Πρακτικά	4ου Συνέδριου		Μάϊος 1988
Δελτ. Ελλην. Γεωλ. Εταιρ.	Τομ. XXIII/3	σελ. 349-363	Αθήνα 1989
Bull. Geol. Soc. Greece	Vol.	pag.	Athens

TELESEISMIC P-WAVE SPECTRA FOR THE KALAMATA EARTHQUAKE OF SEPTEMBER 13, 1986

G. STAVRAKAKIS, J. DRAKOPOULOS, D. PAPANASTASSIOU, G. DRAKATOS, J. LATOUSSAKIS *

ABSTRACT

Teleseismic P-wave spectra, interpreted in terms of the well known Brune's model, are used to estimate the seismic source parameters, such as seismic moment M_o, source dimension r, fault length L, average displacement on the fault plane <u>, stress drop <Δσ>, radiated energy E_s, and apparent stress n<σ> for the Kalamata (southern Greece) earthquake of September 13, 1986.

The striking feature of the obtained source parameters is the low stress drop value by using Brune's model. Madariaga's model gives higher value. The other parameters are in agreement with those obtained by other researchers on the basis of different methodologies and field observations.

ΣΥΝΟΨΗ

Στην εργασία αυτή υπολογίζονται τα φάσματα των P-κυμάτων μεγάλης περιόδου του σεισμού της Καλαμάτας (13 Σεπτεμβρίου 1986) που έχουν καταγραφεί σε τηλεμετρικές αποστάσεις. Θεωρώντας το κυκλικό μοντέλο διάρρηξης, όπως έχει προταθεί από τον BRUNE, υπολογίστηκαν οι παράμετροι της σεισμικής πηγής, όπως η σεισμική ροπή, το μήκος διάρρηξης, η μέση μετατόπιση στο επίπεδο του ρήγματος, η πρώση τάσης, η σεισμική ενέργεια που ακτινοβολείται υπό μορφή σεισμικών κυμάτων και η φαινόμενη πτώση τάσης.

Το κύριο χαρακτηριστικό γνώρισμα των παραμέτρων της σεισμικής εστίας του σεισμού της Καλαμάτας, όπως υπολογίστηκαν με το φασματικό μοντέλο του BRUNE, είναι η χαμηλή πτώση τάσης στο επίπεδο του ρήγματος, περίπου 5 bars.

Γ. ΣΤΑΥΡΑΚΑΚΗΣ, Ι. ΔΡΑΚΟΠΟΥΛΟΣ, Δ. ΠΑΠΑΝΑΣΤΑΣΙΟΥ, Γ. ΔΡΑΚΑΤΟΣ, Ι. ΛΑΤΟΥΣΑΚΗΣ - Φάσματα P - κυμάτων από τηλεμετρικές αποστάσεις, του σεισμού της Καλαμάτας της 13 Σεπτεμβρίου 1986.

* National Observatroy of Athens, Seismological Institute, P.O.Box 20048, 118 10 ATHENS

1. INTRODUCTION

The Kalamata earthquake of magnitude M_s=6.0 occured on September 13, 1986, in the southwestern part of the Hellenic Arc, about 10 km north of the city of Kalamata.

The mainshock was followed by one large aftershock of local magnitude M_L=4.9 (on September 15) and by a large number of smaller aftershocks. Figure 1 shows the epicentral location of about 500 well located aftershocks of magnitude M_L >1.8 which have been recorded by a portable seismic network installed by the Seismological Institute of the National Observatory of Athens in collaboration with the Department of Geophysics of University of Athens and the Institute of the Physics of the Earth (Paris).

The Kalamata earthquake has been interpreted as a normal event (LYON-CAEN et al., 1987) along a fault plane oriented about 30°N and dipping westward at about 45°. DELIBASIS et al., (1988) based on P-waves first motions as reported by WWSSN-stations as well as on short period recording from the National Network of Greece, suggest also normal faulting along a plane striking N173°E and dipping 50°SW.

The main purpose of this study is to determine the seismic source parameters such as, the seismic moment, the source dimension, the fault length, the stress drop, the radiated energy and the apparent stress, by using the far-field displacement seismic source model proposed by BRUNE (1970, 1971). For this purpose, long-period P-waveforms recorded at teleseismic distances by WWSSN instruments have been analysed to obtain the spectrum at each seismological station, considered in the analysis.

By using Brune's model a stress drop of about 5 bars is obtained which is relatively low according to the constant stress drop model for interplate earthquakes (∓30 bars) proposed by KANAMORI and ANDERSON (1975).

On the contrary, by applying Madariaga's model (MADARIAGA, 1976) higher stress drop, of about a factor 3, is obtained.

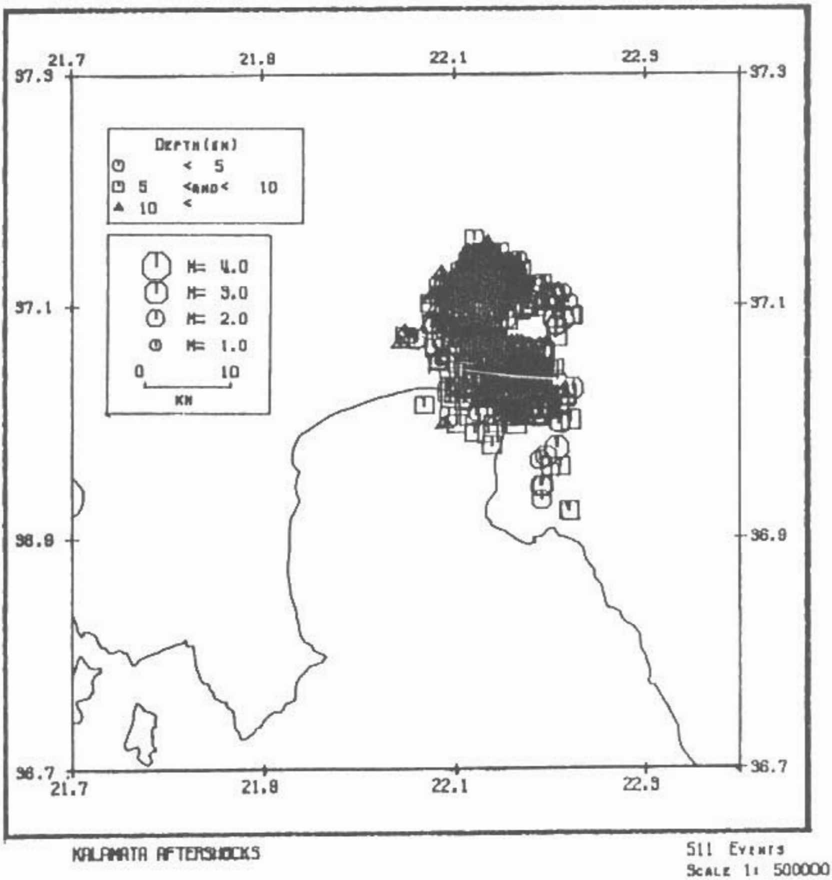
Finally, an attempt is also made to explain the low stress drop value with respect to partial stress drop and to low effective stress models.

2. DETERMINATION AND INTERPRETATION OF BODY-WAVE SPECTRA

BRUNE (1970, 1971) proposed a relatively simple model of faulting for calculating some of the source parameters (seismic moment, source dimension, stress drop, average displacement). One of the important consequences of the model is that the spectrum of the far-field displacement should be exhibit a long-period spectral level Ω_o, which is proportional to the seismic moment, and a corner frequency f_o, which is proportional to the reciprocical of the radius of a circular fault area.

According to this model and for the case of complete effective stress drop, the radius r(S) of a circular source area is given by

$$r(S)=2.34\beta/2\pi f_o(S) \quad (1)$$



Σχ.1.: Κατανομή 500 μετασεισμών του κύριου σεισμού της Καλαμάτας (13 Σεπτ., 1986)

Fig.1: Distribution of 500 aftershocks of the Kalamata earthquake of September 13, 1986.

where β is the shear-wave velocity (3.5 km/sec), and $f_o(S)$ is the corner frequency of the S-wave spectrum. By using the same spectrum, the seismic moment is

$$M_o = 4\pi\rho\beta^3\Omega_o(S)G(\Delta)/R\vartheta\varphi(S) \qquad (2)$$

where:

Ω_o is the long-period spectral level of the S wave ρ is the density (=2.7 gr/cm^3)
$G(\Delta)$ is the geometrical spreading factor in a layered, spherical earth
$R\vartheta\varphi(S)$ is the radiation pattern for the S wave

HANKS and WYSS (1972) extented the model in an attempt to relate the source dimension to a theoretical P-wave spectrum and proposed corresponding relationships, for the radius of the circular source area,

$$r(P) = 2.34\alpha/2\pi f_o(P) \qquad (3)$$

where α is the P-wave velocity (6≃km/sec), $f_o(P)$ is the corner frequency of the P-wave spectrum, and

$$M_o(P) = 4\pi\rho\alpha^3\Omega_o(P)G(\Delta)k/R_{\vartheta\varphi}(P) \qquad (4)$$

for the seismic moment, where:

$\Omega_o(P)$ is the long-period spectral level of the P-wave
ρ is the density
$G(\Delta)$ is the geometrical spreading factor, and
$R_{\vartheta\varphi}(P)$, is the radiation pattern for the P-wave

The geometrical spreading factor is given by

$$G(\Delta) = R(\cos i_o \sin\Delta/\cos i_h)^{1/2} \qquad (5)$$

where i_o, i_h are the incidence and take-off angles, respectively, Δ is the epicentral distance in degrees, and R is the radius (R=6371 km) of the Earth.
The stress drop $\Delta\sigma$ is given by

$$\Delta\sigma = 7M_o/16r^3 \qquad (6)$$

According to HANKS and WYSS (1972), the radiated energy is given by

$$E_s(P,S) = I(P,S)\rho(\alpha,\beta)R^2(2\pi)^2\Omega_o^{\,2}f_o^{\,3}(P,S).(1/3+1/(2^{\nu-3}))1/2R\vartheta\varphi^{2-}(P,S) \qquad (7)$$

with $\nu>1.5$, and I(P,S) is the spatial integration of the P-, S-wave radiation pattern over the source.

The choice of P or S and α or β depends on whether Es is to determined from the P or S phase.

In the present study only P-waves have been used and the spatial integration of the P-wave radiation pattern about the source is taken equal to $I(P)=4\pi/15$ (WU, 1966).

Knowing the radiated energy, the apparent stress $\eta\langle\sigma\rangle$ is then given by

$$\eta\langle\sigma\rangle = \mu(E_\sigma/M_o) \tag{8}$$

where η is the seismic efficiency, $\langle\sigma\rangle=(\sigma_1+\sigma_2)/2$ (σ_1 is the initaial stress, σ_2 is the final stress), and μ is the shear modulus.

Finally, the average displacement on the fault plane is given by (Brune, 1970)

$$\langle u\rangle = \langle M_o(P)\rangle/\pi\mu r^{2}(P) \tag{9}$$

where $\langle M_o(P)\rangle$ is the average of the seismic moments for the stations considered in the analysis.

3. DATA ANALYSIS

Long-period seismograms from WWSSN stations in different epicentral distances have been selected to obtain the far-field shear displacement spectra. For each station, the epicentral distance D (in degree), the epicentral azimuth (AZME), the back-azimuth (AZMS), the emergent angle i_o, the incidence angle i_h, and the geometrical spreading factor $G(\Delta)$ have been determined. All these parameters are summarized in Table 1.

The available seismograms were photographically enlarged and manually digitized with a sampling frequency of 3 Hz. The time windows are choosen so that to avoid contamination of the P-phase with other phases.

However, due to shallow focus all analysed portions include reflected phases and no attempt has been made to introduce correction for these phases.

The displacement spectra have been computed by using the FFT procedure. The obtained uncorrected spectra are shown in Figure 2. In order to estimate the long-period constant level $\Omega_o(P)$, all spectra presented here have been corrected for instrumental response and for an average radiation factor 0.51 for P-waves (FLETCHER, 1980).

One critical point is the correction of spectra for the attenuation along the propagation path. Some researchers (KULHANEK and MAYER, 1979; THATCHER, 1972; HANKS and WYSS, 1972; KULHANEK et al., 1983) have calculated spectra corrected for anelastic attenuation by using curves from JULIAN and ANDERSON (1968) or average Q-values according to ANDERSON et al.(1965) and IBRAHIM (1971), whereas others MODIANO and HATZFIELD (1982), STAVRAKAKIS et al., (1988) preffered to measure the spectra parameters on spectra uncorrected for attenuation.

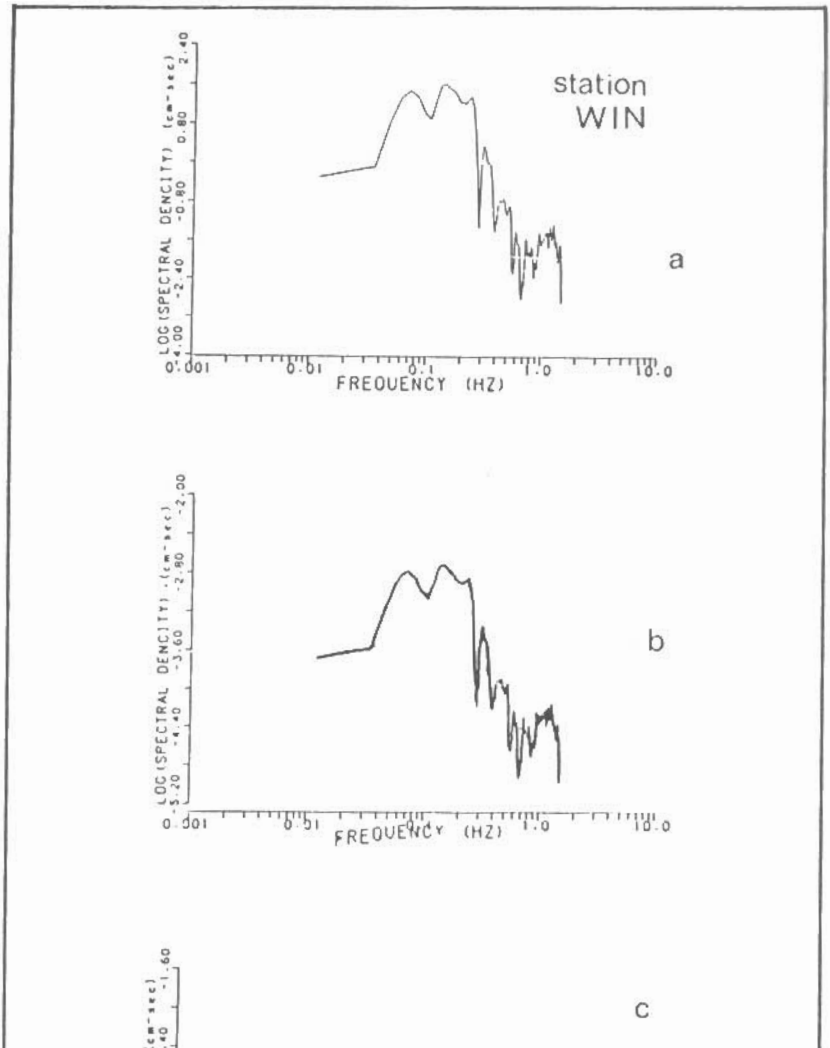
This is due to the fact that Q varies with depth and possibly with frequency (AKI and CHOUET, 1975; TSUIJRA, 1978; AKI, 1980). In the present study, the attenuation along the propagation path

TABLE I: Ray Parameters for the Kalamata earthquake of Sept. 13, 1986.

STATION CODE	D (o)	AZME (o)	AZMS (o)	I_o	I_r	G(Δ) km
WIN	59.80	185.55	4.59	23.9	28.9	8706
SLR	63.03	173.85	354.55	22.9	27.7	9072
WES	68.30	307.48	59.05	21.4	25.9	9642
GRM	70.45	176.12	356.30	20.8	25.1	9876
KOD	56.32	103.61	307.96	24.9	30.2	8326

TABLE II: Spectral Characteristics of the Kalamata earthquake of Sep. 13, 1986.

STATION CODE	f_o(P) (Hz)	Ω_o(P) cm-sec	M_o(P) $x10^{25}$dyne-cm	r(P) (km)	E_s $x10^{19}$ergs
WIN	0.20	0.0015	1.88	12.66	0.4
SLR	0.17	0.0028	2.95	14.90	0.9
WES	0.17	0.0012	1.34	14.90	0.9
GRM	0.20	0.0028	3.28	16.27	1.7
KOD	0.19	0.0016	1.52	13.33	0.4



Σχ.2.: (a) Αδιόρθωτα, (b) Διορθωμένα ως προς την απόκριση του οργάνου, (c) Διορθωμένα ως προς την ανελαστική απόσβεση, φάσματα του σεισμού της Καλαμάτας (13 Σεπτ., 1986).

Fig.2: (a) Uncorrected, (b) Corrected for the instrumental response, (c) Corrected for the anelastic attenuation, spectra of the Kalamata earthquake of September 13, 1986.

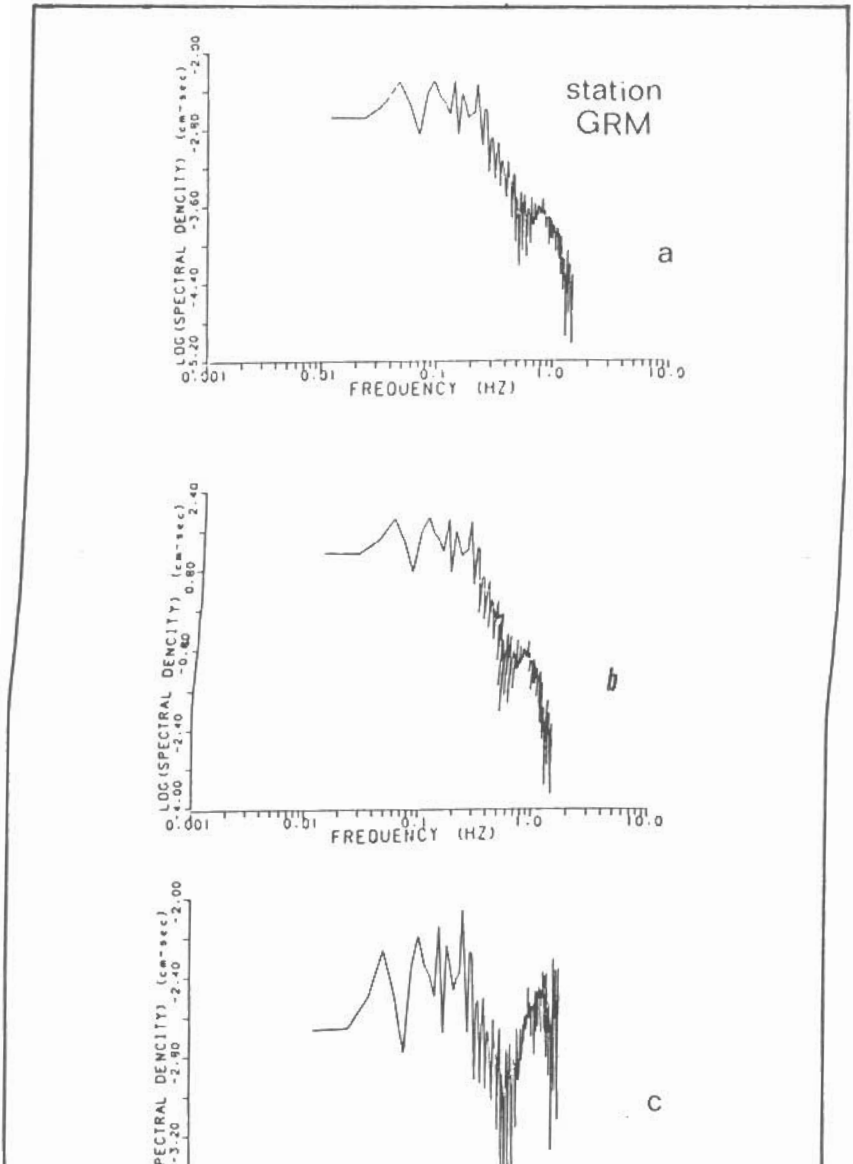

station
GRM
a
LOG (SPECTRAL DENCITY) (cm-sec)
FREQUENCY (HZ)
0.001
0.01
0.1
1.0
10.0
b
LOG (SPECTRAL DENCITY) (cm-sec)
FREQUENCY (HZ)
0.001
0.01
0.1
1.0
10.0
c
LOG (SPECTRAL DENCITY) (cm-sec)
FREQUENCY (HZ)
0.001
0.01
0.1
1.0
10.0

Fig.2.(cont.)

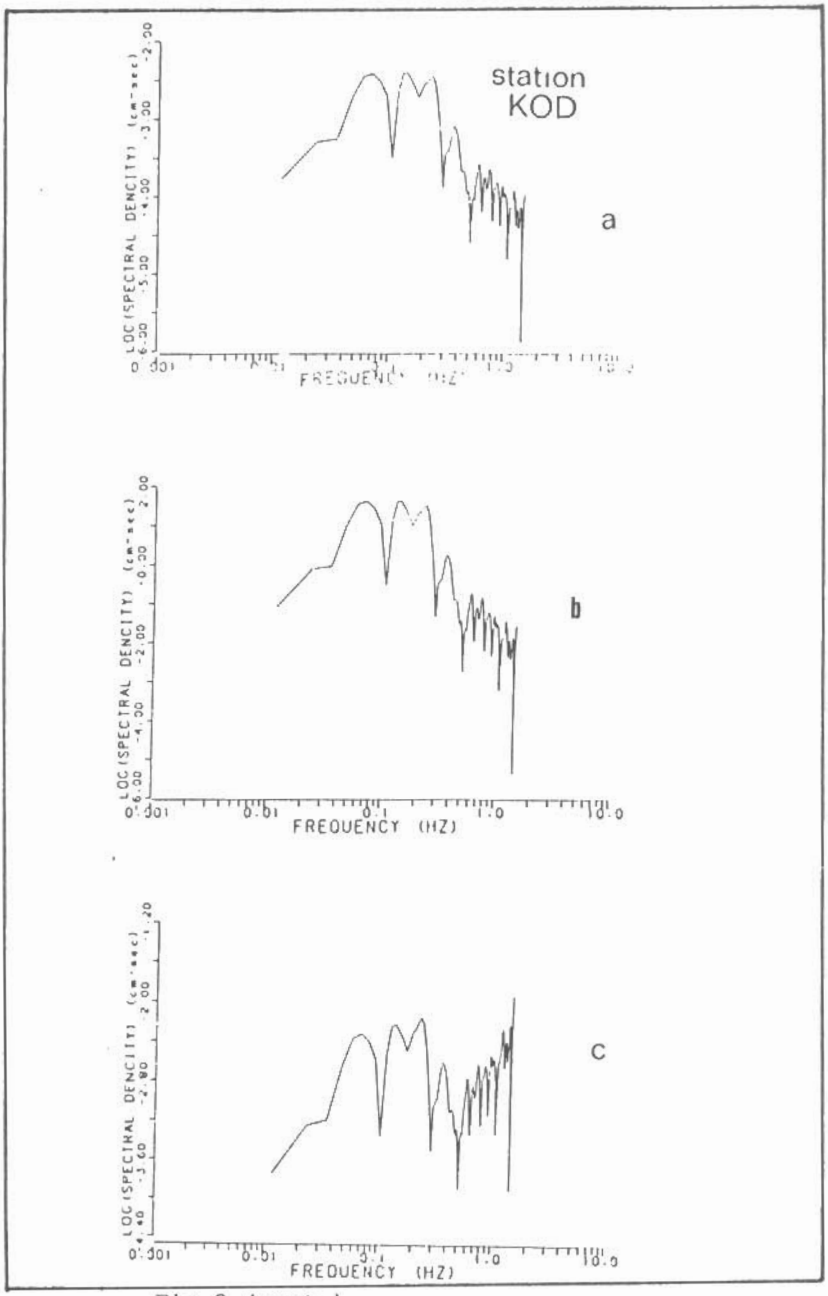


Fig.2.(cont.)

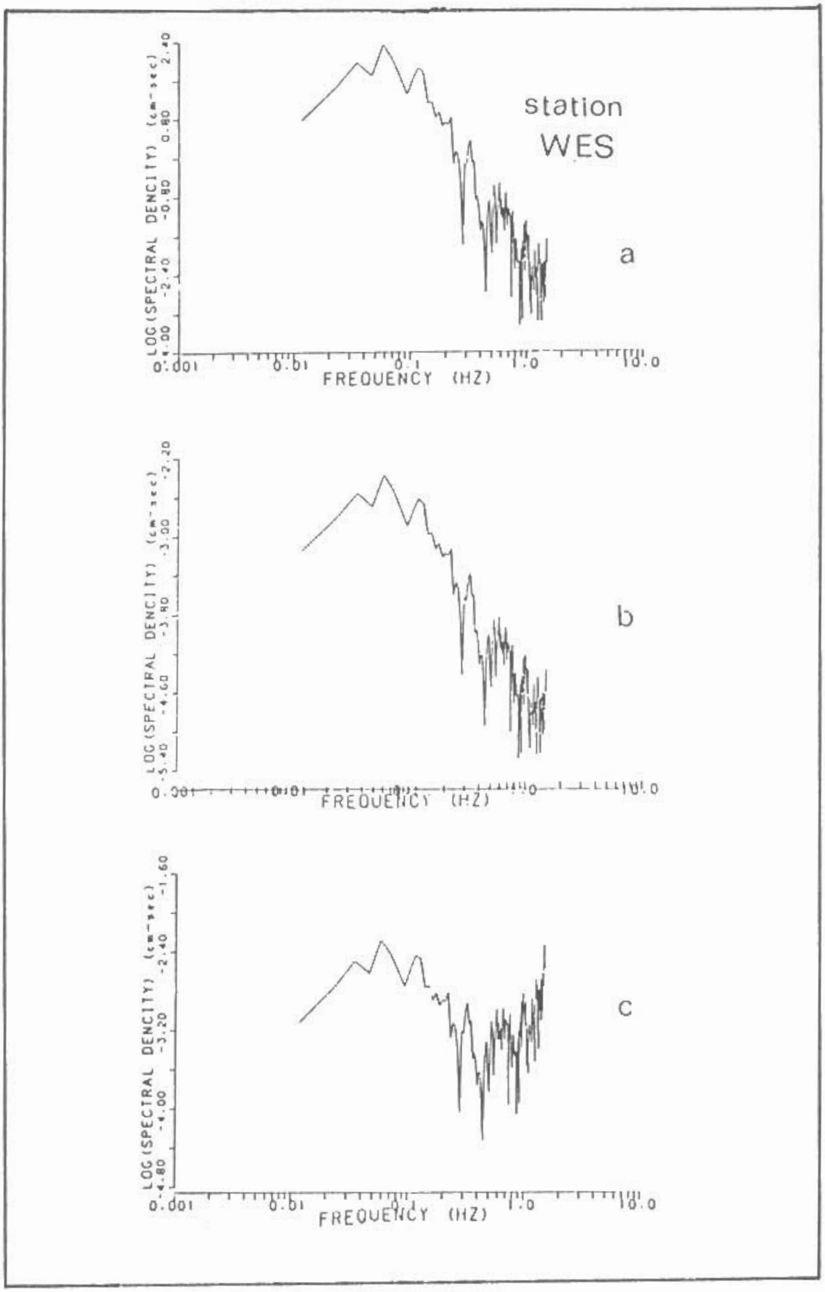

station
WES
a
b
c
LOG(SPECTRAL DENCITY) (cm-sec)
FREQUENCY (HZ)
0.001
0.01
0.1
1.0
10.0

Fig.2.(cont.)

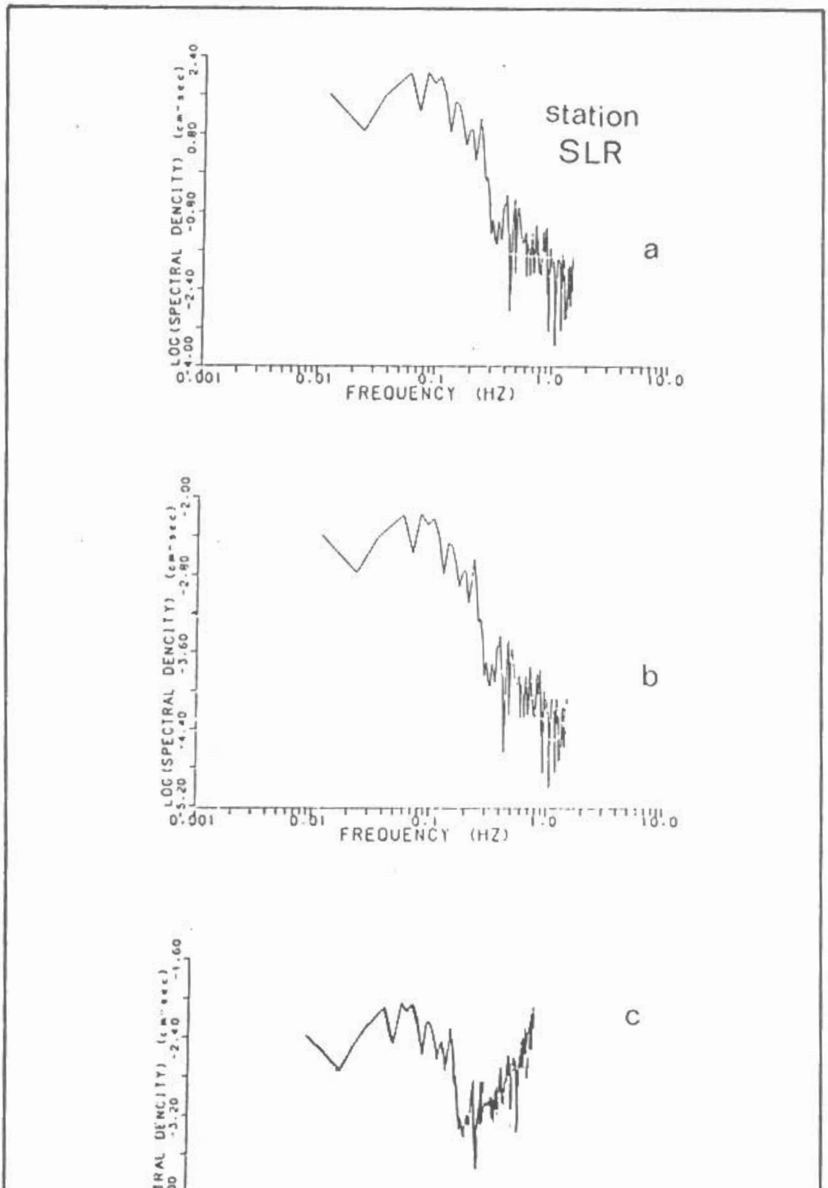

station
SLR
a
LOG(SPECTRAL DENCITY) (cm-sec)
FREQUENCY (HZ)
0.001
0.01
0.1
1.0
10.0
b
c

Fig.2.(cont.)

is taken into account by correcting the spectra for Q according to FUTTERMAN (1962).

The corrected spectra for the instrumental response and for the attenuation factor Q are also shown in figure 2. Comparing the corrected spectra, it is evident that the spectral corner frequency f_o and the long-period spectral level Ω_o does not change very much.

Taking a density $\rho=3.0$ gr/cm^3, a P-wave velocity $\alpha=6.8$ km/sec, and a free-surface reflection factor $k=0.5$, and by using the previous mentioned equations, the seismic source parameters for Kalamata earthquake of September 13, 1986 are determined. Table 2 summarizes the obtained results.

The mean seismic moment is $<M_o>=2.2\times10^{25}$ dyn.cm, and the mean source dimension $<r>=14.4$ km. By using these values, the stress drop $\Delta\sigma$ and the average displacement $<u>$ on the fault plane are obtained

$\Delta\sigma \approx 4.5$ bars

$<u>\approx 11$ cm.

In summary, the dynamic source parameters of the Kalamata earthquake of September 13, 1986 are the following:

$<L> = 28.8$ km

$<M_o>=2.2 \times 10^{25}$ dyne.cm

$<\Delta\sigma>\approx 4.5$ bars

$<u> \approx 11$ cm

4. DISCUSSION AND CONCLUSIONS

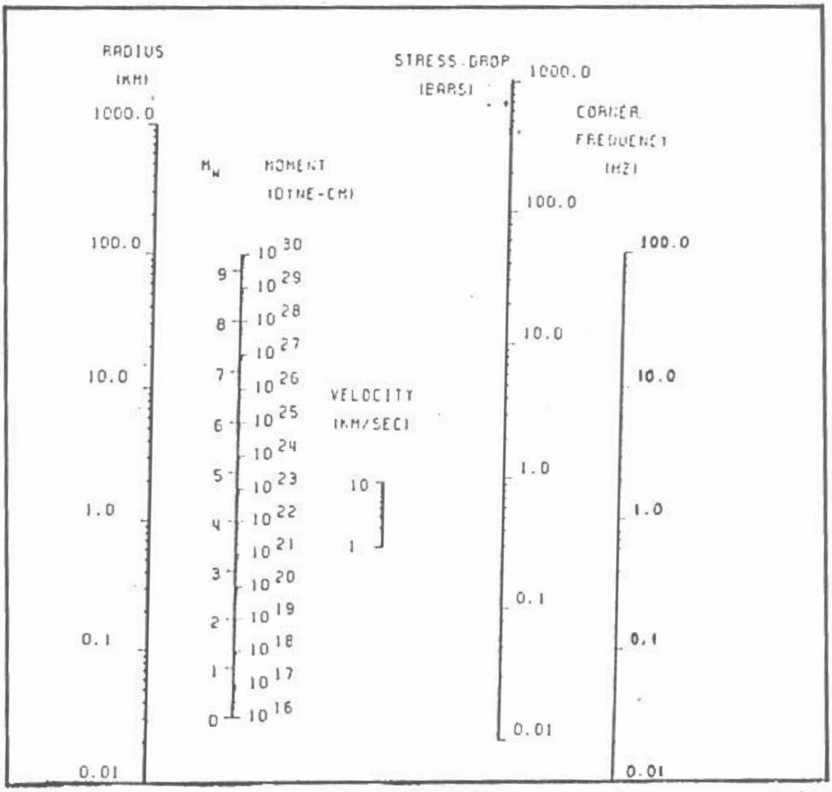
In the present study, teleseismic long-period waves are processed to obtain the far-field displacement spectra of the Kalamata earthquake of September 13, 1986. By using Brune's model, the dynamic source parameters (fault length, seismic moment, stress drop, average displacement on the fault plane)are also determined.

The obtained spectra have been corrected for the instrument response and for the anelastic attenuation along the propagation path.

Although the effect of propagation path attenuation correctly is complicated, the spectral corner frequency and the long-period spectral level does not change very much. This is due to the fact that the corner frequency is less than 0.2 Hz. However, for higher frequencies, the spectral shape changes (see fig. 2).

The estimated source parameters are in agreement with those proposed by other researchers. LYON - CAEN et al; (1987) based on about 500 precisely located aftershocks suggested that the aftershock area extended about 8-15 km long north-southward and 10 km wide with a marked increase in the depth of the events from east to west. The same authors obtained a seismic moment of 6-8x 10^{24} dyne.cm and a displacement of about 6 to 18 cm which is in agreement with the observed displacement on the fault.

In order to check the validity of the obtained source parameters, we used a nomograph to calculate source radius and stress drop from corner frequency, shear velocity, and seismic moment as proposed by MAHDYIAR (1987). Figure 3 illustrates the nomograph. For a corner frequency $f_o=0.186$ Hz and for a shear



Σχ.3.: Νομόγραμμα υπολογισμού σεισμικής ακτίνας και πτώση τάσης από τη γωνία κορυφής, ταχύτητα των P-κυμάτων και από τη σεισμική ροπή (MAHDYIAR, 1987).

Fig.3.: A nomograph to calculate source radius and stress drop from corner frequency, shear velocity, and seismic moment (after MAHDYIAR, 1987).

velocity V_s=3.5 km/sec, a straight line passing through these values to source radius radius´r=15 km, which is in excellent agreement with the value of 14.4 km obtained in this study. Then, a line passing through this r value and M_o=2.2x10^{25} dyne.cm to stress drop scale reads $\Delta\sigma$=0.5 bars. This value, however is very low with respect to our estimates.

It should be emphsasized, that the striking feature of the determined seismic source parameters is the low stress drop value for the Kalamata earthquake by using Brune's model.

BRUNE et al., (1986) used two different models to explain the low stress drop earthquakes. First, "partial stress drop" earthquakes might occur when the fault locks itself soon after the rupture passes so that the average slip over the fault cannot reach a value corresponding to the average dynamic stress drop over the whole fault. It might also occur when the stress release is not uniform and coherent over the whole fault plane, but rather is more like a series of multiple events with parts of the fault remaining unbroken.

The other dynamic model for explaining low stress drop earthquakes is the "low effective stress model". According to this, the effective stress available for accelerating the fault is at all times very low.

KIRATZI et al., (1985) concluded that the earthquakes occurred in the area of Greece are characterized by low stress drop values. The same authors explained the low stress earthquakes in Greece on the basis of the frequency content as it reflects in body-wave magnitude. ARCHAMBEAU (1978) proposed that the ratio M_s/m_b may indicate the stress level at the source. For the area of Greece, KIRATZI and PAPAZACHOS (1984) found that for a given M_s the m_b is considerably smaller than that of other regions.

However, the m_b for the Kalamata earthquake was 6.0 (10 obs) and M_s=5.8 (18 obs) according to PDE.

The main question, however is whether the obtained low stress value for the Kalamata earthquake is source model dependend. If the source radious is calculated according to the Madariaga's model

$$r(P)=0.32\beta/f(P) \text{ with } \beta=3.33 \text{ km/sec}$$
$$=0.32\times3.33/0.186=5.7 \text{ km}$$

a value of 5.7 km is obtained. By using this value, a stress drop of about 52 bars is obtained.

Therefore, the stress drop value is strongly source model depended and much more data are needed to explain whether the Kalamata earthquake was in reality a slow earthquake.

REFERENCES

ANDERSON D.L.,BEN-BENAHEM A.,ARCHAMBEAU C.B., 1965. Attenuation of seismic energy in the upper mantle, J. Geophys. Res., 70, 1441-1448.

AKI K., CHOUET B., 1975. Origin of coda waves: source, attenuation and scattering effects, J. Geophys. Res., 80, 3322-3342.

AKI K., 1980. Attenuation of shear-waves in the lithosphere for frequencies from 0.05 to 25 Hz. Phys. Earth Planet. Interiors 21, 50 - 60.

ARCHAMBEAU C., 1978. Estimation of non-hydrostatic stress in the earth by seismic methods: Lithospheric stress levels along Pasific and Nazca Plate subduction zones. U.S. Geol. Surv. Open-File Rept. 78-943, 47-138.

BRUNE J. N., 1970. Tectonic stress and spectra of seismic *shear waves, J. Geophys. Res.*, 75, 4997-5009.

BRUNE J. N., 1971. Correction, J. Geophys. Res., 76, 5002.

BRUNE J. N., FLETCHER J., VERNON F., HAAR L., HANKS T., and BERGER J., 1985. Low stress-drop earthquakes in the light of new data from the ANZA, california telemetered difital array. Maurice Ewing Series, Vol. 6, Am. Geophys. Union, Geophysics Monograph 37, Washington, DC, pp. 237-245.
DELIBASIS N., DRAKOPOULOS J., STAVRAKAKIS G., 1987. The Kalamata (s.Greece) earthquake of 13 September 1986, Ann. Geophysicae, 5B, 731-734.
FLETCHER J. B., 1980. Spectra from high-dynamic range digital recordings of Oroville, California aftershocks and their source parameters, Bull. Seism. cc. Am. 70, 735-755.
FUTTERMAN. W. I., 1962. Dispersive body waves, J. Geophys. Res., 67, 5279 - 5291.
HANKS T. C., THATCHER W., 1972. A graphical representation of seismic source parameters. J. Geophys. Res. 77, 4393-4405.
HANKS T. C., WYSS M., 1972. The use of body-wave spectra in the determination of seismic-source parameters, Bull. Seism. Soc. Am. 62, 561-589.
IBRAHIM A-B, K., 1971. The amplitude ratio PcP/P and the core-mantle boundary, Pure Appl. Geophys., 91, 114-133.
JULIAN B. R., ANDERSON D. L., 1968. Travel times, apparent velocities, and amplitudes of body waves, Bull. Seism. Soc. Am. 58, 339 - 366.
KANAMORI H., ANDERSON D. L., 1975. Theoretical basis of some empirical relations in seismology, Bull Seism. Soc. Am. 65, 1073 - 1095.
KEILIS-BOROK V. I., 1960. Investigation of the mechanism of earthquakes, Sov. Res. Geophys. (english transl.) 4, 29.
KULHANEK O., MEYER K., 1979. Source parameters of the Volvi-Langadhas earthquake of June 20, 1978 deduced from body-wave spectra at station Uppsala and Kituna, Bull. Seism. Soc. Am. 68, 1289 - 1294.
KULHANEK O., ECK T. V., JOHN N., MEYER K., WAHLSTROM R., 1983. Spectra of the earthquake sequence February-March, 1981, in south-central Sweden, Tectonophysics, 93, 337 - 350.
KIRATZI A. A. and PAPAZACHOS B.C., 1984. Magnitude scales for earthquakes in Greece, Bull. Seism. Soc. Am., 74, 969-985.
KIRATZI A. A., KARAKAISIS, G.F., PAPADIMITRIOU E.E., and PAPAZACHOS B.C., 1985. Seismic source-parameter relations for earthquakes in Greece, Pageoph, 123, 27-41.
LYON-CAEN H., DRAKOPOULOS J., ARMIJO R., BASKOUTAS J.,DELIBASIS N., GAULON R., KOUSKOUNA V., LATOUSSAKIS J., MAKROPOULOS K., PAPASTAMATIOU P., PAPANASTASSIOU D., PEDOTTI G., 1987. The September 13, 1986 Kalamata (Peloponnesus) earthquake, EUG, Abstracts, XII General Assembly, 9-14 April 1987, Strasburg.
MADARIAGA R., 1976. Dynamics of an expanding circular fault, Bull. Seism. Soc. Am. 66, 639 - 666.
MAHDYIAR M., 1987. A monograph to calculate source radius and stress drop from corner frequency, shear velocity, and seismic moment, Bull. Seism. Soc. Am. 77, 264-265.
MODIANO T., HATZFELD D., 1982. Experimental study of the spectral content for shallow earthquakes, Bull. Seism. Soc. Am. 72, 1739 - 1758.
STAVRAKAKIS G., DRAKOPOULOS J., LATOUSSAKIS J., PAPANASTASSIOU D., and G. DRAKATOS (1987). Spectral characteristics of the September 13, 1986 Kalamata (southern Greece) earthquake, Geophysical Journal (in press).
THATCHER W., 1972. Regional variations of seismic source parameters in the northern Baja California area, J. Geophys.Res., 77, 1549 - 1565.
TSJIURA M., 1978. Spectral analysis of the coda waves of local earthquakes, Bull. Seism. Soc. Am. 53, 1-48.
WU F. T., 1966. Lower limit of the total energy of earthquakes and partitioning of the energy among seismic waves, Ph.D. thesis, Ca[illegible]