- or SH-polarization so that they could possibly be due to interactions at rough topography. However, the remaining half of the polarizations are more than 20° from SV or SH polarizations. Since interactions with a rough topography will lead to polarizations which are scattered about SH and SV, the wide range of observed polarizations suggests that surface interactions do not play a major role in orienting the initial shear-wave arrival, although they may well introduce some scatter into the observations.

An important discriminant for anisotropy-induced splitting is that the variation of polarizations with direction should be in a pattern fixed by the geometry of the anisotropy. In ideal circumstances, the delays between the shear waves should also show patterns fixed by the geometry. However, these delays are a much less stable observation (see Crampin & Booth 1985) and in this study we have not attempted to use delays to evaluate anisotropy except to estimate the maximum delay (Crampin & Booth 1985).

Crampin & McGonigle (1981) present stereographic projections (we now prefer equal-area projections) of relative shear-wave delays and polarizations, as observed by horizontal instruments, for propagation through focal spheres with various anisotropic symmetries. These delays and polarizations are characteristic of the geometry and orientation of the anisotropic symmetry, and if the projection patterns can be estimated from surface observations, they place constraints on the possible cause of the anisotropy. Note that Crampin & McGonigle do not take free surface interactions into account, and only the projections within the shear-wave windows (incidence angles less than 40°, say) are valid for surface observations.
Figure 1. (a) Locations of the TDP1 and TDP2 stations used in this study. Contour lines represent heights in metres. Stars are the epicentres of the six largest events located by the Kandilli seismic network (Uğur et al. 1985) in 1979 and 1980 within the area covered by the map: (1) 3.1 m$_s$, 1979 March 14; (2) 2.7 m$_s$, 1979 July 31; (3) 2.7 m$_s$, 1980 January 20; (4) 3.0 m$_s$, 1980 February 24; (5) 3.3 m$_s$, 1980 October 25; (6) 3.5 m$_s$, 1980 October 25. (b) Average orientations of the polarizations of the initial shear wave arrivals at the TDP1 and TDP2 stations from the distributions of orientations in Fig. 2.

2.3 THE ORIENTATIONS OF THE SHEAR-WAVE POLARIZATIONS

Estimates of the polarization directions of the first shear-wave arrivals were made for all earthquakes within the shear-wave window at seven closely-spaced stations which were occupied during TDP1 and TDP2. The positions of these stations are shown in Fig. 1(a). Stations TE, SE, AY, ME and PA were occupied during the TDP1 experiment, and stations TE, SE, AY, DP and PB during TDP2. The average separation between adjacent stations is about 5.5 km, but PA and PB are separated by only 1.2 km. The stations are located in an area of steep and varied topography (Fig. 1a).

The first shear-wave arrival could be identified unambiguously on the great majority of seismograms within the shear-wave window. Polarization diagrams displaying the horizontal projection of the shear-wave particle motion were used to estimate the orientation of the polarization of each incident shear-wave first arrival with respect to true north. These orientations were measured on diagrams rotated relative to the radial direction of the horizontal polarizations and the value added to the azimuth of the station with respect to the earthquake to give the correct geographical azimuth. This procedure lessened any subjective bias in the measurements. The average error in the measurements of the shear-wave polarization orientations is estimated to be about 10°.

The polarization directions of the first shear waves at incidence angles less than 40° are plotted for each station on equal-area projections in Fig. 2, with corresponding histograms of their azimuthal distribution. We do not take account of the polarity of the particle motion of the first shear wave in Fig. 2. The distribution of polarization directions is limited to values between 0° and 180° in each histogram, with the distribution repeated over a further 180° in Fig. 2 and in subsequent histograms (unless otherwise stated) so that the shape of the distribution is seen more clearly. Note that the azimuthal distribution of shear-wave polarization observations at each station is not only dependent on the distribution of well-located earthquakes but also on the focal
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Figure 2. Orientations of the polarizations of the first shear-wave arrivals from local earthquakes observed at five stations occupied during TDP1 (1979) and five during TDP2 (1980). The upper diagrams are equal-area projections, out to incidence angles of 40°, of the horizontal polarizations at the free surface within the shear-wave window. The lower diagrams are histograms of the observed orientations at each station for directions east of north. The underlined figure is the total number of observations in each histogram.

mechanisms of the recorded earthquakes. Thus the earthquake swarm observed due east at AY and ME during TDP1 did not contribute to the shear-wave observations at SE, because stations SE lay in a node of the shear-wave radiation pattern for these earthquakes.

The polarizations show approximately parallel alignments at each station, with the directions of alignment indicated by the peaks in each histogram. The station distribution recorded fewer arrivals within the shear-wave window in 1980 but at those stations operating in both years (AY, SE and TE) the direction is essentially the same. The average orientation of the polarizations at each of the stations is summarized in Fig. 1(b). With one exception, they are all oriented within ±20° of N 100°E. The average orientations at TE are the most divergent of the nearly parallel alignments. This divergence is largely caused by a group of events near the edge of the shear-wave window in the NW quadrant in TDP1, and nearly due north in TDP2. If these were eliminated the scatter at TE would be less, and the average polarization would be nearer to the average at the other stations.

The exceptional station is PA in 1979. The polarizations at PA are aligned in a direction some 60° different from those observed at the other stations. PA may be compared to a nearby site PB, recording in 1980, where the polarizations are again parallel to the general trend. Many of the observations at PA and PB lie on the edge of the shear-wave window, and must be interpreted with caution. Nevertheless, as at many of the other stations, the polarization directions observed at the edge of the shear-wave window show the same alignment as observations well within the window. The majority of these polarizations do not have either the radial alignment of the local SP phase, or the transverse alignment of the SH polarization which dominates beyond the critical angle, and are likely to represent the polarization of the incident shear wave. Note that the
polarities of the horizontal instruments at PA and PB were confirmed by comparing polarities of regional and teleseismic arrivals at PA and PB with those at other stations. The anomalous polarizations at PA are discussed in Section 3.3.

2.4 TIME DELAYS BETWEEN THE SPLIT SHEAR-WAVES

The time delay between the split shear waves was also measured, where possible. In many shear wavetrains, the polarizations become increasingly elliptical after the first shear-wave arrival, and it is difficult to identify objectively the onset of the second shear-wave arrival either at the point where the ellipticity begin to increase, or where the polarization changes direction. Hence there are many fewer observations of time delays than polarization orientations, and the estimated errors in the time delay measurements are considerably greater. For similar reasons, the polarization direction of the second shear wave can seldom be estimated unambiguously as it is usually superimposed on the first shear-wave arrival.

The time delays observed at station TE in TDP1, where there was a good coverage of the shear-wave window, were converted to the equivalent delay over a 10 km hemisphere, centred at TE, and plotted in equal-area projection. The maximum observed time delay is 0.14 s, reduced to the 10 km radius. No clear distribution pattern can be identified in the plot of projected delays, and it is not shown here. Crampin & Booth (1985) suggest that the split shear-wave delays are likely to be a less stable observation than the polarization directions in the analysis of the crack geometry of a dilatant region. However, the maximum split shear-wave delay is a significant observation since it places limits on the possible crack density (Crampin 1978; Crampin & Booth 1985).

3 Interpretation

The polarizations of the initial shear-wave arrivals from small earthquakes recorded within the shear-wave window by the TDP stations are approximately parallel, except for the orientations at one locality in 1979. Three phenomena determine the shear-wave polarizations recorded on the free surface:

1. the polarizations near the receiver may be modified by interactions with the free surface; this may occur even within the shear-wave window if the topography is sufficiently irregular;
2. the polarizations radiated from the source are determined by the double-couple focal mechanisms of the earthquakes; and
3. the polarizations between the source and the receiver may be determined by the fixed polarizations imposed by possible anisotropy along the ray path.

We shall show that effects both near the receiver, and near the source, may be eliminated as the cause of the parallel polarizations, and conclude that anisotropy is the only tenable explanation.

3.1 THE EFFECTS OF TOPOGRAPHY

The surface topography of the area in which the stations are located is very irregular (Fig. 1b). Gradients of one in two over horizontal distances of 500 m are quite common, and one station (ME) is located close to a gorge 1.1 km wide and 500 m deep, trending NW–SE. The incident shear waves have a dominant frequency of about 10 Hz and a wavelength of approximately 0.3 km, thus the character of the topography within a wavelength of recording site may have a wide range of gradients and orientations.
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The effect of seismic wave scattering by an irregular topography has been investigated by Boore (1972), Boore, Harmsen & Harding (1981), and Ohtsuki & Harumi (1982), among others. Existing theoretical models of scattering by topographic irregularities do not yet permit prediction of scattering effects in complicated terrain, but it is generally agreed that such effects are largest when the incident wavelengths are comparable to the dimensions of the topographic features. In such cases, components of the incident shear-wave motion may be amplified, or attenuated, and result in re-alignment of the recorded shear-wave polarizations. Thus it might be expected that the shear-wave orientations would display considerable scatter at the free surface.

However, at six of the seven stations the average azimuth of alignment is within ±20° of N 100°E. The remarkable consistency of alignment of the polarizations at individual stations and over all stations (with the exception of PA) despite the very irregular topography in the area, suggests that topography has only a secondary effect on the average polarizations of the faster shear-wave arrivals, although the topography may well cause much of the scatter in the histograms of Fig. 2. The reason for the secondary effect of topography is that irregularities usually result in de-focusing of signals so that distorting anomalies will be small. Similarly chance focusing effects will occasionally increase the amplitude of the anomaly so that the SP phase may occasionally be the largest signal on the seismogram (Crampin 1985). Note that the SP phase is probably the only crustal phase that can be focused by the surface in this way. We have excluded the SP phase from our analysis whenever its characteristic waveform could be positively identified.

3.2 Polarization Alignments Produced by Focal Mechanisms

Earthquake source mechanisms radiate shear waves with polarizations which are fixed at the source by the geometry and orientation of the focal mechanisms. The alignments of these polarizations will be preserved at a receiver, if shear waves propagating through a homogeneous isotropic structure are recorded at the surface within the shear-wave window.

Evans et al. (1985) determined fault plane solutions for 23 of the larger earthquakes during the TDP2 experiment (see fig. 3 of Evans et al.). The events which are discussed within this section will be those examined by Evans et al. unless stated otherwise. A few localized groups of events appear to have similar fault-plane solutions, but there is a wide variety of orientations in the set of 23 solutions. The shear-wave displacement vectors in the horizontal plane are plotted in the equal-area projections in Fig. 3(a) for six representative solutions from the set of 23. Free-surface interactions are not allowed for in Fig. 3(a), and only arrivals within the shear-wave window model surface observations.

The histograms in Fig. 3(b) show that the polarizations have parallel alignments for significant portions of each shear-wave window. The alignments are approximately parallel for over 50 per cent of the shear-wave window for events 4, 10, 23, and are strongly bidirectional for events 6, 13 and 20. The preferred direction of alignment is clearly not the same for all earthquakes. The distribution of polarization directions in the shear-wave window for all 23 events shows a peak at approximately N 50°E (Fig. 4a). This direction is quite different from the range of N 80°E to N 125°E of the observed polarizations.

The mean preferential orientation of N 50°E from the shear-wave polarizations of the earthquake fault-plane solutions is approximately the mean orientation of the slip vectors of the individual mechanisms (Evans et al. 1985). This is to be expected as shear movement in the slip direction is the source of all the radiated energy of the mechanism and would be expected to be the dominant shear-wave polarization. This preferred direction in Fig. 4(a) would be accentuated if the histogram were weighted by the amplitude of the radiated shear-waves (see Fig. 3a). The preferred direction would also be accentuated if the histograms were constructed for the whole of
Figure 3. (a) Equal-area projections of the horizontal shear-wave polarization vectors of six focal mechanisms representative of the fault-plane solutions of Evans et al. (1985). The diagrams correspond to the projection on the lower focal sphere for each mechanism representing the polarizations as observed by seismometers at the surface from uniform distributions of the appropriate mechanism. The identification number of each diagram corresponds to the solution in fig. 3 of Evans et al. The solid circle on each diagram is the shear-wave window defined by an incidence angle of 40°. (b) Corresponding histograms of the distribution of polarizations for directions east of north within each shear-wave window. Polarity is neglected.

The events chosen by Evans et al. (1985) for mechanism determinations were selected from some of the larger events of the sequence with P-wave onsets over the greater part of the TDP2 network. Unfortunately, the first shear-wave arrivals of these larger events frequently saturated the records at sites in the shear-wave window immediately above the focus. Such waveforms were severely distorted and reliable estimates of the polarizations could not be obtained. There are six observations in the shear-wave window where polarizations can be identified: event 23 at station TE, event 19 at station SE, and events 2, 4, 10 and 13 at station PB. The polarization orientation deduced from the fault-plane solutions deviate from the corresponding observed orientations for these events by 30°, 65°, 80°, 90°, 90° and 40°, respectively. Since the maximum possible deviation between unpolarized directions is 90°, there is little correlation between the observed orientations of the shear-wave polarizations and those expected from the fault-plane solutions.

It seems reasonable to assume that the mechanisms of many of the smaller events are similar to those of the larger events whose mechanisms have been determined, particularly as many of the
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Figure 4. (a) The cumulative distribution of undirected shear-wave polarizations, measured east of north, for all polarizations within the shear-wave window on equal-area plots similar to those in Fig. 3(a), calculated from the 23 fault-plane solutions of Evans et al. (b–f) The distribution of observed undirected shear-wave polarizations at each of the TDP2 stations of Fig. 2 (solid plot, frequency values at the right), compared with the corresponding distribution generated by the 23 fault-plane solutions of Evans et al. (1985) (open plot, values at the left) at each station. The latter polarizations are those of shear waves radiated in the direction of each station, within the shear-wave window.

Events are swarms of doublets. Doublets, with seismograms which are nearly identical except perhaps for changes in amplitude, are common throughout the TDP sequences with sometimes 10 or more repetitions, presumably representing repeated adjustments at small asperities on facets of fault planes. With the assumption that the 23 fault-plane mechanisms of Evans et al. (1985) are representative, Fig. 4(b–f) compares the observed polarizations at each of the TDP2 stations with the polarizations from those segments of the shear-wave windows of the 23 mechanisms which radiate energy in the direction of the particular station. There is very little correspondence between the observed polarizations and the polarizations derived from focal mechanisms.

Since we can identify the fault plane of the 23 larger events (Evans et al. 1985), we can estimate the polarity of the shear waves radiated from the source within the shear-wave window (Fig. 3a). In principle it is possible to compare the observed directed polarizations of the first shear-wave arrival with those predicted from the fault-plane solution. However, although the amplitude of the shear-wave particle motion is usually large enough for the polarization direction to be reliably determined, the sense of the particle motion is frequently obscured by the P-wave coda. This is particularly true if the recording site lies near a node in the S-wave radiation pattern. Although the sense of the first shear-wave motion is a less reliable observation than the polarization direction, we have attempted to assign polarities to the polarizations observed at station TE, which has the largest number and the greatest azimuthal coverage of shear-wave arrivals within the shear-wave window. Vector polarizations have also been assigned to the six observations of shear-wave polarizations from events for which we have corresponding fault-plane solutions.

The vector polarizations from the fault-plane solutions within the shear-wave window correspond to the polarizations which would be observed at the surface of a homogeneous isotropic half-space. The deviation of these polarizations from the observed vector polarizations at the equivalent azimuth and incidence angle should be small if the assumption of isotropy is valid. When the shear waves pass through an anisotropic medium to the receiver, the polarization of shear waves will be determined by the fixed polarizations appropriate for the anisotropic...
Figure 5. (a) Equal-area plot of directed shear-wave polarizations observed in the shear-wave window at station TE in 1979 (this is a subset of the corresponding plot of undirected polarizations at TE in Fig. 2). (b) The distribution of observed shear-wave polarization-vector directions at TE (solid plot, values at right), compared with the corresponding distribution generated by the fault-plane solutions of Evans et al. (1985) within the shear-wave window, radiated in the direction of TE (open plot, values at the left). (c) Cumulative distribution of shear-wave polarization-vector directions from within the shear-wave window of all the fault-plane solutions, equivalent to the corresponding histogram of undirected polarizations in Fig. 4(a).

symmetry along the ray path, subject to excitation by the polarization of the incident wave. Although two vectors may deviate by up to 180°, the deviation of the observed vector polarizations from those fixed by the anisotropic symmetry should not exceed 90°, as the polarity of the initial shear waves from the source will excite corresponding polarities in the fixed polarizations of the anisotropy. For the six observations of shear-wave polarizations for which corresponding fault-plane solutions exist, the deviations between the vector polarizations are 30° at TE, 65° at SE, and 80°, 90°, 90° and 140°, at PB. Only one deviation exceeds 90°. These are consistent with the hypothesis of anisotropy, although it is difficult to draw conclusions from so few observations.

An equal-area plot of directed shear-wave polarizations observed within the shear-wave window at station TE is shown in Fig. 5(a). The corresponding histogram is displayed in Fig. 5(b). Note that the possible distribution of vector directions extends over a range from −180° to +180°, and distributions in Fig. 5 are not repeated over the extended range. The preferred alignment of the polarization vectors is predominantly west of north for observations from events north of TE, and east of north for events south of TE, giving the bimodal distribution of vector directions in Fig. 5(b). The distribution of alignments directed west of north is slightly distorted by alignments due to an earthquake swarm N2WW on the edge of the shear-wave window. These give rise to a subsidiary maximum in the distribution at N140°W which is probably not significant.

We compare the observed distribution of vector polarizations with the distributions which are expected from the fault-plane solutions of Evans et al. (1985) using a treatment which is similar to that used on the undirected polarizations earlier in this section. The cumulative distribution of vector polarizations in the shear-wave window for all 23 fault-plane solutions as shown in Fig. 5(c). This distribution shows a broad peak at approximately N130°W (diametrically opposite to the mean direction of the slip vectors). This direction is significantly different from that of the peak in the distribution of westward-oriented observed alignments at N90°W in Fig. 5(b). In Fig. 5(b) we also compare the distribution of observed vector polarizations at TE with the vector polarizations from those segments of the shear-wave windows of the 23 mechanisms which radiate energy in the
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direction of TE. Again, the peak in the distribution of alignments due to the fault-plane solutions differs significantly from the peak in the distribution of westward-oriented observed alignments.

All events for which fault-plane solutions have been determined by Evans et al. (1985) are located north of TE, and the polarization alignments which are generated by these mechanisms at TE have been shown to be predominantly westward in the shear-wave window (see Fig. 5b, c, and the polarization plots in Fig. 3a). The observed polarizations from events north of TE do show a predominantly westward alignment, although we have noted that there is a significant deviation between the observed and predicted distributions which may be explained by the presence of dilatancy-anisotropy (Crampin & Booth 1985).

The eastward polarizations of shear waves from events to the south-west of TE in Fig. 5(a) suggest that the focal mechanisms of these events are different from the majority of the focal mechanisms which have been deduced for events north of TE, which give predominantly westward polarizations within the shear-wave window (Fig. 5c). However, some of the individual mechanisms of Evans et al. (1985) do give eastward polarizations in the south-west quadrant of the shear-wave window, for example, solutions 6 and 20 in Fig. 3(a). Thus it is not necessary to invoke new fault-plane solutions to explain the eastward sense of observed polarization vectors. We conclude that the observed polarization vectors appear to correspond with the sense (polarity) of the shear-wave polarizations produced by the focal mechanisms of Evans et al., but not their exact orientations.

These mechanisms are likely to have uncertainties due to the poor control over focal depth and the small number of P-wave polarities on which the mechanisms are based. Nevertheless, the mechanisms appear to be relatively reliable as the slip vectors (Evans et al. 1985) and the common tensional stress directions are consistent with other evidence (Crampin & Booth 1985), which lends support to the arguments in this section that the observed polarizations do not directly correspond to the polarizations at the source. The variations in the equal-area plots in Fig. 3 show that the amplitude and orientation of the shear-wave polarizations radiated from a double-couple source are very sensitive to the orientation of the focal mechanism. Thus the strongest argument that the observed polarizations are due to some overall structural feature such as anisotropy of the medium is the relative uniformity of the observed alignment of polarizations within the shear-wave windows at each station and the overall consistency of the alignments at six of the seven stations.

3.3 POLARIZATION ALIGNMENTS AT PA

The orientations of the shear-wave polarizations observed at PA in 1979 (Fig. 2) are over 60° away from the general trend of alignments at the four other recording sites in 1979 and the five sites in 1980 including PB only 1.2 km away from the PA site. We have argued above that the overall consistency of the orientations in very rough topography (Fig. 1a) suggests that scattering at topographic irregularities is not one of the primary causes of the polarization alignments. Thus it is unlikely, although not impossible, that the inconsistent orientations at PA are due to its particular local topography. Similarly it is difficult, although not impossible, to propose source behaviour which could cause anomalous characteristics at just one site.

If, as has been suggested in previous sections, the polarization alignments are the result of the structure (anisotropy) along the ray path, the change in polarization between PA in 1979 and PB in 1980 could be caused by a change in the local effective anisotropy. Fig. 1(a) shows epicentres of the six largest earthquakes in the area of the map between 1979 January and 1980 December. These earthquakes are small, relative to the station density of the Kandilli network used to locate them, and the accuracy of location is probably about 10 km. Fig. 1(a) shows that one of these earthquakes (no. 4) occurred in the interval between the TDP1 and TDP2 experiments very near
to PA and PB. Thus there is some indication, albeit very weak, that the difference in polarizations at PA and PB may be due to strain released by a nearby earthquake. Confirmation that the temporal characteristics of shear-wave splitting can be associated with earthquake strain release is crucial to the hypothesis of extensive-dilatancy anisotropy underlying the TDP experiments (Crampin 1978; Crampin et al. 1984, 1985). However, positive confirmation must await the capture of a larger event by a closely-spaced network of three-component instruments.

4 Shear-wave polarizations in a Hot-Dry-Rock Geothermal Heat experiment

Analysis of microevents generated during and after hydrofracture operations at the Camborne School of Mines Hot-Dry-Rock Geothermal Heat project in Cornwall is beginning to yield similar observations to those from the TDP experiments. Shear-wave splitting is observed on most of the seismograms recorded within the shear-wave window from acoustic emissions at about 2.0 km depth in a homogeneous granite batholith. The polarizations of the faster split shear waves are aligned parallel to the principal axis of compressive stress, as in the TDP recordings. The shear-wave onset is always impulsive with most of the energy in the first cycle and there is little scatter of the energy. This suggests that the seismic wavelengths are, in general, greater than any inclusions within the granite, apart from the major hydrofractures. Since the granite mass is pervaded by micro- and macro-cracks but is mineralogically and structurally homogeneous, it is likely that, as in the TDP experiments, the shear-wave splitting and polarization alignments are the result of the interaction of the source radiation with the effective anisotropy of the distributions of aligned cracks.

5 Conclusions

Shear-wave arrivals recorded in the shear-wave window above the TDP earthquake swarm show abrupt changes of the particle-motion polarizations typical of synthetic shear waves propagating through anisotropic models. Shear wavetrains from small earthquakes have complicated behaviour which is, at present, poorly understood. Thus, we cannot rule out a priori the possibility that the splitting-type behaviour is caused by interaction with a (very irregular) surface topography, or by a combination of source radiation patterns. However, we suggest that both these hypotheses must be rejected. The consistency of the parallel alignment of the polarizations both at individual stations and across the network shows that interaction with the very irregular surface topography is unlikely to be the primary cause of the shear-wave alignments. Similarly, the orientation of the polarizations shows no correlation with the shear-wave polarizations expected from a wide range of events with fault-plane mechanisms subject to an overall stress field and nearly common directions of slip.

The only way that a variety of initial shear-wave polarizations can produce consistent patterns of variation with direction at a number of recording sites is if the propagating medium has some relatively homogeneous internal structure. For elastic-wave propagation such a medium would be elastically anisotropic. The crack-induced anisotropy suggested by Crampin & Booth (1985) would provide an explanation for the shear-wave splitting, the overall alignment of the polarizations, and the temporal variation of alignments which may have occurred near the recording site PA.

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Observations of anisotropy-induced shear-wave splitting

References


