

SHEAR-WAVE SPLITTING AND EARTHQUAKE PREDICTION

Papadimitriou, P., Makropoulos, K. and Drakopoulos, J.

Department of Geophysics, University of Athens, 157 04 Athens, Greece

A B S T R A C T

Shear-wave polarisation analysis has been performed on data from the strong motion recorder installed in the area of Kalamata. The recordings were obtained from an earthquake of magnitude $M_s=5.8$ that occurred on the 13th September 1986 at the northern part of the city and from its aftershocks. The analysis performed on the 1 to 6 Hz bandpass filtered accelerograms reveals a shear-wave splitting for the main event with a $N15^\circ E$ direction axis representing the maximum shear-wave velocity and a time delay between the two orthogonal axes NS and EW of 0.15sec. The direction of the linear polarisation of the particle motion after correcting the records for the anisotropy propagation effects is stable in time and fits the stress field deduced from the focal mechanism of the main event. The same analysis performed on the main aftershock shows a shear wave splitting of 0.11sec and their aftershocks reveal that the anisotropy effect is less pronounced. These results indicate that monitoring of the behaviour of in situ stress field and its associated anisotropy effects prior to an earthquake, is a promising tool of earthquake prediction.

ΔΙΑΦΟΡΟΠΟΙΗΣΗ ΤΗΣ ΤΑΧΥΤΗΤΑΣ ΤΩΝ ΕΓΚΑΡΣΙΩΝ ΚΥΜΑΤΩΝ ΚΑΙ ΠΡΟΓΝΩΣΗ ΤΩΝ ΣΕΙΣΜΩΝ

Παπαδημητρίου, Π., Μακρόπουλος, Κ. και Δρακόπουλος, Ι.

Π Ε Ρ Ι Λ Η Ψ Η

Στην εργασία αυτή μελετάται η πόλωση των εγκαρσίων κυμάτων του κύριου σεισμού που έγινε βόρεια της πόλης της Καλαμάτας στις 13 Σεπτεμβρίου 1986, καθώς επίσης και των μετασεισμών του. Για τον σκοπό αυτό χρησιμοποιήθηκαν οι οριζόντιες συνιστώσες των επιταχυνσιογραφημάτων του σταθμού της Καλαμάτας. Προκειμένου να περιοριστεί η επίδραση των υψηλών συχνοτήτων εφαρμόστηκε ζωνοπερατό φίλτρο εύρους 1-6Hz. Για τον κύριο σεισμό η μέθοδος έδειξε τη διαφοροποίηση της ταχύτητας των εγκαρσίων κυμάτων που είχε σαν αποτέλεσμα χρονική καθυστέρηση 0.15 δευτερόλεπτα στην ΑΔ συνιστώσα σε σχέση με την ΒΝ. Με την ανάλυση αζιμουθιακής ετεροσυσχέτισης βρέθηκε ότι ο κύριος συμπίεστικός άξονας έχει διεύθυνση $N15^\circ E$. Η διεύθυνση αυτή συμφωνεί με την αντίστοιχη του μηχανισμού γένεσης του σεισμού. Το φαινόμενο αυτό αποδίδεται στην ύπαρξη ανισοτροπικού μέσου που συνδέεται με ισχυρή συμπίεστική τάση. Ανάλογα αποτελέσματα βρέθηκαν και για τον κύριο μετασεισμό.

Αντίθετα, ο βαθμός ανισοτροπίας που προέκυψε από την ανάλυση των μετασεισμών τους ήταν πολύ μικρότερος. Τα αποτελέσματα αυτά μας οδηγούν στο συμπέρασμα ότι η συστηματική παρακολούθηση της μεταβολής της ανισοτροπίας μπορεί να αποτελέσει τη βάση για πρόδρομα σεισμικά φαινόμενα.

INTRODUCTION

A large number of seismological observations world wide have revealed the presence of the shear-wave splitting in the vicinity of the area studied and provide a strong evidence of anisotropy effects (Ando et al., 1983; Crampin, 1987; Iannaccone and Deschamps, 1989). This phenomenon is usually attributed to the presence of aligned cracks parallel to the maximum compressive stress (Crampin, 1985). The unequal principal axes of a deviatoric stress acting on a cracked rock produce a redistribution of cracks that is necessarily anisotropic to seismic waves. In this case, when a shear-wave propagates in an anisotropic medium then this wave is decomposed in two quasi shear-waves which have different velocities and orthogonal directions of polarisation on the axes of anisotropy. The angle of the seismic ray with respect to the axes of anisotropy controls the time delay between the two phases (Crampin, 1985).

Booth et al., (1985), observed that the orientation of the polarisation near the strike-slip North Anatolian Fault is aligned in N100°E direction. This orientation is similar to the direction of the compressive stress field. The interpretation given was that the shear-wave splitting is due to the stress-aligned crack anisotropy. Similar results are obtained by Zollo and Bernard (1989), when studied the Imperial Valley aftershock that occurred on October 10, 1979. They observed that the fast S polarisations are mainly oriented between N0°E and N25°E directions and have a mean delay of 0.12 sec between the slow and the fast S waves.

On September 13, 1986 an earthquake of magnitude $M_s=5.8$ (ISC) and focal depth $h=42$ km occurred near the Kalamata city (southern Peloponnesus, Greece) without any foreshock activity. The earthquake was followed by a large number of aftershocks, located by a dense portable seismographic network (Lyon-Caen et al., 1988; Papazachos et al., 1988). The spatial distribution of the aftershocks and the waveform analysis performed until now, indicate a normal fault of N-S direction and E-W extension (Papadimitriou, 1988).

In this study, the strong motions caused by the main event and its aftershocks, recorded by the Kalamata accelerographic station are analysed by the S-wave polarisation method in order to identify the possible existence of anisotropy and its variability within the sequence.

DATA

The strong motion accelerographic station (SMA-1) installed in the city of Kalamata was triggered and recorded the seismic waves during the earthquake that occurred on 13 September 1986,

a few kilometres north of the city. On September 15, 1986 the station was also triggered by the main aftershock located under the city. Five more records were obtained during this period. The location, magnitude and origin time of each one of them is tabulated in Table 1, and their spatial distribution is shown in figure 1. From this figure it can be seen that four aftershocks are located very close to the main event and one aftershock is located close to the main aftershock.

Each one of the seismic signals was digitised at a rate of 100 sample/sec and for a duration of 10 seconds. In order to obtain a clear representation of the seismic waves a bandpass filter is applied on the frequency range of 1 to 6 Hz.

Table 1. List of events

	DATE	TIME	M_L	LAT.	LONG.
1.	13.09.1986	17:24:34.3	5.5	37.09	22.11
2.	13.09.1986	18:30:35.4	3.3	37.08	22.09
3.	13.09.1986	22:40:12.1	3.6	37.08	22.10
4.	14.09.1986	00:29:28.7	3.3	37.09	22.10
5.	14.09.1986	22:48:41.8	3.4	37.10	22.09
6.	15.09.1986	11:41:27.9	4.8	37.06	22.11
7.	15.09.1986	12:47:33.6	3.6	37.06	22.10

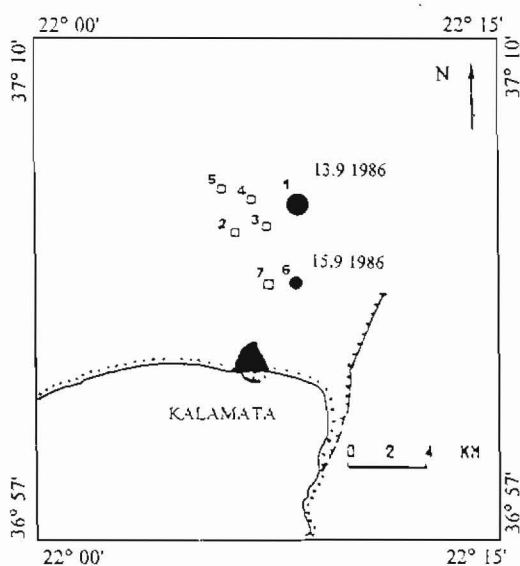


Fig.1. Map showing epicenters of the seven earthquakes listed in table 1.

METHODOLOGY

The method consists of analysing the S-polarisation vector recorded at the station, estimating the time delay and the principal axis of anisotropy by a cross correlation function and relating it to the focal mechanism. In order to obtain a clear polarisation diagram, the horizontal traces have to be rotated in the NS and EW directions and filtered at different frequency bands.

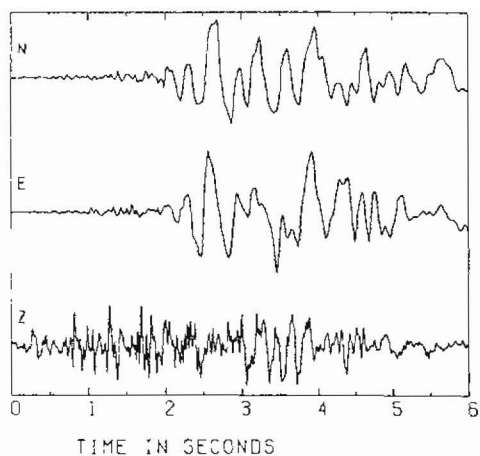
The three dimensional ground motion vectors can be parameterized by a modulus and a direction (polarisation unit vector), both being generally a function of time (Booth and Crampin, 1985; Bernard and Zollo, 1989). In the case of near field records like the ones studied in the present work, theoretical tests and data analysis suggest that when the angle of incidence is within the so-called "shear wave window" and a frequency range, the S-wave polarisation is not significantly perturbed by the velocity structure or by the free surface and thus it is not altered along a given ray path (Aki and Richards, 1980).

Figure 2 shows the horizontal NS, EW traces as well as the vertical Z trace of the main event. From the horizontal traces it is clear that the S waves arrive about 2 sec after the beginning of the traces. It also can be observed that the horizontal NS component is faster than the EW one. This anomaly of the S-waves travel time is also clear at the bottom of figure 2, where the polarisation vector is plotted as a function of time. The non-linearly polarised vector in figure 2 does not correspond to the direct S wave which was radiated by a point source. This anomaly is interpreted as an anisotropy effect.

ANALYSIS AND RESULTS

Crampin (1978) showed that when a shear-wave propagates in an anisotropy medium then this wave is decomposed in two quasi shear-waves (qs_1 and qs_2) which have different velocities and orthogonal directions of polarisation on the axis of anisotropy. The angle of the seismic ray with respect to the axis of anisotropy controls the time delay between the two phases. Cross-correlation between orthogonal rotated components will give a maximum time delay at the rotation angle corresponding to the polarisation directions of the fast and slow split shear-waves. In the present case we rotate the horizontal traces between 0° and 90° with a step of 1° in order to find the direction of the principal axis of anisotropy using a cross correlation function. The time delay associated with the particular maximum value, is the measure of the different arrival times between the two horizontal traces found by the cross correlation method.

Figure 3a shows the variation of the cross correlation function versus azimuth, while figure 3b shows the same function versus time. In the first figure it can be seen that the direction of the principal axis of anisotropy is $N15^\circ E$ whereas the second figure shows that the maximum time delay has the value of 0.15 sec. Thus, the direction of the maximum velocity is $N15^\circ E$ and the perpendicular direction $N105^\circ E$ corresponds to the minimum velocity, while the observed time delay is attributed to the anisotropic propagation of the S waves. The direction of the principal axis of



FILTER 1.00 6.00 HERTZ

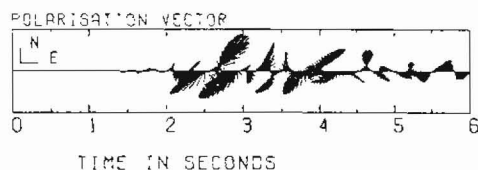
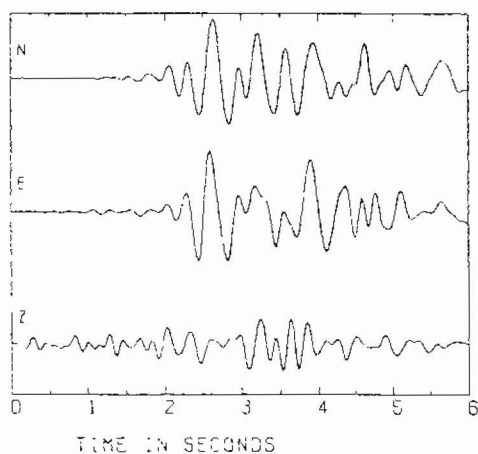


Fig.2. Traces of the main event and their filtering. At the bottom the polarisation vector is plotted versus time.

anisotropy found ($N15^{\circ}E$) is in good agreement with the focal mechanism solution (strike= 210° , dip= 46° and rake= -75°), obtained by modelling teleseismic body waves (Papadimitriou, 1988), indicating a compressive stress field in $N19^{\circ}E$ direction, as well as with the direction of the observed fault $N20^{\circ}E$. When we remove the time delay, the resulted linearity of the polarisation vector (see figure 4) and the theoretical polarisation produced by the mainshock at the station of Kalamata (Bernard and Zollo, 1990) confirms the existence of anisotropy of the medium.

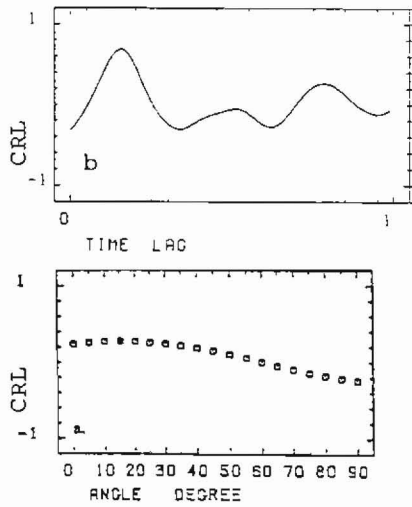


Fig.3. a.Cross-correlation variation versus azimuth and b.versus time.

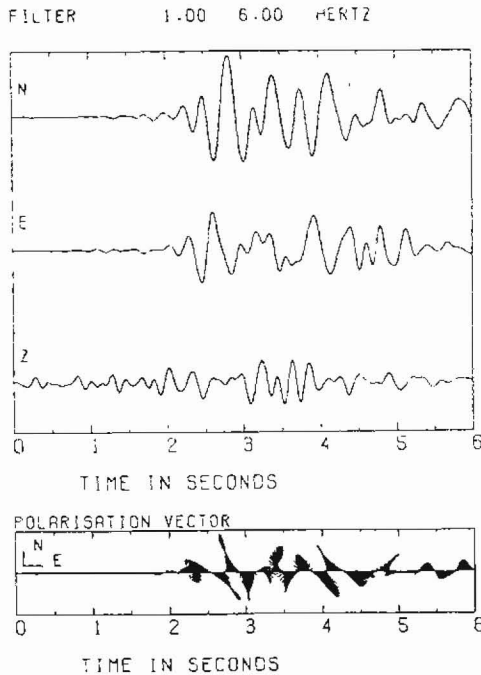


Fig.4. Corrected filtering traces of the main event. At the bottom the polarisation vector is plotted versus time.

Using the same procedure, figure 5 shows the filtered traces and the corrected polarisation vectors of four aftershocks close to the main event. These polarisations have a more E-W direction (except the first one that has NE-SW direction) than the main event. The calculated time lag of the first event is 0.02 sec, the second 0.05, the third 0.01 and the last one 0.02, values much

smaller than the observed one for the main event. This abrupt change is attributed to the stress field relaxation.

Figure 6 shows the main aftershock traces as well as the variation of the polarisation vector. In this case we also observe a non linear polarised vector. Applying the above technique we obtained a direction of compressive stress field $N32^{\circ}E$ and a time lag 0.11sec illustrated in figure 7a and 7b respectively. When the time lag is removed a linearized polarisation vector is obtained as it can be seen in figure 8. Finally, figure 9 shows the traces of the aftershock located close to the main aftershock and the direction of the polarisation vector. In this case a stable polarisation vector with no anisotropy effect is observed. Concerning the directions of polarisation of these events, they are in agreement with the one of the main event, indicating similar focal mechanism solutions. However it is necessary to generate synthetic seismograms to verify the above assumption.

CONCLUSIONS

The polarisation analysis of the shear-wave strong motion records obtained from the Kalamata, 1986 earthquake sequence shows that for the main event and the main aftershock substantial shear-wave splitting exists, while their aftershocks are characterised by a much smaller splitting. This is attributed to the existence of an anisotropic medium associated with a strong compressive stress field most probably growing during the preparatory phase, while after the release of the stress the cracks healed and hence the medium became less anisotropic.

Previous work (Crampin, 1987) has shown that the polarisation of the faster split shear waves is aligned parallel to the principal axis of compressive stress. From the azimuthal cross correlation analysis of the horizontal components of the main event the direction of this axis is found to be $N15^{\circ}E$. This is in good agreement with the compressive axis obtained from the focal mechanism analysis of the main event as it can be seen in figure 10. However the $N32^{\circ}E$ direction of the principal axis of the compressive stress found for the case of the main aftershock, show a small clockwise rotation in relation to the one of the main event.

The observed strong anisotropic effects during the main events and their dramatic decrease during the aftershock activity found in this work, coupled with the plausible hypothesis that during the preparatory phase the medium should become more and more anisotropic due to the progressively increasing stress field causing crack widening, leads to the conclusion that studies like the present one may provide an additional and promising technique for monitoring earthquake precursors.

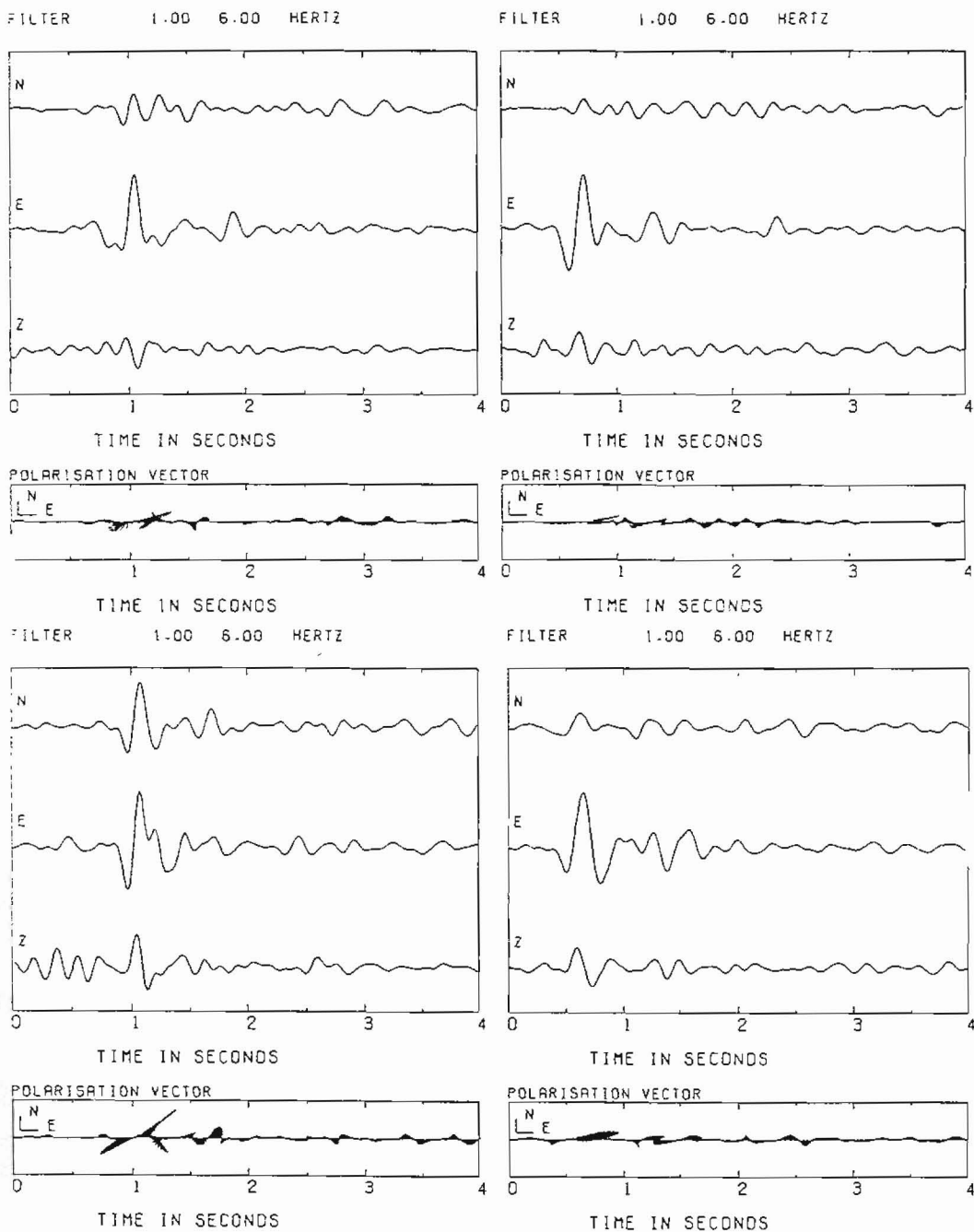


Fig.5. Corrected filtering traces of the aftershocks and corresponding polarisation vector versus time.

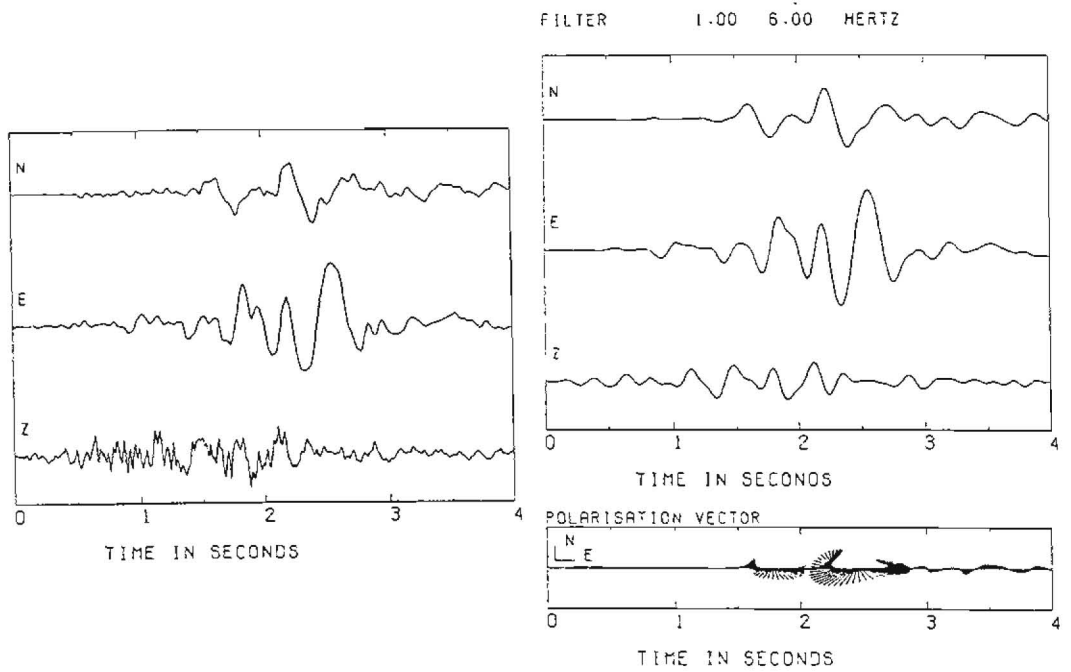


Fig.6. Traces of the main aftershock and their filtering. At the bottom the polarisation vector is plotted versus time.

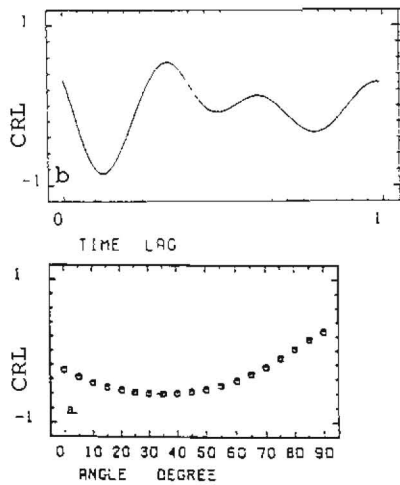


Fig.7. a. Cross-correlation variation versus azimuth and b. versus time.

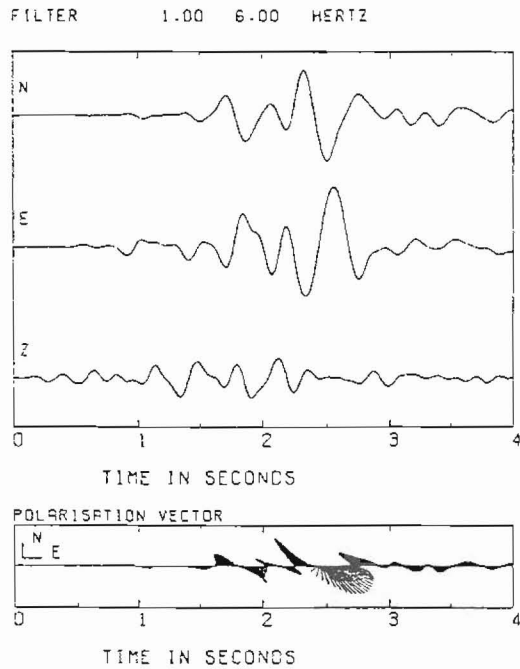


Fig.8. Corrected filtering traces of the main aftershock. At the bottom the polarisation vector is plotted versus time.

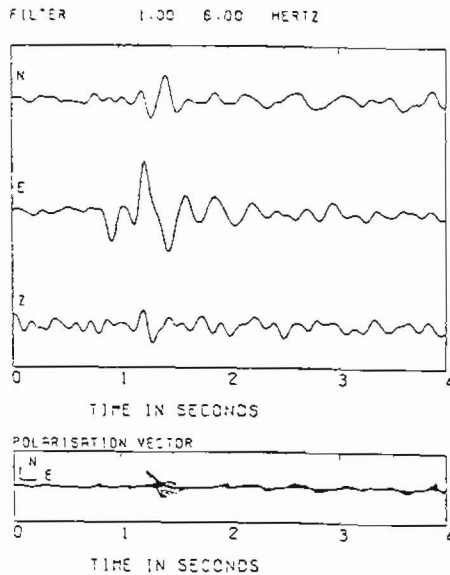


Fig.9. Corrected filtering trace and at the bottom the polarisation vector is plotted versus time.

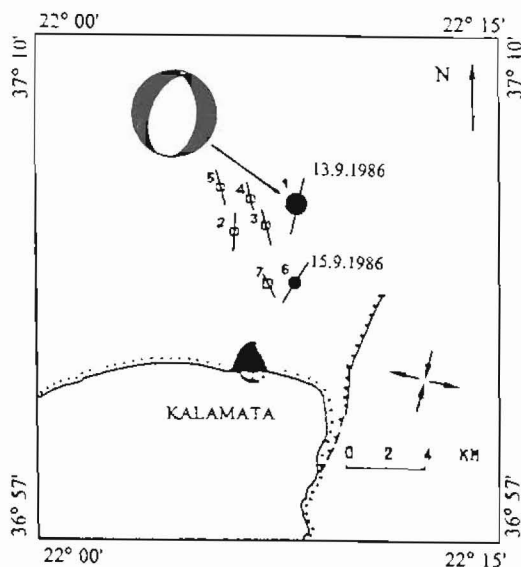


Fig.10. Map showing epicenters of the seven earthquakes listed in table 1. The lower hemisphere's focal mechanism of the main event is plotted and the heavy line is the observed surface rupture.

ACKNOWLEDGEMENTS

We are very grateful to P. Bernard for offering helpful comments and discussion and to the NOA, ITSAC for providing the accelerograph data used in this study.

REFERENCES

- Aki, K. and Richards, P., (1980). *Quantitative Seismology: Theory and Methods*, W.H. Freeman, San Francisco.
- Ando, M., Ishikawa, Y. and Yamazaki, F., (1983). Shear wave polarisation anisotropy in the upper mantle beneath Honshu, Japan, *J. Geophys. Res.*, 88, 5850-5864.
- Booth, D.C. and Crampin, S., (1985). Shear wave polarisations on a curved wavefront at an isotropic free-surface, *Geophys. J. R. Astr. Soc.* 83, 31-45.
- Booth, D.C., Crampin, S., Evans, R. and Robererts, G., (1985). Shear-wave polarisations near the North Anatolian Fault - I. Evidence for anisotropy-induced shear-wave splitting. *Geophys. J. R. astr. Soc.*, 83, 61-73.
- Bernard, P. and Zollo, A., (1989). Inversion of near source S polarisation for parameters of double couple point sources, *Bull. Seism. Soc Am.* 79, 1779-1809.
- Bernard, P. and Zollo, A., (1990). Stress field in the upper crust as revealed by anisotropy: some new results and questions,

- XXII General Assembly, ESC, Barcelona, 1990.
- 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., (1985). Evaluation of anisotropy by shear wave splitting. *Geophysics*, 50, 159-170.
- Crampin, S., (1987). The basis for earthquake prediction. *Geophys. J. R. astr. Soc.*, 91, 331-347.
- Iannaccone, G. and Deschamps, A., (1989). Evidence of shear-wave anisotropy in the upper crust of central Italy. *B.S.S.A*, 79, 1905-1912.
- Lyon-Caen, H., Armijo, R., Dracopoulos, J., Baskoutas, J., Delibasis, N., Gaulon, R., Kouskouna, V., Latoussakis, J., Makropoulos, K., Papadimitriou, P., Papanastasiou, D. and Pedotti, G., (1988). The 1986 Kalamata (South Peloponnesus) earthquake: detailed study of a normal fault, evidences for East-West extension in the Hellenic Arc, *J. Geophys. Res.*, 93, 14967 - 15000.
- Papadimitriou, P., (1988). Etude de la structure du manteau superieur de l'Europe et modelisation des ondes de volume engendrees par des seismes egeens, Doctorat de l'Universite Paris VII.
- Papazachos, B., Kiratzi, A., Karakostas, B., Panagiotopoulos, D., Scordilis, E. and Mountrakis, D., (1988). Surface fault traces, fault plane solution and spatial distribution of the aftershocks of the September 13, 1986 earthquake of Kalamata (southern Greece), *Pure Appl. Geophys.*, 126, 55-68.
- Zollo, A. and Bernard, P., (1989). S-waves polarisation inversion of the 15 October 1979, 23:19, Imperial Valley aftershock: evidence for anisotropy and a simple source mechanism.