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MEASUREMENT AND CONFIRMATION OF TECTONIC STRESS DIRECTIONS USING THREE-COMPONENT SEISMIC DATA

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(6 figures)

ABSTRACT. – Analysis of all suitable recordings of three-component seismic data, from both earthquake and man-made sources, reveals that the shear-waves display characteristic shear-wave splitting with preferential directions of polarization. Modelling experiments indicate that this behaviour is caused by shear-waves propagating through distributions of stress-aligned, parallel, vertical, liquid-filled inclusions. Such distributions of inclusions, which can have many shapes, are known to permeate, and shear-waves indicate that they are aligned, throughout at least the upper 10 to 20 km of the Earth's crust in a variety of tectonic environments. Various parameters of these inclusions can be estimated by analysing shear-waves, such as the crack density, and, most important, their orientation which is parallel to the direction of maximum horizontal compressive stress causing the orientation. Such research has important implications in hydrocarbon and geothermal reservoir monitoring, earthquake prediction, mining, and in many other geological fields in which a knowledge of the cracks and stress is important. The results of such monitoring will be demonstrated. It is suggested that our knowledge of stress directions in NW Europe could be considerably improved by analysis of more three-component seismic data.

1. INTRODUCTION

Almost all digital three-component records of shear-waves propagating through the uppermost 10 to 20 km of the Earth's crust, and generated by both earthquakes and man-made sources, display shear-wave splitting (shear-wave birefringence). This implies that the Earth's crust is anisotropic to shear-waves (Crampin 1987a).

Three important features indicate the cause of the splitting:

1) Shear-wave splitting has been observed worldwide in waves which have propagated through a wide variety of sedimentary, igneous, and metamorphic rocks in a range of tectonic settings;

2) The direction of polarization of the leading (faster) split shear-wave is parallel or subparallel to the direction of the current local maximum horizontal compressional stress;

3) Temporal changes in the delays between the split shear-waves have been observed before and after earthquakes (Peacock *et al.* 1988; Crampin *et al.* 1988; Booth *et al.* (1990), and before and after hydraulic fracturing (Crampin & Booth, 1989).

We know that most crustal rocks are permeated by distributions of fluid-filled cracks and pores. Such fluid-filled cavities tend to be aligned perpendicular to the direction of minimum compressional stress (or parallel to the direction of maximum compression) by processes such as subcritical crack growth (Atkinson 1984), similar to the orientations of industrial hydraulic fractures. These distributions of preferentially aligned, fluid-filled pores and cracks are the only sources of anisotropy which can satisfy the three criteria above, and are known as extensive-dilatancy anisotropy or EDA (Crampin *et al.* 1984; Crampin 1985). The cavities themselves are known as EDA-cracks, because, although they may exhibit a wide variety of geometries, ranging from flat, joint-like cracks to spheroids showing a small degree of preferential flattening, many of the effects can be simulated by distributions of flat parallel cracks.

Geophysical analysis of seismic waves generated by earthquakes and various man-made techniques

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has relied traditionally on the relatively small amount of information (chiefly the arrival-time) carried by the P-wave train. The use of such P-wave analysis has led to the success of exploration seismology, and the ability to locate earthquakes accurately in space. P-waves, however, are insensitive to the internal structure of the rocks through which they propagate.

Recent technological advances in hardware and software permit digital three-component recording at high sampling rates with appropriate display facilities. Typically, shear-waves have at least three times the information content of the equivalent P-waves (Crampin 1985), and this information content is fundamentally different from that contained in the P-wave train.

Shear-waves vibrate in a plane approximately at right angles to their direction of propagation, and are very sensitive to the three-dimensional internal structure of the medium along the raypath. This property enables us to look at the fundamental three-dimensional structure within the rockmass, and any change in dimensions or orientation of the EDA-cracks can be monitored by analysing the split shear-waves. There are many potential applications of this research, including the determination of the internal structure and preferred flow directions in hydrocarbon and geothermal reservoirs and radioactive waste repositories, and, possibly, earthquake prediction (Crampin 1987a, 1987b).

The information relating to the three-dimensional properties of the rocks through which the shear-waves have propagated is available when the data are processed correctly, and this analysis will be described below. BGS has developed a large amount of expertise in the detailed analysis and interpretation of three-component seismic data of all types as a result of processing the large amount of earthquake data recorded in Turkey during the Turkish Dilatancy Projects (Crampin *et al.* 1985; Evans *et al.* 1987), and elsewhere.

This paper describes the analysis of the shear-wave seismograms, and illustrates how current tectonic stress directions may be estimated. The relevance of such work to stress patterns over northern Europe is discussed.

2. SHEAR-WAVE ANALYSIS

Shear-wave splitting

Typically two distinct phases with different arrival times and different directions of polarization are shown on three-component records of shear-waves which have propagated through the crust. This phenomenon is called shear-wave splitting or shear-wave birefringence, and can be modelled by shear-waves propagating through a homogeneous and elastic anisotropic solid which has the same directional variation of seismic velocities as the in situ rock (Crampin 1984).

Modelling indicates that the behaviour of these observed shear-waves can be explained if they propagate through rocks containing distributions of fluid-filled cracks and microcracks which are constrained by the current tectonic stress into vertical alignments, perpendicular to the minimum compressional stress. These are the distributions of EDA-cracks.

Figure 1 shows schematically the behaviour of a shear-wave propagating through a rock containing EDA-cracks. When a shear-wave, generated either by a natural or man-made source, enters such a cracked region, it splits into, typically, two components, each with a different velocity and direction of polarization (shear-wave splitting). The polarization and velocity differences between the split waves introduce a characteristic signature into the three-dimensional particle-motion of the wavetrain as the components separate with increasing time. Additionally, the polarization direction of the faster, or leading, split shear-wave is parallel to the direction of maximum horizontal compression, as shown in Figure 1.

Physically this is because the leading split shear-wave is vibrating in the plane of the aligned cracks, so experiences less resistance to its passage than the slower ray, which vibrates in a direction normal to the plane of the cracks.

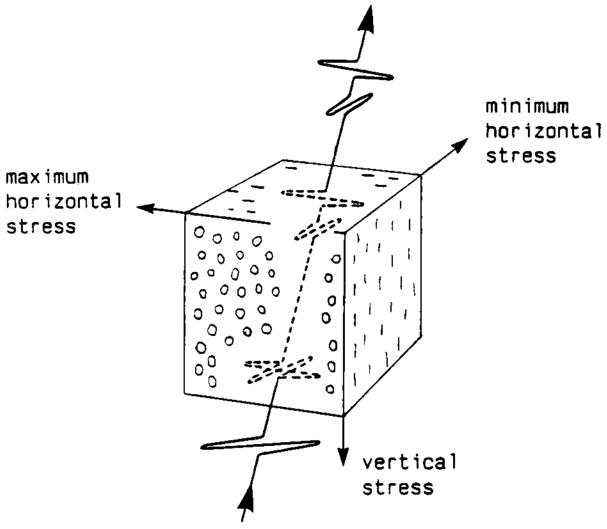


Figure 1. Schematic illustration showing the behaviour of a shear-wave passing through a region containing vertical, liquid-filled cracks aligned parallel to the maximum compressive stress.

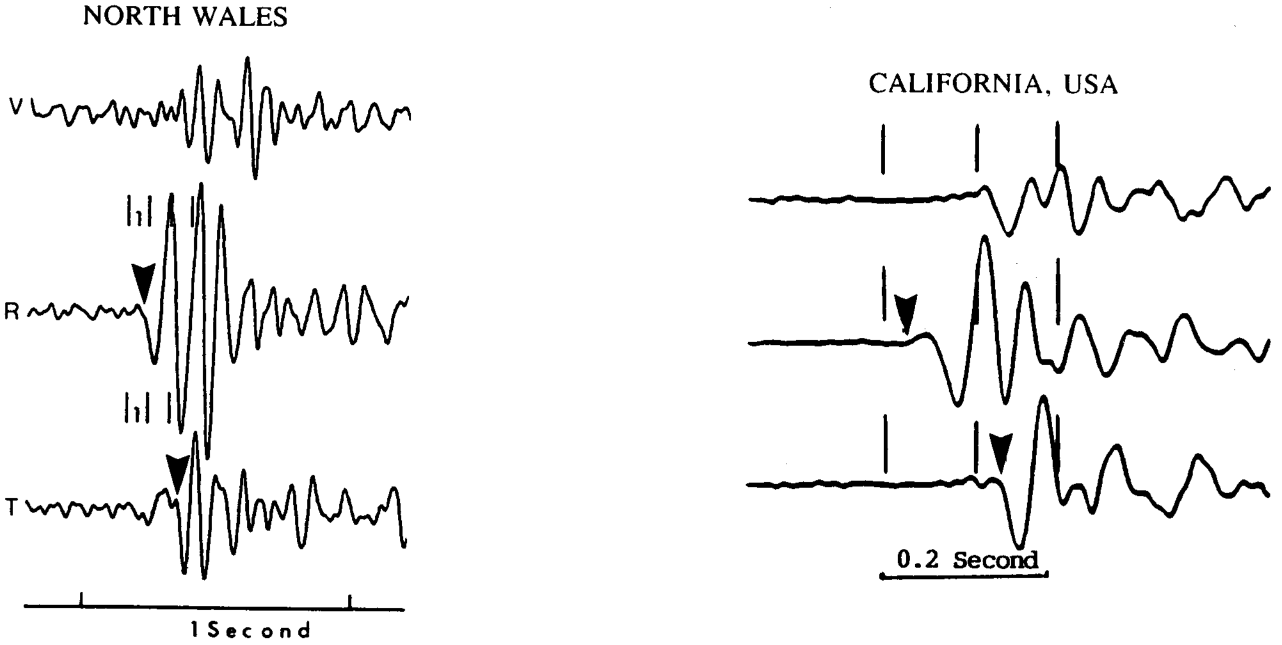


Figure 2. Examples of three-component seismograms showing shear-wave splitting. In both cases a clear time delay can be seen between the first and second split shear-wave arrivals (arrowed).

Shear-wave splitting can sometimes be observed directly in seismograms, some examples of which are shown in Figure 2 where the splitting is seen as different arrival times of shear-waves on the horizontal components. This only occurs when the polarizations of the shear-waves are parallel to the axes of the recording instruments. In general, the most useful technique is to identify the split shear-waves in polarization diagrams.

Before we describe polarization diagrams, however, we must mention a restriction in surface observations. Shear-waves at the surface must be recorded within the shear-wave window.

The shear-wave window

When the recording station is on the surface, as is normally the case in earthquake observations, the concept of the shear-wave window (Evans 1984) is an important consideration in shear-wave analysis. During analysis of Turkish data (Crampin & Booth 1985; Booth *et al.* 1985) it became apparent that some shear-wave arrivals were severely modified by contact with the free surface, so much so that apparent polarization readings are unreliable or misleading. This phenomenon was investigated and it was realised that the shear-wave perturbation occurred when shear-waves were incident at the surface at high angles. The critical angle of incidence below which shear-wave arrivals are unaffected is sin^{-1} (VS/VP), where VS and VP are the velocities of shear- and P-waves respectively. This angle is about 35° assuming a Poisson's Ratio of 0.25.

Thus shear-waves must always be observed at the surface within the shear-wave window (Figure 3) - the roughly circular area of ground above the shear-wave source within which incidence angles are less than the critical angle. However, topographic irregularities may distort the window substantially, especially in areas of high relief. Such anomalies were observed at two

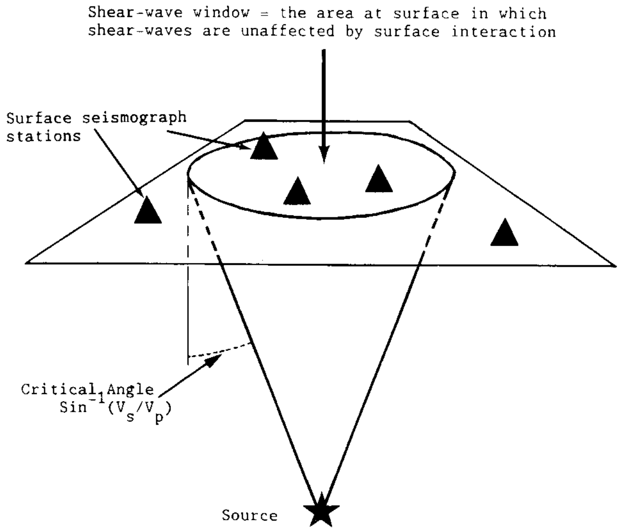


Figure 3. Diagrammatic representation of the shear-wave window concept above a source. Shear-waves incident on this area are not affected by surface interaction. Polarization directions measured within this area are reliable.

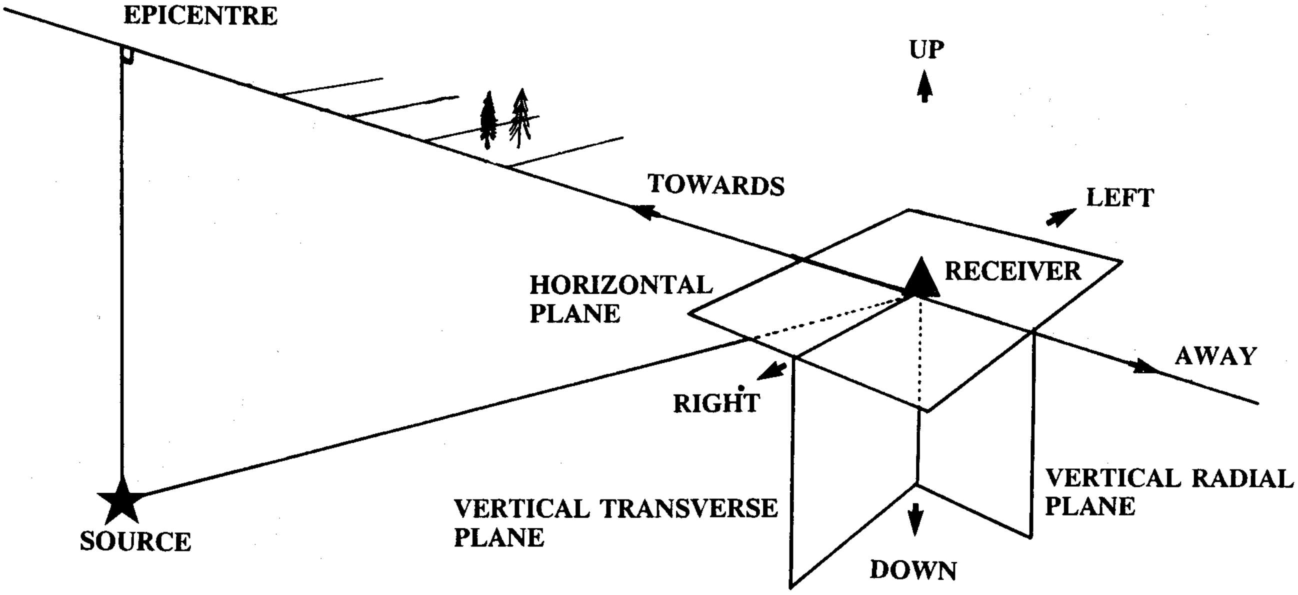


Figure 4. Schematic diagram showing a typical receiving station, the orientations of the cross-sections taken of the rays, and sign conventions used in the derivation of polarization diagrams.

seismograph stations in the TDP projects (Crampin & Booth 1985; Booth *et al.* 1985). The stations were only a kilometre or two apart, yet the polarization directions of the leading split shear-waves were about 60° different. At first, this was attributed to perturbation of the local stress field by a large local earthquake which occurred in the interval between the recording periods. It is now recognised that this was the effect of local topography on the shear-waves (Chen *et al.* 1987). In practice, the angle subtended by the boundary of the shear-wave window with the vertical at the source is generally slightly greater than 35° owing to refraction of upward-going rays by lower velocity layers near the surface. The curvature of the wave front from a small, relatively shallow earthquake also increases this critical angle.

Polarization diagrams

Subject to the restrictions of recording within the shear-wave window above the earthquake, the shear-wave splitting can be most easily identified in polarization diagrams. Polarization diagrams are three, mutually orthogonal cross-sections of the particle motions of the seismograms plotted for successive small time-intervals along the seismograms (Crampin 1978). The geometry of these orthogonal planes, the vertical-radial, vertical-transverse and the horizontal, are illustrated schematically in Figure 4. The horizontal components of the seismograms are first rotated into directions radial and transverse to the epicentre-receiver line (Figure 4), and then particle displacements in these sections are plotted for small time intervals which include one or two cycles of the wave motion.

The two vertical sections (Figure 4) are only used to ensure that the arrival is a true shear-wave and not merely a converted phase. The horizontal section (Towards-Away-Left-Right, Figure 4) contains most of the shear-wave energy for shear-waves propagating nearly vertically, and polarization direction measurements are usually made from this section. The direction of polarization of the leading, or faster, split shear-wave in the horizontal section is generally approximately parallel to the direction of the maximum compressional component of the local stress-field.

The ability to monitor the three-dimensional internal structure of *in situ* rock masses using shear-wave analysis techniques has important implications in many geological fields. The applications range from the estimation of the internal structure of hydrocarbon and geothermal reservoirs (Crampin 1987a) to earthquake prediction research (Crampin 1987b), and the measurement and confirmation of directions of tectonic stress.

3. MEASUREMENT OF POLARIZATION DIRECTIONS FROM POLARIZATION DIAGRAMS

It is presupposed that the locations of the shear-wave source and receiver in three-dimensional space are known. This will generally be true for the artificial sources used in seismic exploration techniques, such as VSPs, but not necessarily so for earthquake sources, when great care should be taken to ensure

3 JUNE 1984, 10:04:08, DEPTH 7.7 KM, EPICENTRAL DISTANCE 3.6 KM AZIMUTH (EPI TO STN) 108 DEG, STATION SE.

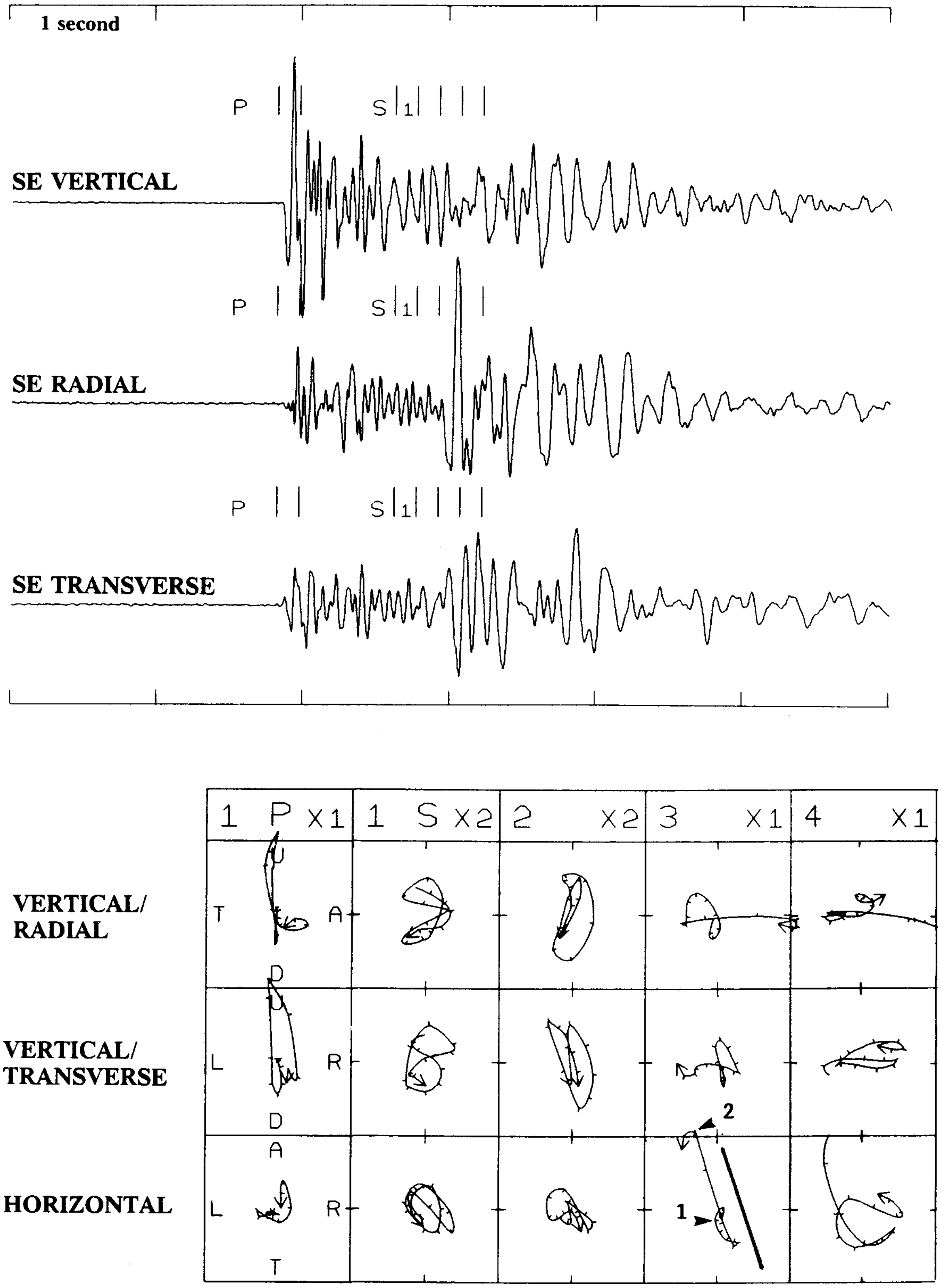


Figure 5. Three-component seismogram (above), and polarization diagrams (below) for an earthquake in Turkey recorded at station SE (Figure 6a). The time-windows for the P- and shear-waves are marked above the seismograms. The polarization diagrams for each time-window are plotted at x1 or x2 gain for the three orthogonal sections of Figure 4. The onsets of the two split shear-waves are arrowed, and the polarization direction of the leading split shear-wave is shown as a bar on the horizontal section in time window S3.

that the earthquake location is calculated as accurately as possible.

Figure 5 shows a three-component seismogram and corresponding polarization diagrams from a small earthquake in Turkey. This figure will be used as an example of the measurement of the direction of maximum compressional stress.

The two horizontal components of the seismogram in Figure 5 have been rotated mathematically into components radial and transverse to the epicentre-receiver line (see Figure 4). Splitting can be clearly seen between the shear-wave arrivals on the radial and transverse components, and it can be seen that the first split shear-wave arrives as a towards-away movement on the radial component in time-window 3 at about 0.06 second before the second arrival on the transverse component.

The onset of the leading split shear-wave can be identified from the horizontal section of polarization diagrams by, ideally, an abrupt and well-defined linear movement in the time window corresponding to the shear-wave onset on the seismogram. Here the two arrivals are arrowed in Figure 5, and the arrival direction of the leading split shear-wave is indicated on the horizontal polarization diagram in Figure 5 by a bold bar in time-window 3. This represents the polarization direction of the leading split shear-wave with respect to the epicentre-receiver line. This direction of motion makes an angle of about -20° with the Towards-Away direction. This horizontal section is oriented with respect to the observer-source line, so it is a simple matter to take the polarization angle with respect to this line, and then, knowing the azimuth of this line from the earthquake location program, to rotate the polarization angle into geographical coordinates (N, S, E, W). In this case, the polarization angle, -20°, is added to the azimuth of the epicentre-receiver line given by the earthquake location program as 108° (Figure 5), making an angle of N88°E. This angle then represents the direction of maximum compressive stress for that particular area of Turkey. This is very close to the orientation of the maximum compressive stress of N100°E derived by shear-wave analysis (Booth *et al.* 1985; Chen *et al.* 1987) and confirmed by earthquake fault-plane solutions (Evans *et al.*, 1985; Lovell *et al.*, 1987) during three separate earthquake monitoring experiments in that area.

This measurement process is repeated at all stations in the network where shear-waves are recorded clearly. If the recording stations are within the shear-wave window (see above), then a plot of their polarization directions should show the parallel alignments found in many areas of the world and described in the following section. In practice, readings will show some scatter, owing to the difficulty of measuring the exact polarization angle in poorly defined cases. In some cases, the polarization angle is impossible to measure as the arrival may be obscured by noise and the P-wave coda, so that the shear-wave arrival is elliptical.

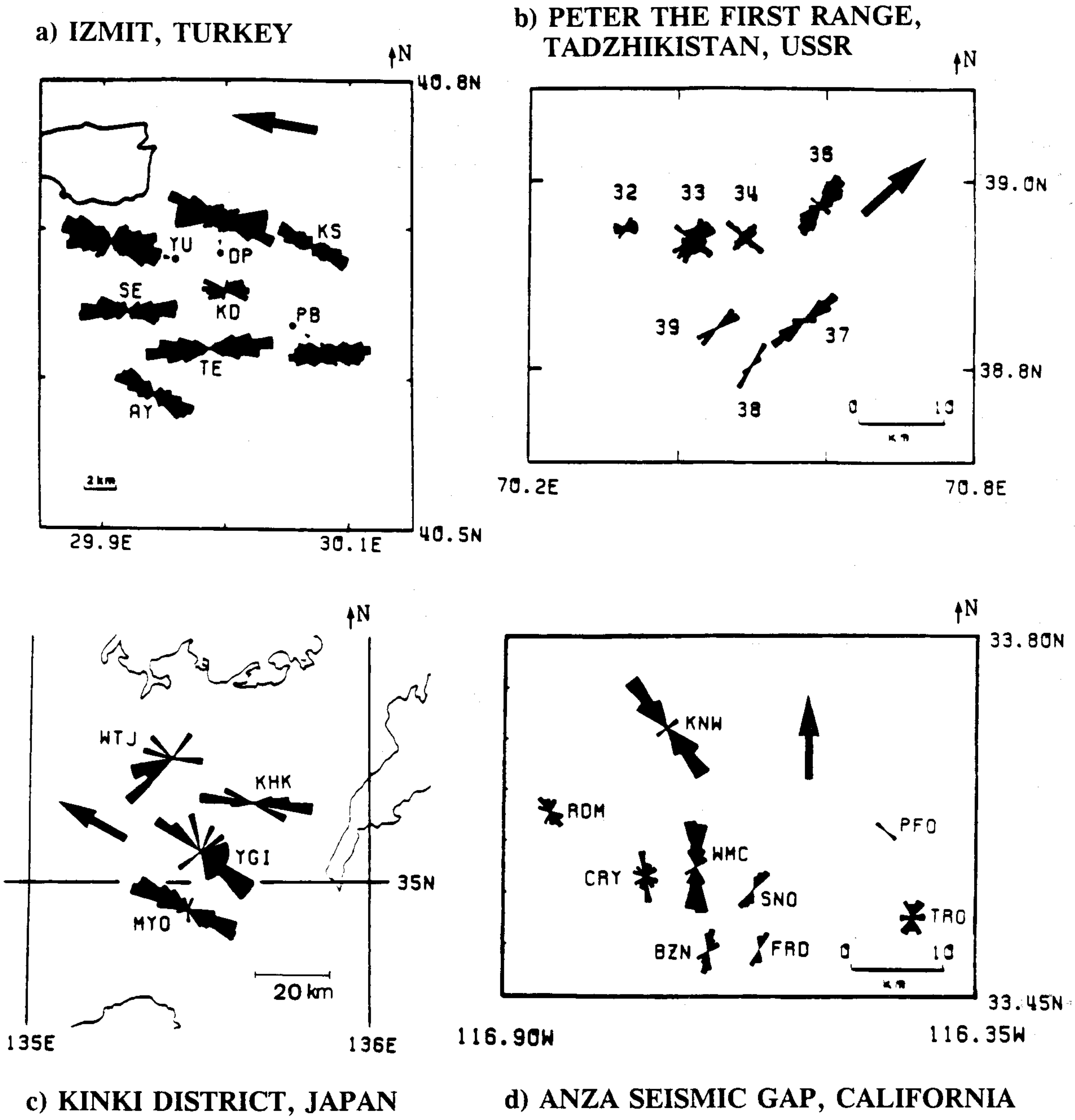
4. OBSERVATIONS OF SHEAR-WAVE SPLITTING

The first observations of shear-waves exhibiting splitting and distinctively aligned polarizations were seen during the three Turkish Dilatancy Projects (Crampin *et al.* 1980, 1985; Booth *et al.* 1985). Here, very close agreement was obtained between tectonic stress directions derived from shear-wave analysis and independently from earthquake fault-plane solutions (Evans *et al.* 1985; Lovell *et al.* 1987).

Figure 6 shows rose diagrams of the distinctive alignments of the leading split shear-waves above earthquakes in four areas of the world. In each case, it is clear that there is close agreement between these mean polarizations and the directions of maximum compressive stress (indicated by heavy arrows) which have been independently derived. Data from Turkey (Figure 6a) include the example from the previous section, and it can be seen that the stress orientation of N88°E is consistent with the remainder of that data set.

Shear-wave splitting has now been reported from many different parts of the world. A full review of the observations will be found in Lovell *et al.* (1990), but, briefly, it has been reported from sedimentary, igneous and metamorphic rocks in tectonic environments ranging from areas of active deformation and high seismicity (such as Japan, California, the Alpine-Himalayan mountain chain), to the oceanic crust and intraplate regions such as the UK and central USA, wherever small arrays of three-component seismometers have been installed for monitoring purposes. In addition, numerous VSPs and shear-wave reflection studies, primarily by the oil industry, have shown that shear-wave splitting occurs in sedimentary basins.

It seems clear from these observations of shear-wave splitting, caused by stress-aligned EDA-cracks in the Earth's crust, that at least the upper 10 to 20 km of the crust are pervaded by stress-aligned fluid-filled cracks.



a) IZMIT, TURKEY

b) PETER THE FIRST RANGE, TADZHIKISTAN, USSR

c) KINKI DISTRICT, JAPAN

d) ANZA SEISMIC GAP, CALIFORNIA

Figure 6. Rose diagrams showing the polarization directions of the leading split shear-waves recorded above small earthquakes: (a) near the North Anatolian Fault in Turkey; (b) in the Peter the First Range, Tadzhikistan, USSR; (c) in the Kinki District of Japan; and (d) in the Anza seismic gap, California. The heavy arrows show the directions of regional compression. (After Crampin 1987b).

5. TECTONIC STRESS ORIENTATIONS OVER NORTHWEST EUROPE

In general terms, the direction of maximum compressive stress over most of the UK, northwest Europe, the North Sea and Fennoscandia is approximately horizontal and oriented between NW-SE and NNW-SSE. This is consistent with the plate tectonic forces currently operating in a southeasterly direction from the North Atlantic spreading centre to the northwest, and the generally northward push of Africa from the south. These stress directions have been confirmed or measured in many areas, using a variety of methods (reviewed by Evans (1987)), and show great consistency from just north of the Alps to northwest Scotland. For example, an overlay of the nodal planes from fault-plane solutions of earthquakes occurring as far apart as the western seaboard of Britain, the northern North Sea, and Liège in Belgium shows a common horizontal compressional stress direction of NNW-SSE (Marrow & Turbitt 1989; Marrow & Walker 1988). Additionally, these earthquakes have sampled a wide range of crustal depths. Over most of the southern half of the UK mainland, Evans (1987) describes measurements of stress directions using the borehole breakout method, and suggests that the directions found are consistent over the UK mainland. In France, stress measurements (Froidevaux *et al.* 1980) give a regionally consistent NNW-SSE horizontal compression direction. In central Europe, work by Ahorner (1975) also suggests a NNW-SSE stress orientation, while in the North Sea, earthquake fault-plane solutions derived by Hansen *et al.* (1989) give compressive stress in approximately the same direction.

This necessarily brief and incomplete review illustrates the consistency of the maximum compressive stress direction over most of northwest Europe. Local and regional variations do occur, however, and have been delineated because of the availability of a sufficiently closely spaced data set. For example, Evans (1987) suggests variations in the Isle of Wight and elsewhere in the UK, and Clauss *et al.* (1989) describe variations in the North Sea, and in Fennoscandia where E-W compression directions have been attributed to fault-bounded cold blocks in the crust. Such data sets are generally to be found in areas of active exploration, where borehole and geophysical exploration techniques have been much used, for example, in the North Sea and southern Britain, or in areas, for example Fennoscandia, where sufficiently well-located earthquakes give good fault-plane solutions. We suspect that many more local anomalies remain to be discovered, and await a more homogeneous distribution of stress measurements.

6. DISCUSSION

We have seen that shear-wave analysis has provided us with a powerful tool with which to monitor small changes in the detailed crack structure of rocks caused by stress, and the many applications in the geological field have been reviewed by Crampin (1987a, 1987b). In particular, it has been demonstrated here that shear-wave analysis can be used to derive current tectonic stress directions. This is true not only for the more seismically active and well explored areas of the world but also for more quiescent areas of northwest Europe. For example, recent modelling of a multi-offset shear-wave VSP in the Paris Basin (Bush & Crampin 1989) has confirmed the stress direction measured by Froidevaux *et al.* (1980); analysis of shear-waves from the aftershocks of the 1984 Lleyn Peninsula earthquake (Peacock, 1985) yields a stress direction very close to that measured locally (Douglas *et al.* 1987), and this has been confirmed by fault-plane solutions (Marrow & Walker 1988); and the stress direction derived from seismic monitoring of the Hot-Dry-Rock geothermal project in the Cornubian Batholith, Cornwall (Roberts & Crampin, 1986) shows close agreement with that measured in a local mine (Batchelor & Pine 1986).

These examples illustrate the use of shear-wave analysis techniques in the European area, and have confirmed the overall compressive stress orientation of NW-SE. However, various anomalies have been noted in other studies, for example, by Whittaker *et al.* (1989). These are thought to be due to deep-seated faults and other structures, and a greater knowledge of the stress pattern is needed before they can be satisfactorily resolved.

It has been shown that the shear-wave analysis method can be applied to earthquake and commercial seismic data. We therefore have the ability to sample not only most of the crustal thickness in areas where three-component instruments exist, but also to model commercial data, which are now widespread. In addition, the recent extension of the UK seismograph network into eastern, and its future extension into southeastern England, will enable us to use as a data set the previously poorly-located earthquakes in the North Sea area, which will fill in many gaps in the stress pattern around the Brabant Massif, and, hopefully, allow some correlation of seismicity with deep-seated structures. Recently, the improved instrumental coverage of the UK and data-exchange between BGS and continental earthquake monitoring agencies has allowed the relocation of earthquakes in the Channel area, and the derivation of many fault-plane solutions which confirm the stress patterns already established (Ritchie & Walker 1989).

7. CONCLUSIONS

The inhomogeneous distribution of stress measurements over northern Europe has led to an incomplete picture of the overall stress pattern. This illustrates the need for a measurement method which can be independently applied to areas of interest. We believe that such a method has been demonstrated in this paper, and suggest that its potential has been proved by the examples cited. In addition, the potential exists for sampling almost the complete crustal thickness using both earthquake and commercial seismic data, thus giving a much more homogeneous spread of data points, and an improved idea of the complex regional distribution of stress directions.

In the near future, given the financial support of those having responsibilities in the region, the British Geological Survey will be installing a seismograph network in the southeast corner of Britain. This, together with the data-exchange already taking place between BGS and various European research bodies under CEC and other agreements, should give added impetus and encouragement to further research in this area, and help to elucidate the complicated stress patterns which are at present poorly known.

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