The Turkish Dilatancy Project (TDP3): multidisciplinary studies of a potential earthquake source region

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Summary. The section of the North Anatolian Fault lying near the city of Izmit, at the east of the Marmara Sea, has been identified as a seismic gap and the possible site of a future major earthquake. Previously published studies of records from an earthquake swarm within the gap (TDP1 and TDP2) provided the first evidence that shear-wave splitting occurs in earthquake source regions, a conclusion since verified by many studies at other locations. A third field study (TDP3) was mounted in the Izmit region during the summer of 1984. Observations were made over an eight-month period and included geomagnetic and geoelectric measurements in addition to a series of observations utilising dense arrays of three-component seismometers. Earthquake activity in the principal study area was monitored over a period of eight months. Records showed features similar to those observed in the earlier studies. In particular:

(1) almost all shear waves emerging within the shear-wave window displayed shear-wave splitting; and

(2) the polarizations of the first arriving (faster) split shear-waves showed sub-parallel alignments, characteristic of propagation through a distribution of parallel vertical cracks striking perpendicular to the minimum compressional stress.

These and other observations support the conclusion of earlier studies - that the upper crust is pervaded by distributions of micro-cracks aligned by stress, known as *extensive-dilatancy anisotropy*. A search for time dependence in shear-wave phenomena has revealed temporal variations in the delays between the split shear-waves throughout the course of the TDP3 study, but as yet this has not been correlated with specific earthquake activity.

1 Introduction

The potential of shear-wave analysis as a tool of value in earthquake prediction studies was initially recognized by Crampin (1978), who suggested monitoring shear-wave propagation through a potential earthquake source region as a method for identification and examination of the crack systems developed during rock dilatancy. With this objective in view, the initial phases of the Turkish Dilatancy Project (TDP1 in 1979 and TDP2 in 1980) were set up by the British Geological Survey, in collaboration with Kandilli Observatory, Istanbul. It had been noted from the earthquake catalogues for Western Turkey, generated by Kandilli Observatory using the MARNET telemetered network (Üçer *et al.* 1985), that there was a long-lived swarm of small earthquakes near the city of Izmit, on the eastern arm of the Marmara Sea (see location map, Fig. 1). This swarm lies near the centre of the seismic gap identified by Toksöz et *al.* (1979) between the sites of the 1967 (Mudurnu) and 1963 (Çinarcík) earthquakes, and may become the site of a future large earthquake. Small earthquakes, generated by the relief of shear stress across a facet of a fault at depth, provide an excellent source of shear-waves with which to examine shear-wave propagation effects. The field studies in 1979 and 1980 deployed closely-spaced networks of three-component seismometer systems immediately above these small events in order to record the radiated waveforms modified by propagation along direct raypaths through stressed rocks in the vicinity of the fault. Detailed analysis of these waveforms led to investigations into various aspects of shear-wave propagation through cracked and anisotropic materials and into the interactions between shear-waves propagating from depth and the Earth's free surface.

The results of these studies may be summarized as follows:

(1) The polarizations of almost all shear waves emerging within the *shear-wave window* (Nuttli 1961; Evans 1984; Booth & Crampin 1985) showed evidence of *shear-wave splitting* - abrupt changes in direction of polarization, diagnostic of the presence of some form of anisotropy along the wave path (Crampin et *al.* 1985, Booth et *al.* 1985);

(2) The polarizations of the leading (faster) shear-waves showed clear parallel alignments (Booth et *al.* 1985). The direction of alignment was found to be consistent with the hypothesis of propagation through a material containing a distribution of cracks aligned by the regional stress field (Crampin & Booth 1985).

(3) The polarizations were consistent in sign, but not in azimuth, with shear-waves, radiated from sources with double-couple mechanisms satisfying the P-wave first-motion directions observed for the swarm (Evans et *al.* 1985), propagating through an isotropic medium. The

observed polarizations were consistent in sign and azimuth with shear-waves radiated from such double-couple sources but propagating through a material containing a distribution of aligned cracks (Crampin & Booth 1985).

(4) The orientation of the anisotropy derived from analyses of the polarization of shear-waves was consistent with that derived from independent inversion of P- and S-wave arrival times (Doyle *et al.* 1985).

The results of these initial studies at Izmit have since been confirmed by studies at many other locations and differing tectonic settings in Tadzhikistan, USSR (Crampin *et al.* 1986), Japan (Kaneshima *et al.* 1987), the UK (Peacock 1985) and elsewhere. See Crampin (1987a) for a review of observations of shear-wave splitting. It is now well established that shear-wave splitting is a widespread phenomenon and has been observed on almost every occasion when it has been sought. Many of the detailed conclusions of the initial studies have been confirmed by these later works. A further advance was made by Peacock *et al.* (1987), who observed temporal changes in the behaviour of shear-wave splitting near the Anza seismic gap in southern California and modelled their observations as an increase in the aspect ratio of fluid-filled microcracks caused by the development of stress in advance of a larger earthquake.

Studies were continued in the Izmit area during 1984 with a multi-disciplinary programme of geophysical measurements. The field programme was conducted over a longer period than the earlier studies. This paper describes the conduct of the experiment, the instrumentation and the analysis methods, and summarises the new results so far obtained from the project.

2 Extensive-dilatancy anisotropy (EDA)

The hypothesis of extensive dilatancy anisotropy or EDA (Crampin *et al.* 1984) unites recent work in rock physics with geophysical observation of crustal properties and theoretical knowledge of seismic wave propagation into a physical basis for crustal processes and the development of earthquake precursors (Crampin 1987b). The key element underlying the concept of EDA is the alignment of crack systems in rocks under stress. There is substantial evidence that most of the Earth's crust is pervaded by fluid-filled microcracks (Crampin 1987a). Laboratory experiments have shown that under the application of comparatively low levels of shear stress, the geometry of these cracks is modified by mechanisms such as sub-critical crack-growth (Atkinson 1984). These processes give rise to an alignment of the cracks with consequent anisotropic effects on the bulk properties of in-situ crustal rockmass. Details of crack orientation, density, and aspect ratio may be derived from analysis of seismic shear-waves, which have propagated along suitable raypaths through the cracked rock. The potential for application in the field of earthquake prediction is high, as EDA opens up the possibility of monitoring both effective stress and internal rock structure through comparatively direct methods. A fuller description of EDA and its application to earthquake prediction is presented elsewhere in this issue (Crampin 1987b).

3 The study region

The North Anatolian Fault (NAF) is a prominent right lateral transcurrent fault which dominates the tectonics of Northern Turkey. It has been the site of many major earthquakes, and, in particular, of a well recognised instance of migration of earthquakes (Pamir 1944; Ambraseys & Zatopek 1969). Beginning with the M_S 7.9 earthquake of 1939, which destroyed the city of Erzincan at the eastern end of the NAF, successive earthquakes of M_S 6.5 or greater occured in 1942, 1943, 1944, 1949, 1951, 1957 and 1967, and broke segments of the fault in a westward moving pattern as far as Adapazarí at longitude 31°E. At this point, the character of the NAF changes as the strike-slip regime merges into the zone of extensional tectonics associated with western Anatolia and the Aegean (Dewey & Şengör 1979). At this point, the NAF is split into several branches with differing seismic characteristics (Üçer et *al.*, 1985).

The most prominent and apparently most active branch strikes due west across the northern part of the Marmara Sea, where it is marked as a graben feature by Izmit Bay (the eastern arm of the Marmara Sea) and by a trough of deep water within the Sea itself (Crampin & Üçer 1975). Several parts of the fault system within the Marmara region have been the site of large earthquakes within the last hundred years. The eastern parts around 30°E - the Izmit Bay and Iznik Lake areas - stand out because of the absence of large earthquakes, yet there is ample evidence of recent tectonic activity in the local topography as well as of destructive earthquakes in the historical record (Ambraseys 1970). Thus, the east-west line of the North Anatolian Fault, from Erzincan in the east to the west of the Marmara Sea, has been traced by sizeable earthquakes except for the segment around Izmit. There is therefore every reason to suspect that this eastern area of the Marmara Sea region constitutes a seismic gap : that stresses have been transferred into this area as a result of activity in adjacent sections of the North Anatolian Fault; that the local fault system is capable of generating a major earthquake; and that there is an enhanced probability of a major earthquake occurring in the area.

Records from the MARNET seismic network (Üçer et al. 1985) show a long-lived centre of low-magnitude swarm activity near the easternmost extremity of Izmit Bay (the centre of the seismic gap). The TDP1 and TDP2 field studies showed that microearthquakes in the magnitude range $0.5 \leq M_L \leq 2.5$ were occurring within the swarm at a steady rate of more than 100 per month and were detectable over a sufficiently large area that they could be located reliably using routine methods. The depth of these microearthquakes - about 8 to 11 km - together with the impulsive nature of the radiated shear-waves, makes them very suitable for investigating shear-wave propagation. Networks of closely spaced seismometers centred over the earthquakes sample a range of raypaths at varying azimuth and incidence angles through the upper crust.

Examination of P-wave first motions from larger events within the swarm shows that the focal mechanisms are predominantly strike-slip with a strong component of normal faulting, in good agreement with surface morphology and the larger scale tectonic setting (Evans et al. 1985, Crampin & Evans 1986). The stress system inferred from the focal mechanisms shows a near-vertical axis of compression, and a near-horizontal axis of tension aligned within the northeastern quadrant.

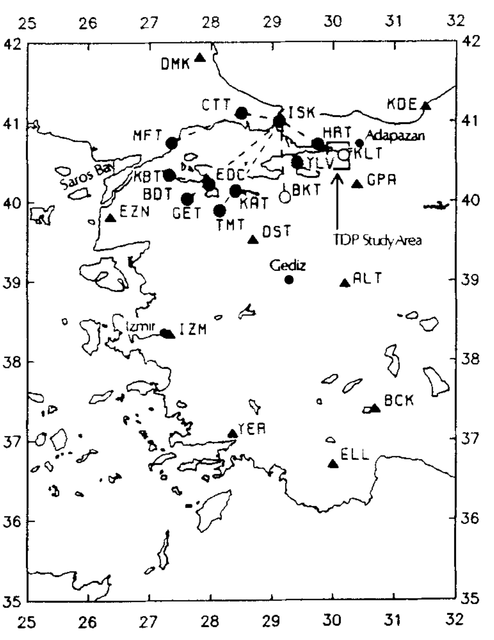

Figure 1. Map of western Turkey showing the position of the study region. Large circles indicate the locations of stations of the MARNET telemetered seismic network, triangles the locations of other stations operated by Kandilli Observatory and registering on locally sited paper recorders. The study area is indicated by the box centered at 30.0°E, 40.7°N.

This and other evidence led Crampin & Booth (1985) to conclude that the horizontal axes of stress in the region lie at N 10°E (tensional) and N 100°E (probably intermediate), with the tensional component being dominant.

4 Objectives of the TDP3 study

The TDP1 and TDP2 studies determined the characteristics of the Izmit swarm and established the presence of shear-wave splitting within the study area. The principal objectives of the TDP3 study were to investigate the phenomenon of shear-wave splitting at higher resolution; with the overall goal of earthquake prediction, to search for any possible time-dependent variation; and to correlate seismic observations of EDA with parallel observations in other branches of geophysics. A multidisciplinary programme of fieldwork was mounted during the summer of 1984. The 1984 study combined :

(1) six months operation of a stable seismological network;

(2) parallel operation of a geomagneto-telluric array;

(3) closer spacing of three-component seismometer stations;

(4) digital recording; and

(5) subsidiary experiments designed to provide data complementary to the principal study of the Izmit area.

During the planning stage, further geological, geophysical and geodetic studies of the Izmit area were proposed by a number of potential collaborators. Of these, only one is still in progress - a regional micro-gravimetric survey which is being conducted by the University of Edinburgh working with the Technical University of Istanbul. There is clearly substantial potential for further investigations in this area; a detailed geological survey conducted with an emphasis on neotectonic features would be particularly valuable; other geophysical measurements would assist greatly in defining the conditions in the preparation zone.

Parallel investigations are now being undertaken on an adjacent section of the North Anatolian Fault in the context of a collaboration between Turkish and German research groups (Zschau et *al.* 1981, 1982). A wide-ranging programme of geophysical methods including seismic, magnetotelluric, ground chemistry and deformation monitoring has been set up along the Adapazarí to Gerede section of the Fault, immediately to the east of the Izmit section, and these studies may well reveal further details of the manner in which stress is generated and released throughout the seismotectonic province of northwestern Turkey.

5 Seismological experiments

During the 1979 and 1980 field studies respectively, six and nine three-component seismic stations were established and fully operational for six and nine weeks within the study area. In 1984, eight three-component stations were operated over the entire study period of twenty-five weeks. Three of the sites used for three-component stations in 1984 were new occupations (Table 1 and Fig. 2), reflecting the tailoring of the network to suit the geometry of the earthquake swarm and the requirements of shear-wave analysis. The network of 1979 was found to have been offset to the south of the swarm; stations established to the north of the swarm in 1980 were subsequently found to be rather too distant, producing few arrivals within the shear-wave window (the full implications of which were not understood until later - Evans 1984; Booth & Crampin 1985); the geometry attained in 1984 was designed to produce the maximum number of records suitable for polarization analysis without sacrificing any accuracy in event location.

Logistics also play a part in station planning. Apart from the problems of cultural noise experienced in any survey, and the demands of the telemetry system for line-of-site between out- and base-stations, security considerations dictated the substitution of site PB in the 1980 study for the adjacent site, PA, used in 1979. Polarization analyses of these two data sets produced differing results (Booth et *al.* 1985), and gave rise to speculation that the difference might be due to strain release associated with small earthquakes ($M_L \sim 3.0$) which occurred between the two field studies. Security notwithstanding, it was therefore considered essential that both sites be occupied simultaneously during the 1984 field study, in order that direct comparison be made between the two sites. In the course of the 1984 study, PA was occupied for a total of 27 days, during which time it was vandalised twice. On the second occasion, all the instrumentation disappeared and the pitliner was smashed, effectively rendering the site unusable. Altogether, 15 days' recordings were obtained, sufficient to fulfil the scientific objective of obtaining suitable records for comparison (see below and Chen et *al.* 1987). It must be noted that these incidents were entirely atypical of our experiences in Turkey where, over some 100 station-years of operation, local people have, with this sole exception, consistently afforded us every possible assistance.

5.1 INSTRUMENTATION

As in the 1979 and 1980 studies, Willmore MkIIIA seismometers were employed throughout the experiment. Since the microearthquake signals typically analysed during this study lie in the range 5 to 20 Hz, for practical purposes, this instrument produces an output proportional to ground velocity. The principal factor governing its response in this frequency range is the motor constant of the coil-magnet assembly, which instrumental design and practical experience have shown to be easily determined and stable over long periods. The motor constants of the seismometers were determined at the start of the experiment, along with the effective source impedance. The instruments were set to a free period of 1.0 s immediately before installation, to ensure that the transfer function was accurately known. Racal FM amplifier-modulators were used at most sites, fitted with a modified feedback damping circuit to produce an

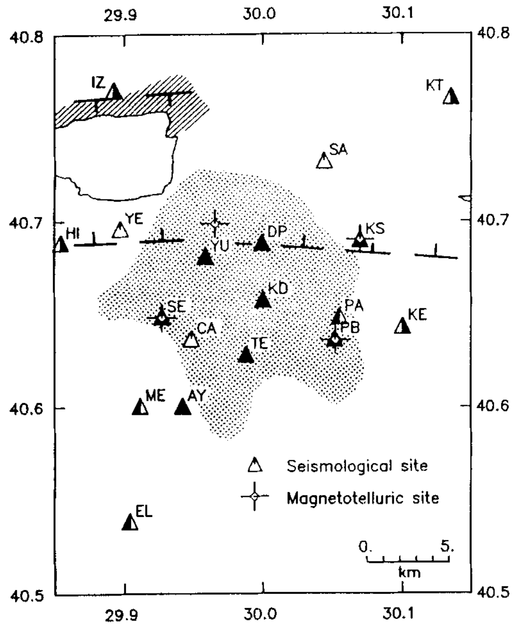

Figure 2. Station locations in the context of local tectonic features. The dotted area indicates the region of principal microseismic activity, and the hatched area the urban district of Izmit. The vertical offsets (normal faults) which mark the graben structure of the North Anatolian Fault in this area are also shown. Filled triangles indicate the sites of three-component seismometer systems during the 1984 study, part filled triangles three-component sites occupied during previous studies, and open triangles sites occupied by single-component seismometers - full details of station occupancy are given in Table 1. The network geometry has been optimised through the course of the three studies so that most of the three-component stations lie above the region of principal microseismic activity. During the 1984 study, data was telemetered to a base station at Hereke, about 25 km to the north-west of the swarm centre, where a fifth magnetotelluric site was located.

Table 1. Site occupancy in the Izmit area during each of the TDP field experiments. x indicates that the site was occupied with a three-component instrument through most of the respective study period; + that it was occupied for a shorter interval; and 1 that it was occupied using a single-component instrument. In addition, an array of six three-component stations was installed near YU for a two-month period during the 1984 study.

Year \ Site	SE	TE	AY	PA	ME	EL	CA	PB	DP	KT	IZ	HI	KE	HE	KS	YU	KD	YE	SA
1979 (TDP1)	x	x	x	x	x	x	1												
1980 (TDP2)	x	x	x					x	x	x	x	x	x	1					
1984 (TDP3)	x	x	x	+				x	x						x	x	x	1	1

effective damping coefficient of 0.6.

Data was telemetered using UHF FM systems to a single base station at a telephone relay site west of Izmit. Considerable problems were experienced on account of operating on nearly every channel within the 1MHz band allocated by the authorities, along near-parallel paths, and with varying signal strengths due to differences in placement of transmitting antennas. As well as FM telemetry, a small number of Earth Data 9690 digital data transmission systems were available and were operated successfully.

5.2 DATA RECORDING

Data was recorded both continuously using FM recorders and in triggered mode using a specially designed triggered digital system. As in the 1979 and 1980 studies, three 'Geostore' FM recorders were employed, each accommodating ten seismic channels. The maximum tape recording speed of 2.4 mm. s^{-1} was used. At this speed, due to tape head alignment errors, it is possible for the record/replay system chain to introduce systematic timing errors of up to 0.05 s on certain seismic channels. The possible magnitude of this source of error is similar to, and sometimes larger than, the reading and residual errors in the microearthquake arrival time data, so can represent a limiting factor in such studies, unless special steps are taken to compensate. To ensure that such alignment errors have minimum effect on the correlation of recordings from three-component seismographs, three-component sets were consistently recorded on adjacent channels. In the Geostore recorder, this has the effect of reducing the timing error between the two horizontal components of each set to less than 0.002 s.

Digital recording of seismological data offers significant advantages in terms of:

(1) dynamic range - FM recorders are limited to about 60 db;
(2) linearity;
(3) timing accuracy; and
(4) convenience.

Consequently, a digital system was developed and first employed during the TDP3 programme. Based on the DEC LSI-11/23 mini-computer, the system is capable of monitoring up to 60 seismic channels simultaneously, and of conducting additional operations such as data quality control and archiving simultaneously with network monitoring. Extension to undertake automatic analysis of captured data is planned. The trigger initially employed an algorithm based on the modified differential function or MDF (Lee & Stewart 1981). Such algorithms have produced good results in the UK, where high microseismic noise levels can generate numerous false triggers, and in other difficult conditions (Houliston et al. 1984). In the present implementation, the MDF algorithm was found to be overly sensitive to dropouts generated in the FM telemetry system, and a short-term/long-term average algorithm, modified to incorporate a band-pass filter, was substituted. Following the customary practice in network trigger systems, recording of the complete network was triggered only when several stations reported an event within a short time-window. This practice of 'station polling' produced very significant reductions in the numbers of false triggers. Although the digital system operated only intermittently through the study period, more than a hundred events were well recorded and provide a valuable reference against which the performance of the FM system can be assessed.

5.3 ARRAY STUDIES

Alongside the principal network, a variety of further field studies were conducted to investigate specific aspects of the project objectives. The most extensive of these experiments consisted of a small array of three-component seismometers deployed almost immediately above one of the most active subswarms in the Izmit area. Six stations were arranged in a cruciform pattern with a station spacing of 220 m. Using the Earth Data 9690 digital telemetry system, the stations were linked by cable to a version of the triggered digital system described above, tailored to accept and record the digital data directly. The recording system was housed in a light van parked at the roadside, powered by a temporary mains electricity supply and operated successfully over a period of two months, during which it registered most of the local events within the swarm. This data will be analysed to determine the degree of spatial consistency in shear-wave polarizations and frequency-wavenumber techniques will be used to estimate the contribution of converted phases and other non-direct arrivals to the shear-wavetrain.

5.4 SUPPLEMENTARY FIELD STUDIES

In an attempt to determine how far the Izmit swarm was typical of seismicity in the Marmara Sea region, and with a view to installing a second network of three-component seismometers over another suitable swarm, an exploratory network of single-component seismometers was installed, first on the Büyükçekmece fault, near the MARNET station CTT and later in the vicinity of Harmancík, south of station BKT (Fig. 1). Each of these localities has been identified as a site of occasional swarm activity (Crampin & Üçer 1975, Üçer et *al.* 1985), but neither is associated with the east-west trending graben structures typical of the Marmara region and so clearly exhibited at Izmit. These sites therefore appeared to offer the opportunity of conducting an investigation of shear-wave propagation under slightly different tectonic conditions but within the same overall stress regime.

Each of the supplementary networks was operated for a six week period. Although both recorded a considerable number of blasts from local quarrying and mining activity, the Büyükçekmece network recorded no natural events at all, and the Harmancík network only one small earthquake ($M_L \sim 0.5$). This observation supports the suggestion that the long-lived swarms associated with graben features in the Marmara, and the TDP swarm at Izmit in particular, are comparatively unusual and differ from the more sporadic activity of the rest of western Anatolia (Üçer et *al.* 1985).

5.5 DATA ANALYSIS

FM and digitally recorded data were checked for quality immediately they were recovered from the field recording site and a few events were selected for immediate analysis from each tape. Phase data was read using paper records from the FM replay system and the events located using HYPO71 (Lee & Lahr 1975). Each of the FM tapes was monitored and possible events identified by listening to data replayed at 80 x real time; by associating possible events from the various tapes, a list of probable events was constructed. These steps allowed the field team to remain aware of the performance of the network. Detailed analysis was conducted in Edinburgh at the conclusion of the field study. Sections of the FM tapes corresponding to each of the events identified by the audio scan were digitized and phase arrivals picked using high resolution graphics terminals. HYPO71 was again used to calculate reference locations, after which paper copies of high-gain time domain and particle motion seismograms were produced in volume. Fig. 3 shows examples of such seismograms, illustrating the effects of shear-wave splitting. Station magnitudes were calculated from peak particle velocity, using a simple logarithmic formula derived in the course of the previous studies, and used by analysts as the basis for assigning individual earthquake magnitudes. The final stage of routine analysis - the assessment of polarization diagrams - is discussed in detail by Chen et *al.* (1987) and some of the results of this analysis are included in Fig. 5.

The features of the TDP microearthquake swarm described by Crampin et *al.* (1985) were again confirmed. Both *P*- and *S*-waveforms observed at stations within the shear-wave window were impulsive in character, indicating the simple nature of the sources, and shear-wave splitting was again observed on almost all suitable three-component recordings. Comparison of Fig. 4 with Fig. 3b of Crampin et *al.* (1985) shows that earthquake activity was at a similar level to that of 1979 and 1980, with about a hundred events each month being observed by sufficient instruments

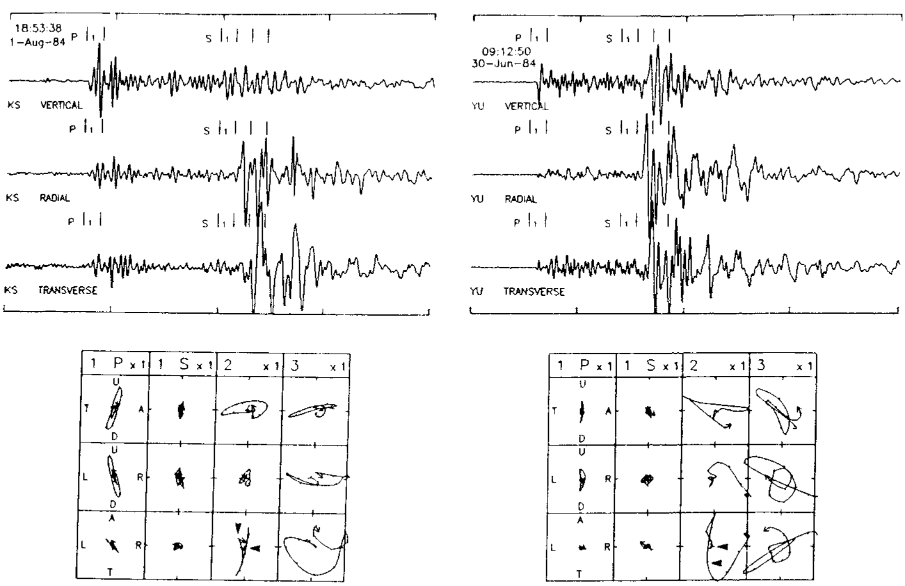

Figure 3. Seismograms recorded during the 1984 study continue to show impulsive *P*- and *S*-wave arrivals suitable for polarization analysis, and shear-wavetrains display shear-wave splitting. These four-second record segments from two of the sites first occupied in 1984 are typical of recordings from the TDP networks. As well as the time domain traces (above), polarization diagrams of the *P*- and *S*-wave arrivals are shown (below). See Chen et *al.* (1987) for a detailed description of the format. The distances, depths, and azimuths of the events are (a) 5.6 km, 10.4 km, 107°; (b) 6.7 km, 6.8 km, 115°.

for their locations to be estimated. The most striking feature of the locations themselves is that, with remarkably few exceptions, all well-determined hypocentres lie within the depth range 8 to 11 km. Since the activity is distributed over a horizontal area of roughly 15 km dimension, the hypocentres form a horizontal sheet. Cross-section plots of the activity show no suggestion of any resolvable dip on this structure and this feature is ascribed to the the presence of a maximum in crustal strength which both marks and defines the base of the seismogenic zone (Meissner & Strehlau 1982).

6 Geomagnetic experiments

Earthquake-related dynamic processes are capable of modifying many physical properties of rocks, amongst them electrical resistivity. Laboratory experiments have shown that rock types, whose resistivity is controlled by the volume and geometry of microcracks, can undergo large resistivity variations in response to the large strain accumulation and subsequent release that accompanies major earthquakes (Beamish 1982).

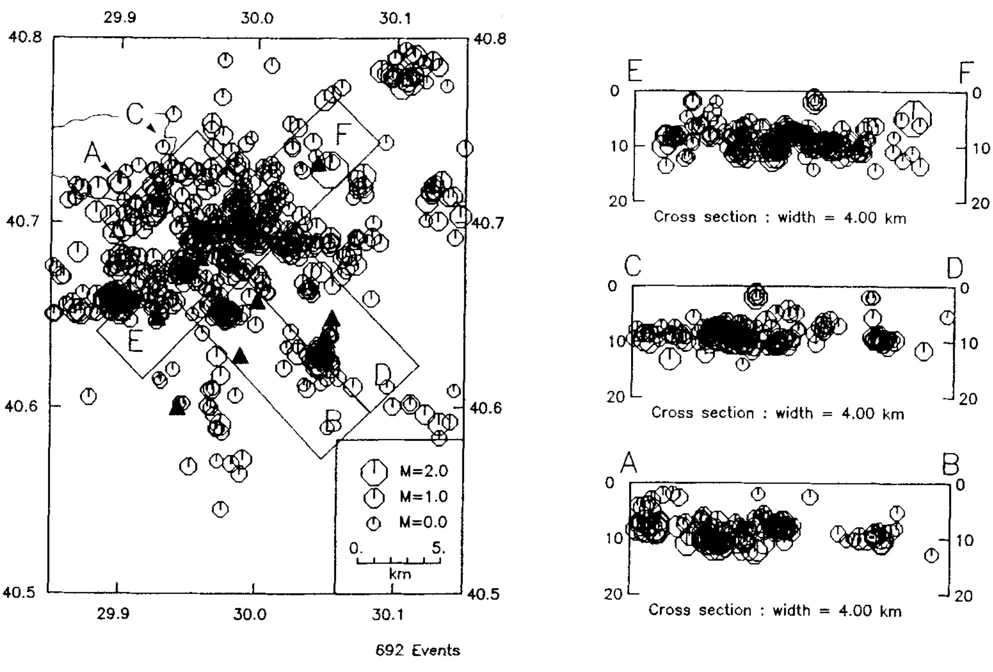

Figure 4. Epicentral maps and vertical sections through the foci of 692 events located by six or more arrivals on the TDP3 network in 1984. This figure is directly comparable with figure 3b of Crampin et *al.* (1985), based on similar data obtained during a two-month period in 1980. Comparison shows clearly that activity within this swarm centre has remained approximately constant in level and geometry over the five year period covered by the TDP studies. Magnitudes *M* are local magnitudes.

The origin of EDA as the response of fluid inclusions to even low levels of stress suggests that magneto- telluric (MT) methods may contain additional information about EDA-cracks. Stress changes at comparatively low levels of stress in the EDA hypothesis, modify microcrack geometry and hence the bulk resistivity measured using MT techniques. Thus, EDA provides a viable physical mechanism for time-dependent variation of crustal resistivity as well as seismic velocities.

The TDP3 experiment incorporated a small scale MT array. Five five-component MT systems were deployed alongside three-component seismometers as shown in Fig. 2. A cluster of four sites were occupied within the shear-wave window of swarm activity with the fifth, base, site on the northern margin of the graben acting as a remote reference. The array database is being examined to investigate the time-dependence of MT parameters and the derived models of geoelectric structure in order to test the hypotheses generated by the parallel seismological investigations.

6.1 INSTRUMENTATION AND DATA HANDLING

Triaxial fluxgate magnetometers of standard design were used throughout the experiment. The telluric variations were measured using copper/copper sulphate electrodes arranged to form a cross with 100 m between electrode pairs. The sensors have a useful bandwidth from several seconds to DC, and a system of digital data transfer based on FM telemetry was developed to handle the long term registration of these low-frequency fields.

The microprocessor-controlled field systems (Beamish & Riddick 1985) sample the sensor signals at five-second intervals and generate an FSK (frequency shift keying) signal compatible with the standard seismological FM radiolink system. The field data were telemetered to a base station next to the seismological base station where the demodulated data were logged using a 30-channel acquisition system, based on a DEC LSI-11/23 minicomputer. As with the seismological logger, the system permits data quality control and archiving to take place without interruption to the basic task of data capture. The use of identical equipment for telemetry and data logging in both seismological and magnetotelluric experiments encouraged collaboration between the project teams and permitted deeper levels of spares backup for both studies.

6.2 SUPPLEMENTARY AUDIO-MAGNETOTELLURIC STUDIES

High-frequency (0.1 to 100 Hz) audio-magnetotelluric (AMT) measurements were also carried out across the TDP3 study area. These investigations provided supplementary information on geoelectric parameters at shallow crustal depths. Data recorded in the vicinity of Izmit, the main industrial town of the region, reveal a complex pattern of electromagnetic noise sources associated with the fundamental mains harmonic (50 Hz). Many of the noise characteristics are attributable to an unbalanced power distribution grid which at times interfered with the low-frequency telluric fields recorded by the principal MT array.

7 Particular investigations

The volume of data generated in the course of the TDP3 study was very much greater than that produced during TDP1 and TDP2 and has served to confirm those key features of the earlier datasets which spurred the development of the EDA concept. It also permits finer features to be examined in detail.

7.1 CLUSTERING WITHIN THE SWARM

The development of EDA as a tool for routine application in earthquake prediction requires that shear-wave propagation through the impending source region be regularly monitored using precise repetitive sources such as shear-wave VSPs. As a substitute at this stage of development, we note that many of the subswarms or *clusters* of activity within the TDP swarm include sequences of almost identical microearthquakes, and suggest that such sequences provide a natural substitute capable of providing the repetion. Lovell et *al.* (1987), elsewhere in this issue, examine several such clusters in detail. Whilst all clusters included a number of earthquakes exhibiting varying waveforms, and therefore presumably unrelated in their source geometry, most clusters also included one or more sequences of events for which the suite of waveforms showed striking similarity. In some cases, sequences of events were found in which, after scaling, the waveform at every station was identical. Lovell et *al.* show examples of these earthquake families or 'doublets' recorded immediately above the earthquake foci. Unfortunately, although Lovell et *al.* were able to identify several such sequences persisting through a large part of the TDP3 project, none were identified which could link any two of the three separate field programmes.

Logan (1987) has examined waveforms of doublets within these clusters and, using a cross-correlation technique, has found that small differences in the waveforms can be reliably detected and measured. Variations in the relative arrival time of the *P*- and *S*-waveforms were measured to an accuracy of 0.001 s. Ascribing these variations to differences in source location, Logan applied a joint hypocentral location method to several of the clusters found in the TDP datasets, with a resulting relative location accuracy of better than 30 m and, in this way, explored their detailed geometry. Whilst one cluster was found to comprise a group of essentially indistinguishable sources, the others formed linear and planar features of a few hundred metres dimension. The size and orientation were found to be comparable with results derived from spectral analysis (Evans et *al.* 1982) and P-wave first-motions (Evans et *al.* 1985, Lovell et al. 1987). The close spacing of the TDP networks above the earthquake foci probably renders these families the most closely observed to date, and it is believed that the geometry of slip due to microearthquakes at depth is being resolved for the first time.

7.2 TIME DEPENDENCE IN SHEAR-WAVE SPLITTING

In a further study, Chen *et al.* (1987) have applied and extended the polarization methods of Booth et *al.* (1985) and Crampin & Booth (1985) to the TDP3 dataset. The analyses showed that the polarizations of the leading (faster) split shear-waves were essentially the same in 1984 as in 1979 and 1980. The initial polarization of the shear wavetrains continued to show a strong tendency to alignment in an east-west direction. Shear-wave polarizations at station PA (see section 5 above) were found to be similar to those observed during the TDP1 study in 1979, and the anomalous suite of polarizations observed at this station are now ascribed to the effects of severe local topography. Chen *et al.* took advantage of the much larger quantity of data gathered during the TDP3 study to examine in detail the delays between split shear-waves. They found some evidence for long-term temporal variation between 1979 and 1984, and indications of a possible shorter-term variation within the six months of 1984 covered by the TDP3 study. These observations are interpreted in terms of a decrease in the *density* of EDA cracks between 1979 and 1984, and an increase in *aspect ratio* during 1984. Although both variations are to be anticipated during the earthquake cycle of stress build-up and release, insufficient data is available to determine whether the cycle is associated with earthquakes within the TDP swarm, or with the development of the regional stress system.

7.3 THE RELATIONSHIP BETWEEN SEISMIC AND GEOELECTRIC ANISOTROPY

The results obtained from the magneto-telluric (MT) data set provide information on the distribution of resistivity across the study area. In summarizing the preliminary findings from this experiment, it should be noted that

(1) MT fields sample earth structure throughout a region surrounding the observing site, and not, as in the case of seismic shear-waves, the structure along a (comparatively) well-defined path within the earth's crust; and

(2) the data modelling of the geoelectric structures must take account of the inherently three-dimensional nature of the geoelectric response at each of the five observing sites.

The MT results, including the vertical magnetic field, broadly conform to a pattern of near-surface, thin-sheet distortions superimposed on a major two-dimensional boundary. Two principal results indicate a substantial geoelectric boundary underlying the graben floor. Firstly, a reversal in the phase of the vertical field is observed between the base site, on the northern fault margin, and the remaining array sites. Secondly, the apparent resistivity at the base site (10^4 to 10^6 ohm m) is three orders of magnitude greater than that at the four array sites

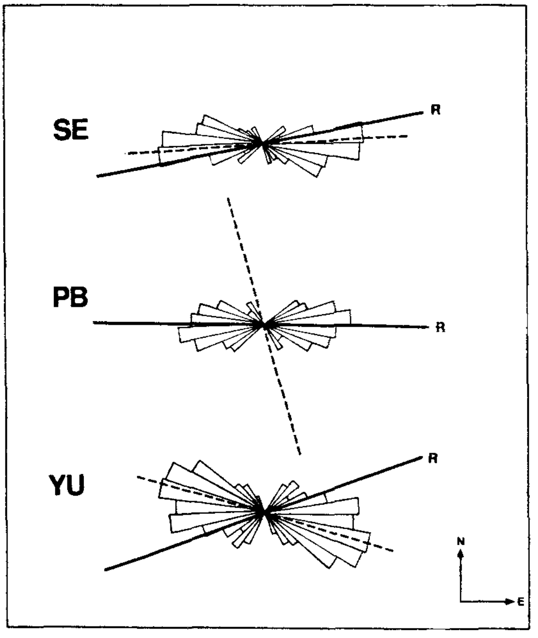

Figure 5. Geoelectric strike azimuths at sites SE, PB and YU, superimposed on equal-area rose diagrams of the polarizations of the leading split shear-waves observed at the same sites. (Sufficient geoelectric data of suitable quality is not available from site KS.) Geoelectric strike azimuths are divided into local contributions (broken lines) and regional contributions (solid lines). The regional strike of the geoelectric field is in general agreement with the shear-wave polarizations, and is attributed to the presence of EDA cracks. The anomalous local strike at PB is attributed to local topographic effects.

(10^1 to 5.10^2 ohm m). Although the spatial extent of these low-frequency observations is limited, they suggest that the NAF transects two crustal units of widely differing resistivity. The southern unit, within which the swarm activity is occurring, is characterised by comparatively low crustal resistivity.

Taking into account the scaling factor introduced by near-surface distortions (Larsen 1975), it has been possible to obtain a representative vertical profile at sites SE and PB (Fig. 2). The upper crust appears as a homogeneous conductive unit (resistivity 40 to 100 ohm m) of 12 km thickness, overlying a deeper layer in which resistivity is an order of magnitude greater. The upper, conductive region appears to represent a zone permeated by fluid-filled cracks - the region of extensive-dilatancy anisotropy already identified by shear-wave splitting - whilst the resistivity transition at 12 km corresponds to the lower limit of observed seismic activity (Fig. 3) - the base of the seismogenic zone.

The analysis of Zhang et *al.* (1987) was applied to extract the local (near-surface) and regional (two-dimensional) geoelectric strike directions. Broadly speaking, the regional strike is representative of the predominant axis of structural anisotropy, while the local strike direction is indicative of the azimuthal influence of near-surface variations. The results determined at three of the sites are shown in Fig. 5, superimposed on equal-area rose diagrams of the shear-wave polarizations observed at the same point. Regional azimuths are consistent across the array and are in good correspondence with the shear-wave polarizations determined by the seismological array overall and with the alignments at SE and PB in particular. The local azimuth at PB is parallel to a substantial topographic feature and is interpreted as a near-surface effect. The comparison at site YU, situated within the fault graben, is less satisfactory, since here the local azimuth displays a better correspondence with the shear-wave alignments. The level of agreement overall is considerable and indicates that the regional axes of geoelectric and seismic anisotropy are inter-related (Russell 1987).

8 Conclusions

The Turkish Dilatancy Projects, TDP1 and TDP2, designed to search for shear-wave splitting above small earthquakes, provided the first positive identifications of shear-wave splitting in the crust (initially reported by Crampin et *al.* 1980). This stimulated Crampin et *al.* (1984) to put forward the hypothesis of extensive-dilatancy anisotropy (EDA) as the cause of the splitting. Originally expected to exist only in earthquake preparation zones, shear-wave splitting, and by implication EDA, has now been identified widely in the crust (reviewed by Crampin 1987a). The third phase of the projects in Turkey, TDP3, confirmed and reinforced the findings of the initial projects that shear-wave splitting in the crust is the result of the effective anisotropy of EDA-cracks.

Following observations of time-dependant variations in southern California by Peacock *et al.* (1987), detailed investigation of the TDP dataset by Chen *et al.* has revealed strong indications of temporal variation in shear-wave delays and further supports the hypothesis of EDA. It is likely that the geoelectric observations, whose preliminary interpretation is reported here, will lead to further associations of EDA-cracks with the electro-magnetic phenomena associated with earthquakes and that the geometry of EDA-cracks may be affected by low levels of applied stress.

Crampin (1987b), later in this issue, argues that this possibility can best be explored, and its success exploited, through the routine monitoring of an earthquake source region with shear-wave vertical seismic profiling. Unfortunately, the possibility of such extension of the work in the Izmit seismic gap seems remote, in the absence of a suitably deep borehole. However, the presence of the earthquake swarm which originally led to the selection of the Izmit area as a suitable site for earthquake prediction studies continues to offer the possibility of routinely monitoring shear-wave splitting using natural sources. In consequence the establishment of a permanent three-component network in the Izmit gap must be viewed as a highly desirable development. We would further argue that the development of array methods for the identification and elimination of contaminating non-direct shear-wave arrivals must now be accomplished and predict that this will shortly become a powerful tool in the establishment of shear-wave methods for determining the structure of the earth's crust.

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References

Ambraseys, N.N., 1970. Some characteristic features of the Anatolian fault zone, *Tectonophysics*, **9**, 143-165.

Ambraseys, N.N. & Zatopek, A, 1969. The Mudurnu Valley, West Anatolia, Turkey, earthquake of 22 July 1967, *Bull.seism.Soc.Am.*, **59**, 521-589.

Atkinson, B.K., 1984. Subcritical crack growth in geological materials, *J. geophys.Res.*, **89**, 4077-4114.

Beamish, D., 1982. The time-dependence of electromagnetic response functions, *Geophys.Surv.*, **4**, 405-434.

Beamish, D. & Riddick, J.C., 1985. TDP3 II. Magnetotelluric array instrumentation, *Brit.geol.Surv.Geomagnetism Res.Group Report 85/22*.

Booth, D.C. & Crampin, S., 1985. Shear-wave polarizations on a curved wavefront at an isotropic free surface, *Geophys.J.R.astr.Soc.*, **83**, 31-45.

Booth, D.C., Crampin, S., Evans, R. & Roberts, G., 1985. Shear-wave polarizations near the North Anatolian Fault - I. Evidence for anisotropy-induced shear-wave splitting, *Geophys.J.R.astr.Soc.*, **83**, 61-73.

Chen, T-C., Booth, D.C. & Crampin, S., 1987. Shear-wave polarizations near the North Anatolian Fault - III. Observations of temporal changes, *Geophys.J. R.astr.Soc.*, **91**, this issue.

Crampin, S., 1978. Seismic-wave propagation through a cracked solid: polarization as a possible dilatancy diagnostic, *Geophys.J.R.astr.Soc.*, **53**, 467-496.

Crampin, S., 1987a. Geological and industrial implications of extensive-dilatancy anisotropy, *Nature*, **328**, 491-496.

Crampin, S., 1987b. The basis for earthquake prediction, *Geophys.J.R.astr.Soc.*, **91**, this issue.

Crampin, S. & Booth, D.C., 1985. Shear-wave polarizations near the North Anatolian Fault - II. Interpretation in terms of crack-induced anisotropy, *Geophys.J.R.astr.Soc.*, **83**, 75-92.

Crampin, S., Booth, D.C., Krasnova, M.A., Chesnokov, E.M., Maximov, A.B. & Tarasov, N.T., 1986. Shear-wave polarizations in the Peter the First Range indicating crack-induced anisotropy in a thrust-fault regime, *Geophys.J.R.astr.Soc.*, **84**, 401-412.

Crampin, S. & Evans, R., 1986. Neotectonics of the Marmara Sea region of Turkey, *J.geol.Soc.Lon.*, **143**, 343-348.

Crampin, S., Evans, R. & Atkinson, B.K., 1984. Earthquake prediction: a new physical basis, *Geophys.J.R.astr.Soc.*, **76**, 147-156.

Crampin, S., Evans, R. & Üçer S.B., 1985. Analysis of records of local earthquakes: the Turkish Dilatancy Projects (TDP1 and TDP2), *Geophys.J.R.astr. Soc.*, **83**, 1-16.

Crampin, S., Evans, R., Üçer S.B., Doyle, M., Davis, J.P., Yegorkina, G.V. & Miller, A., 1980. Observations of dilatancy-induced polarization anomalies and earthquake prediction, *Nature*, **286**, 874-877.

Crampin, S. & Üçer S.B., 1975. The seismicity of the Marmara Sea region of Turkey, *Geophys.J.R.astr.Soc.*, **40**, 269-288.

Dewey, J.F. & Şengör, A.M.C., 1979. Aegean and surrounding regions: complex multiplate and continuum tectonics in a convergent zone, *Bull.geol.Soc. Am.*, **66**, 843-868.

Doyle, M., Crampin, S., McGonigle, R. & Evans, R., 1985. Inversion of arrival-times in a region of dilatancy-anisotropy, *Pageoph*, **123**, 375-387.

Evans, R., 1984. Effects of the free surface on shear wavetrains, *Geophys.J.R. astr.Soc.*, **76**, 165-172.

Evans, R., Crampin, S. & Üçer, S.B., 1982. Source parameters determined for small earthquakes in north western Turkey (abstract), *EOS*, **63**, 1269.

Evans, R., Asudeh, I., Crampin, S. & Üçer, S.B., 1985. Tectonics of the Marmara Sea region of Turkey: new evidence from micro-earthquake fault plane solutions, *Geophys.J.R.astr.Soc.*, **83**, 47-60.

Houliston, D.J., Waugh, G. & Laughlin, J., 1984. Automatic real-time event detection for seismic networks, *Computers & Geosciences*, **10**, 431-436.

Kaneshima, S., Ando, M. & Crampin, S., 1987. Shear-wave splitting above small earthquakes in the Kinki district of Japan, *Phys.Earth planet.Int.*, **45**, 45-58.

Larsen, J.C., 1975. Low frequency (0.1-6.0 cpd) electromagnetic study of deep mantle electrical conductivity beneath the Hawaiian Islands, *Geophys.J.R. astr.Soc.*, **43**, 17-46.

Lee, W.H.L. & Lahr, J.C., 1975. HYPO71 (Revised): a computer program for determining hypocentre, magnitude and fault motion patterns of local earthquakes, *Open File Rep.U.S.geol.Surv.*, *73-311*.

Lee, W.H.L. & Stewart, S.W., 1981. Principles and applications of micro-earthquake networks, *Adv.Geophys.*, Supp.2.

Logan, A.L.L., 1987. Accurate relative relocation of similar earthquakes, *PhD dissertation*, University of Edinburgh.

Lovell, J.H., Crampin, S., Evans, R. & Üçer, S.B., 1987. Microearthquakes in the TDP swarm, Turkey: clustering in space and time, *Geophys.J.R.astr. Soc.*, **91**, this issue.

Meissner, R. & Strehlau, J., 1982. Limits of stresses in continental crusts and their relation to the depth-frequency distribution of shallow earthquakes, *Tectonics*, **1**, 73-89.

Nuttli, O., 1961. The effect of the earth's surface on the *S* wave particle motion, *Bull.seism.Soc.Am.*, **51**, 237-246.

Pamir, H.N., 1944. Kuzey Anadolu'da bir deprem çizgisi, *Istanb.Univ.Fen Fak. Mecm.A.*, **9**, 143-158.

Peacock, S., 1985. Shear-wave polarizations: IV, aftershocks of the North Wales earthquake of July 1984 (abstract), *Geophys.J.R.astr.Soc.*, **81**, 341.

Peacock, S., Crampin, S., Booth, D.C. & Fletcher, J.B., 1987. Shear-wave splitting in the Anza seismic gap, southern California: temporal variations as possible precursors, *J.geophys.Res*, submitted.

Russell, M., 1987. Electromagnetic induction studies in an area of active crustal dislocation, *PhD dissertation*, University of Edinburgh (in preparation).

Toksöz, M.N., Shakal, A.F. & Michael, A.J., 1979. Space-time migration of earthquakes along the North Anatolian Fault zone and seismic gaps, *Pure appl.Geophys.*, **117**, 1258-1270.

Üçer S.B., Crampin, S., Evans, R., Miller, A. & Kafadar, N., 1985. The MARNET radiolinked seismometer network spanning the Marmara Sea and the seismicity of Western Turkey, *Geophys.J.R.astr.Soc.*, **83**, 17-30.

Zhang, P., Roberts, R.G. & Pedersen, L.B., 1987. Magnetotelluric strike rules, *Geophysics*, **52**, 267-278.

Zschau, J., Nehl, B., Roth, F. & Noell, U., 1981. Cyclic earthquake activity near Adapazarí, western Turkey (abstract), *Terra Cognita, special issue spring 1981*, 33.

Zschau, J., Isikara, A.M., Berckhemer, H., Bonatz, M. & Meissner, R., 1982. The Turkish-German earthquake prediction research project near Adapazarí, western Turkey (abstract), *EOS*, **63**, 1272.