DETERMINATION OF SOURCE PARAMETERS FROM SEISMIC SPECTRA IN CENTRAL GREECE

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A B S T R A C T

In the present study source parameters and their scaling relationships are estimated and compared from earthquakes of two areas in Central Greece, the Northern Sporades and the Pagassitikos gulf. The events, divided into two groups, were recorded by the digital local network VOLNET, and had small magnitudes, the second group comprising of aftershocks of the M_S=5.7 April 30, 1985 main shock. The assessed values of source parameters (seismic moment, source radius, stress drop and fault slip) and the local magnitudes were compared for the two data sets. The analysis showed that the use of seismic moment in relationships with the other source parameters has a better correlation than the magnitude. The relationship between seismic moment and magnitude for the small Pagassitikos aftershocks was found to be in good agreement with the assessed relationship for large earthquakes. The values of stress drop and fault slip were generally low, especially for the aftershocks, when compared to those of the same magnitude for the N.Sporades events. It is concluded that, if the source parameters of small earthquakes of a broader area are determined after a careful delineation of the seismic zones in a small scale, they are able to provide valuable information concerning the seismotectonic regime of the area and the behaviour of the fault zones in future large earthquakes.

ΦΑΣΜΑΤΙΚΗ ΑΝΑΛΥΣΗ ΣΕΙΣΜΩΝ ΤΗΣ ΚΕΝΤΡΙΚΗΣ ΕΛΛΑΔΑΣ ΓΙΑ ΤΟΝ ΠΡΟΣΔΙΟΡΙΣΜΟ ΤΩΝ ΠΑΡΑΜΕΤΡΩΝ ΤΗΣ ΣΕΙΣΜΙΚΗΣ ΠΗΓΗΣ

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Π Ε Ρ Ι Λ Η Ψ Η

Στη μελέτη αυτή υπολογίζονται οι φασματικές παράμετροι της σεισμικής πηγής και οι σχέσεις μεταξύ τους, και συγκρίνονται σεισμοί των Β.Σποράδων και του Παγασητικού κόλπου. Οι σεισμοί καταγράφηκαν από το τοπικό δίκτυο VOLNET, είχαν μικρά μεγέθη και χωρίστηκαν σε δύο ομάδες, ανάλογα με τη θέση του επικέντρου τους. Οι σεισμοί της δεύτερης ομάδας ήταν μετασεισμοί του κύριου σεισμού της 30 Απριλίου 1985 (M_S=5.7). Οι φασματικές παράμετροι που υπολογίστηκαν (σεισμική ροπή, πτώση τάσης, ακτίνα πηγής και ολίσθηση του ρήγματος) συγκρίθηκαν μεταξύ τους και με το τοπικό

μέγεθος. Από την ανάλυση προέκυψε ότι η χρήση της σεισμικής ροπής στις σχέσεις με τις υπόλοιπες παραμέτρους δίνει καλύτερη συσχέτιση από το μέγεθος. Η σχέση σεισμικής ροπής και μεγέθους για τους μετασεισμούς μικρού μεγέθους στον Παγασητικό συμφωνεί με τη σχέση για μεγάλους σειομούς που έχει ήδη βρεθεί. Οι τιμές της πτώσης τάσης και ολίσθησης ήταν γενικά μικρές, ιδίως αυτές των μετασεισμών, όταν συγκρίθηκαν με τις αντίστοιχες ίδιου μεγέθους σεισμών των Β.Σποράδων. Συμπεραίνεται ότι αν οι φασματικές παράμετροι μικρών σεισμών μίας ευρύτερης περιοχής προσδιοριστούν μετά από προσεκτικό χωρισμό των σεισμικών ζωνών σε μικρή κλίμακα, μπορούν να δώσουν πολύτιμες πληροφορίες για το σεισμοτεκτονικό καθεστώς της περιοχής και για τη συμπεριφορά των ρηξιγενών ζωνών σε μελλοντικούς μεγάλους σεισμούς.

INTRODUCTION

It is well known that in a tectonic regime the strain energy release that causes shallow seismicity is associated with movement along faults. The 'size' of these earthquakes is therefore controlled by the effective stress on the fault, the strength of the fault material and the dimensions of the dislocation producing the event. All the aforementioned can be assessed by spectral analysis of the records, from which the key parameters constant spectral amplitude, Ω_0, and corner frequency, f_c, can be obtained. The constant spectral amplitude is obtained from the displacement spectrum which, when plotted on a log-log plot, corresponds to lower frequencies and decays linearly with log frequency at higher frequencies, whilst f_c is defined by the intersection of the low period spectral level and the high frequency asymptote. The values of Ω_0 and f_c are used as input for the estimation of the source parameters, i.e. the seismic moment, M_0, the source radius, r, the stress drop, $\Delta\sigma$, and the fault slip, s, through worldwide accepted formulas.

The seismic moment, associated to long period spectral level, is widely used to measure the 'size' of an earthquake, and has helped to improve understanding the contribution of earthquakes to the tectonic slip. Although in the beginning Aki (1966), used surface waves to determine this parameter, much emphasis has since been placed on the easier-to-handle body waves (e.g. Brune, 1970), and the trend continued with the stress drop measurement of minor earthquakes. The latter method is followed in the present study. The source radius is estimated from f_c, whereas the stress drop produced by the event and the mean slip of the fault are determined from the assessed values of M_0 and r.

The present study, aiming at a more detailed description of the seismotectonic regime in the area of Northern Sporades - Volos - Almiros (Central Greece) seismic zone by determining the above mentioned source parameters, is motivated by the existence of high quality digital data recorded by the seismic network, VOLNET, during January 1983 - April 1985.

The above area is characterized by high seismicity and shallow earthquakes (figure 1). In the 20th century three major earthquakes with magnitudes over 6.4 (1954, 1957, 1980) occurred in the area, and caused major damage and death toll.

Seismotectonic studies suggest that the predominant stress field in the area is extensional in the direction N-S, with normal faults (Drakopoulos and Delibasis, 1982). More specifically, north of Almiros basin lies a highly faulted zone with main direction ENE, and 50 km length (Papazachos et al., 1983). It is believed that the Nea Ankhialos fault that was activated and caused the 1980 earthquake (M_s=6.4) belongs to the same zone.

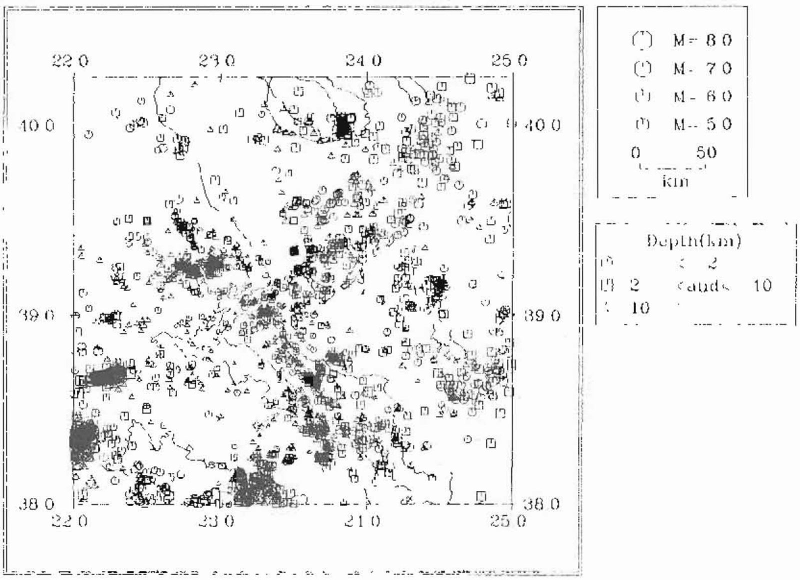

Fig.1. Map of epicentres for earthquakes with $M_s \geq 4.0$ of the studied area during the period 1900-1987 (Makropoulos et al., 1989).

Thus, as seen below, spectral analysis is performed to the records from earthquakes in the above mentioned area and the source parameters are determined in an attempt to contribute towards a better understanding of the general pattern of the area's stress regime. Furthermore, relationships among them are established and their significance is discussed.

DATA

The data used in this study were obtained from the regional seismic network, the so-called VOLos NETwork (VOLNET), the configuration of which is shown in figure 2, and cover the period January 1983 - April 1985. This network was installed by the University of Athens and the British Geological Survey in 1982.

It includes one central 3-component station in northern Evia, VSI, and 8 satellite stations, covering the Volos - Almiros - Atalanti area, radio-linked to the central station, and equipped with Willmore MKIII 1.5 sec period and 0.7 damping seismometers. The seismic channels and radio time are recorded analogue on magnetic tape at the central station VSI. For data reduction, the tapes are digitized for a time window around events at 50 samples per second, which limits the range of frequencies sampled faithfully to 0-25 Hz. This sampling frequency is quite adequate, since the 24 db/oct low pass filter of the seismometers has a corner frequency at 16 Hz.

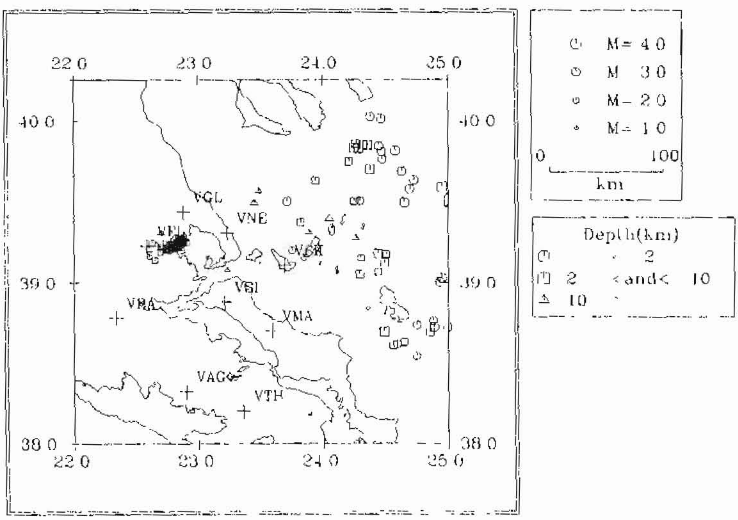

Fig.2. The seismological stations of VOLNET and the epiceutral distribution of the sample earthquakes.

P- and S-waves arrivals are measured to locate the events using the program HYPO71 (Lee and Lahr, 1975), and the velocity-depth model used follows Makris' results from seismic refraction surveys in Evia (Makris, 1977). Magnitudes analogous to M_L are determined by converting the ground velocity to displacement on an equivalent Wood-Anderson response (Lee and Lahr, 1975) and then following the procedure laid down by Richter (1958). The whole procedure is described in the VOLNET bulletins.

The events recorded during the period January 1983 - April 1985 were mostly shallow, with small magnitudes. In the area of Pagassitikos gulf two clusters are clearly defined, i.e. the western cluster, which is near the coast and Almiros town, and the eastern cluster, where the 1980 earthquake was located. Both clusters are characterized by shallow earthquakes (around 10 km depth). As far as the Northern Sporades seismicity is concerned, it is characterized by spatial dispersion.

In April 30 1985, VOLNET recorded a shallow (39.24°N, 22.82°E, depth of focus 14.9 km, M_s=5.7) earthquake, with a small number of foreshocks and hundreds of aftershocks. The sufficient azimuthal coverage of the network with regard to the epicentral area allowed the location parameters of the sequence to be accurately determined, with the epicentres of the aftershocks concentrated in the western cluster, near the town of Almiros.

The earthquakes studied here are separated into two groups, the first containing N.Sporades earthquakes and the second aftershocks of the 1985 earthquake. The selection criteria are the following:

I. First group
* epicentral locations in the vicinity of VOLNET
* excellent recording quality
* recorded by more than five stations
* low RMS values

II. Second group
* excellent recording quality
* recorded by at least three stations (including the central 3-component station)
* low RMS values

The final data sets for further spectral analysis processing and source parameters relationships contain 67 and 117 events for the two groups respectively. For many of the N.Sporades events the spectral analysis was performed by Condon (1985). The events of this group, located at the NE side of the network, had epicentral error values between 1.2-19.5 km.

METHODOLOGY AND ANALYSIS

The determination of the source parameters presumes a theoretical model of fault rupture, which will produce relationships between source parameters and spectra. The most applicable models are those of Brune (1970, 1971) and Madariaga (1976). The former assumes a constant stress at any point immediately, before and after the rupture. The latter considers that the effective stress (i.e. the difference between tectonic and frictional stress) on the fault at any time depends on the preceding movement on the fault. Both models provide a quantitative link between the fault and the seismic record and an indication of the physical processes occuring within a tectonic region.

Since P-wave analysis was carried out in this study, Madariaga's dynamic model of source dislocation was used for the inversion of seismic spectra to produce source parameters. This model considers particle velocity and stress separately from the slip velocity on the fault. By making the 'far field approximation' i.e. the epicentral distance R>>r, the source radius, the following relationships between the spectral parameters (Ω_0,f_c) and various source parameters (M_0,r,$\Delta\sigma$,s) can be deduced:

$$M_o = \frac{4\pi\rho\alpha^3 R\Omega_o}{2\sqrt{2R_{\Phi\Theta}}} \quad in\ Nm \tag{1}$$

$$r = \frac{0.32\beta}{f_c} \quad in\ m \tag{2}$$

$$\Delta_o = \frac{7}{16}\frac{M_o}{r^3} \quad in\ bars \tag{3}$$

$$s = \frac{M_o}{\pi r^2 \mu} \quad in\ mm \tag{4}$$

The seismic moment, M_0, calculated for each value of the low period spectral level, is obtained by the formula (1) and assumes that small earthquakes can be approximated by circular faults of radius r. The events of this study were found close to the VOLNET stations, and therefore no correction was thought necessary for anelastic attenuation. In this formula, since all the events are shallow, ρ, i.e. the crustal density, is taken equal to 2.7 gr/cm^3, α the specific value of the P-wave velocity for each VOLNET station and for each event is assigned according to the event's focal depth and P-wave travel time (from Makris, 1977), R is the hypocentral distance and $R_{\Phi\Theta}$ is the correction for the radiation pattern, which was taken here to be cylindrical, with an average value of 0.6.

Since the errors associated with the interpretation of Ω_0 and f_c on a log-log plot are lognormally distributed, for earthquakes with more than one interpreted values of the low period spectral level the seismic moment is taken as the logarithmic mean.

The source radius, r, is calculated directly from the P-wave corner frequency f_c, from equation (2) for P-waves, which assumes a rupture velocity 0.9β for propagation of the crack tip, where β=2/3α. Similar to the seismic moment, the mean source radius is taken as the logarithmic mean.

The mean stress drop, Δσ, is calculated from the logarithmic means of seismic moment and source radius by the formula (3) and the average displacement, s, of the fault, is taken from equation (4), where the rigidity modulus of the fault material $\mu=3*10^{10}$ Nm^{-2}. Errors are again carried forward by the uncertainty in moment and radius, similar to errors in stress drop.

The step-by-step procedure followed can be described as:

* Collect all the digital data for analysis.
* Locate the events (HYPO71) and select those for spectral analysis according to the selection scrutiny already described.
* Compute the 75% of the P-wave train to define the two time windows at each station (figure 3a), long enough for the FFT to adequately define the amplitude of all frequencies in the spectrum, but without contaminating it by S-wave arrivals. The position and length of the windows were

obtained using a series of relevant programs provided by the british Geological Survey (BGS). The window length was identical before and after the P-arrival. The first window was used to analyse the present noise levels and remove this effect from the spectrum obtained from the second window. Their length was chosen as 75% of the difference between the observed P-arrival time and the theoretical (if there is no observed value) S-wave arrival time from Makris' (1977) crustal model, as suggested by Main (1985), using the distance of each VOLNET station from the epicentre, so as to avoid any possible early S-wave energy.

* Obtain an FFT of the digital velocity seismogram record at each station for the signal and noise.
* Correct to displacement spectrum via the instrument response correction.

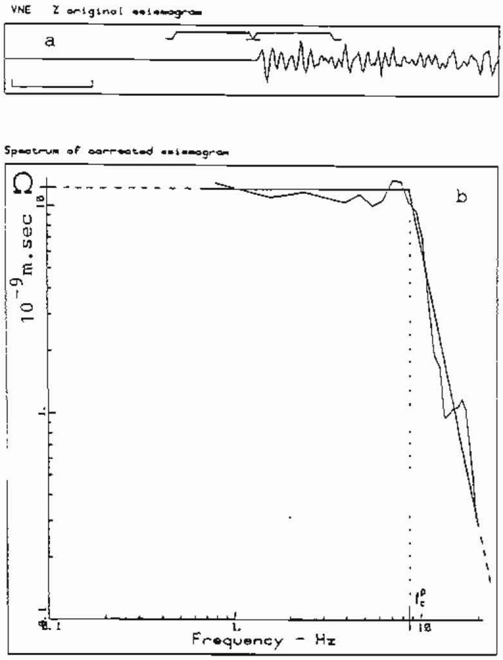

Fig.3. An example of spectral analysis of an earthquake: a. original digital velocity seismogram containing the preevent noise and the P-wave train and indicating the 75% window of noise and P-wave train b. log-log displacement spectrum of corrected seismogram (after noise correction and smoothing), indicating the spectral level estimation (y-axis, in 10^{-9} m*sec) and the corner frequency (x-axis, in Hz) (after Burton et al., 1991).

* Remove noise from signal and smooth to obtain a final spectrum. This procedure greatly assists the eye fit of two

straight lines for the Ω_0 and f_c measurement (figure 3b).

* Copy the event's magnitude, focal depth, and for each VOLNET station the hypocentral distance, R, and travel time, t.
* Fit by eye a theoretical Ω_0 to the Fourier Transform of the displacement spectrum and an f_c at the point where the spectral density begins to decline (figure 3b).
* Discard the events for which measurements of Ω_0 and f_c were impossible and list the remaining, from which the source parameters will be determined (54 and 102 events, tables 1 and 2 for each group of earthquakes respectively and figure 2).
* Convert to source parameters using the equations (1)-(4) (tables 1 and 2 for each group respectively, table 2 containing the events with ML>1.7).

The average reading errors in Ω_0 and f_c (figure 4d) were approximately ±40% and ±25% respectively (e.g. fig. 3). The calculation of seismic moment and source radius taking the logarithmic mean of their values from all stations, decreased the additional random uncertainties that would arise for these parameters from equations (1) and (2), and led to standard deviations of the order of about 10% of the log-value of the parameters. Additional errors due to the crustal density value used and to the uncertainties in focal depth, velocity model and radiation pattern assumption should also be taken into consideration. Consequently these errors influence the obtained values of stress drop and fault slip. Of course the source parameters are highly model dependent, and this could also effect how the errors are quantified.

In order to determine the relationship between seismic moment, source radius, etc. and local magnitude, the various parameters were plotted on log-log scale (figures 4-9).

RESULTS AND DISCUSSION

The earthquakes analysed in the present study are all small events, with local magnitudes ranging between 1.7-3.7 and 1.1-2.9 for the two examined groups, respectively. Previous studies on source parameters determination and moment-magnitude relationships carried out for Greek earthquakes (e.g. Kiratzi et al., 1985, Main, 1985, Tselentis et al., 1988) mainly involve major earthquakes, but it would be unwise to apply such relationships to earthquakes of smaller magnitudes. Therefore the only way to estimate the source parameters of small earthquakes is through spectral analysis. However, an investigation of the scaling properties between the smaller and the larger events would prove fruitful since, if some properties of the numerous, more frequent small events prove to be related to those of the rare larger events, then this has profound implications for the estimation of the seismogenic slip rate and the seismic hazard of an area.

For the 1983-1984 N.Sporades earthquakes the obtained values of $<\Omega_0, f_c>$ do not show any large or systematic differences at each station, at least within the error limits. Similar results were obtained by Condon (1985). On the contrary, for the 1985 aftershocks, significant differences for the same event at each VOLNET station were found. Since the aftershocks are all concentrated in a more or less limited epicentral area, these differences may be attributed to the different attenuation of the media through which the seismic waves travel from the foci to the azimuthally surrounding stations, which may cause damping of higher frequencies (ray path attenuation). They may also be due to the preference of surface geological conditions of the recording station to a specific frequency band, which can cause site amplification (site effect).

Table 1. List of 1983-1984 N.Sporades events for which spectral analysis was performed and obtained values of source parameters (MAG: local magnitude, M_0 in 10^{12} Nm, r in m, $\Delta\sigma$ in bars, s in mm).

N	DATE	ORIGIN	LAT N	LONG E	DEPTH	MAG	Mo	r	Δσ	s
1	83 113	3 6 8.13	38-36.60	22-53.10	14.26	3.0	9.6	244.5	1.0	0.86
2	83 114	224 33.06	39-11.05	24-26.17	5.00	3.2	22.6	270.6	5.0	3.28
3	83 2 1	15 9 47.63	38-36.10	23-33.16	14.09	2.7	4.4	261.3	1.1	0.68
4	83 227	146 21.12	39-01.77	24-57.06	0.94	3.3	4.2	209.7	2.0	1.02
5	83 227	352 23.50	39-29.82	23-26.91	11.14	3.1	76.2	455.4	3.5	3.90
6	83 319	1012 57.30	39-04.94	23-14.03	16.97	1.9	9.3	282.5	1.8	1.24
7	83 325	3 0 16.05	38-47.66	23-27.87	14.43	2.1	5.8	180.1	4.4	1.90
8	83 4 8	133 34.86	38-26.91	23-43.01	11.16	2.5	27.4	411.7	1.7	1.72
9	83 411	236 39.88	39-38.17	24-43.45	0.64	3.2	8.6	169.0	7.8	3.21
10	83 417	526 19.65	38-36.61	24-33.72	5.00	2.7	3.3	226.5	1.2	0.68
11	83 419	2139 52.57	39-29.88	24-39.08	1.31	3.5	30.8	229.1	11.2	6.22
12	83 524	1740 25.25	38-41.55	24-29.33	5.00	3.5	29.6	463.7	1.3	1.46
13	83 618	2324 55.80	38-05.63	23-08.24	3.62	2.5	3.6	293.1	0.6	0.44
14	83 7 5	2343 16.18	39-50.95	24-21.53	3.80	3.3	17.9	284.3	3.4	2.35
15	83 710	1255 14.56	39-30.32	24-15.13	5.00	2.6	21.6	242.0	6.7	3.92
16	83 8 6	1937 49.84	39-42.02	24-22.63	6.39	3.3	63.3	259.6	15.8	9.96
17	83 8 6	20 6 36.91	39-35.68	24-57.14	5.00	3.5	67.9	431.8	3.7	3.86
18	83 8 6	2121 8.66	39-48.99	24-34.64	1.88	3.4	33.8	235.4	11.3	6.47
19	83 8 7	3 1 54.94	39-41.31	24-37.74	0.62	3.0	15.7	213.6	7.0	3.64
20	83 8 7	1421 11.80	39-45.78	24-28.52	0.55	2.8	9.1	237.8	2.9	1.70
21	83 8 7	1831 26.40	39-34.82	24-41.60	0.30	3.2	2.6	167.6	2.5	1.00
22	83 8 8	1849 25.89	39-50.65	24-26.78	0.57	3.2	8.6	166.8	8.1	3.26
23	83 817	138 44.65	39-24.01	24-03.10	11.34	3.7	7.1	299.2	1.2	0.84
24	83 817	936 31.47	39-22.67	23-49.29	6.93	2.4	2.1	126.2	4.6	1.41
25	83 822	6 3 46.29	39-51.16	24-19.37	7.45	3.1	28.7	286.9	5.3	3.70
26	83 824	1143 1.06	39-37.89	23-56.33	9.66	2.6	3.0	240.1	1.0	0.56
27	83 827	2249 7.84	39-49.73	24-17.16	7.87	3.3	55.7	265.7	13.0	8.37
28	8310 7	225 51.93	39-50.12	24-14.74	5.00	3.3	110.3	286.6	20.5	14.25
29	831010	15 4 40.02	38-32.44	24-44.84	0.99	2.6	6.2	240.6	1.9	1.13
30	831013	755 21.59	39-44.97	24-12.49	9.95	2.9	22.5	251.0	6.2	3.79
31	831029	17 0 48.23	39-30.48	24-17.79	1.96	2.9	41.2	270.1	9.1	5.99
32	8312 8	1347 7.60	39-12.25	23-45.19	0.32	2.3	2.7	130.9	5.3	1.69
33	84 1 6	1138 41.33	39-00.33	24-56.01	0.57	3.2	2.9	171.2	2.5	1.04
34	84 2 5	2311 16.57	39-51.45	24-16.01	5.00	3.1	81.5	306.7	12.4	9.19
35	84 3 3	1729 50.01	39-10.92	23-51.62	0.88	1.7	1.7	122.1	4.2	1.23
36	84 314	3 8 37.76	39-48.54	24-27.96	2.62	2.6	4.7	263.8	1.1	0.72
37	84 4 2	830 1.47	39-09.37	24-18.19	3.15	2.1	12.9	157.0	14.6	5.55
38	84 421	2358 16.60	40-01.54	24-22.84	0.24	3.0	5.1	187.1	3.4	1.53
39	84 5 2	1649 49.05	38-45.68	24-52.89	0.87	2.8	2.0	126.2	4.4	1.34
40	84 5 7	2053 57.10	39-04.11	24-26.48	5.79	2.3	5.1	178.6	3.9	1.69
41	84 531	721 38.99	39-07.65	24-29.36	5.00	3.0	6.6	201.1	3.6	1.74
42	84 6 6	120 10.31	38-44.04	24-44.99	0.87	2.9	1.8	152.6	2.2	0.82
43	84 6 6	1752 6.15	40-00.69	24-28.03	0.20	3.1	5.3	216.5	2.3	1.21
44	84 710	1918 4.99	39-10.76	24-30.24	5.00	2.6	2.4	147.6	3.3	1.17
45	84 715	1038 49.52	38-37.03	24-35.45	0.92	2.8	2.5	160.7	2.6	1.03
46	84 725	2344 7.62	38-37.71	24-38.94	0.10	2.8	3.6	264.9	0.9	0.55
47	84 815	541 6.71	39-34.10	23-29.08	13.39	2.6	10.1	292.5	1.8	1.25
48	84 831	17 5 32.91	39-03.26	24-17.55	6.54	2.9	72.0	294.5	12.3	8.80
49	84 9 6	052 17.37	38-43.07	24-59.65	0.83	3.1	4.3	187.9	2.8	1.28
50	84 919	22 9 31.98	39-18.93	23-53.19	14.37	2.7	1.3	159.0	1.4	0.55
51	84 920	19 4 27.76	39-16.81	24-15.68	11.10	2.9	5.3	162.0	5.5	2.14
52	841120	855 33.04	38-41.45	24-51.39	4.90	2.8	10.5	203.9	5.4	2.69
53	8412 1	1818 46.43	39-30.31	23-42.81	0.16	3.1	1.5	146.8	2.1	0.75
54	841223	2238 57.18	38-43.35	24-53.31	1.19	3.4	36.8	309.7	5.4	4.07

The seismic moment values determined in the present study range between $0.1-11*10^{13}$ Nm and $0.1-23.4*10^{12}$ Nm for the two data sets respectively (tables 1 and 2). The fault radii ranged between 110-550 m for both data sets, but their average value was larger for the N.Sporades events. Consequently the stress drop and fault slip values calculated for the first data set were significantly larger than the values of the second. The observed differences can be explained by the fact that the first data set generally contains larger magnitude earthquakes.

Table 2. List of 1985 Pagassitikos aftershocks with ML>1.7, for which spectral analysis was performed and obtained values of source parameters (MAG: local magnitude, M_0 in 10^{12} Nm, r in m, $\Delta\sigma$ in bars, s in mm).

N	DATE	ORIGIN	LAT N	LONG E	DEPTH	MAG	Mo	r	Δσ	s
2	85 430	1924 10.18	39-17.31	22-49.91	25.63	1.8	1.2	152.4	1.5	0.57
5	85 430	1944 51.84	39-08.55	22-39.06	5.00	1.7	0.5	173.2	0.4	0.29
6	85 430	20 0 13.89	39-15.41	22-50.69	13.56	2.5	9.3	237.3	3.0	1.72
7	85 430	20 2 35.46	39-15.18	22-49.48	13.61	2.3	3.7	188.0	2.4	1.16
8	85 430	20 7 56.50	39-13.34	22-47.38	9.88	2.0	1.1	252.5	0.3	0.20
9	85 430	2013 50.59	39-11.60	22-41.71	13.76	1.7	1.7	191.6	1.0	0.54
10	85 430	2020 34.06	39-14.40	22-49.51	19.04	1.7	0.7	168.7	0.6	0.38
13	85 430	2047 34.83	39-15.45	22-51.29	9.09	2.3	1.6	169.4	1.4	0.62
14	85 430	2056 29.79	39-14.14	22-49.71	9.96	2.4	4.2	336.1	0.5	0.41
15	85 430	21 5 13.01	39-12.72	22-45.81	15.82	2.2	2.3	189.8	1.5	0.75
17	85 430	2119 28.53	39-15.06	22-37.76	5.00	1.9	1.1	137.8	1.8	0.63
18	85 430	2146 35.76	39-12.90	22-36.32	9.50	2.2	1.7	181.7	1.2	0.53
21	85 430	22 7 34.71	39-16.88	22-52.65	8.86	2.5	6.3	188.4	4.1	1.90
22	85 430	2220 20.69	39-13.91	22-50.56	12.38	1.9	2.5	192.1	1.5	0.76
25	85 430	2252 43.80	39-14.77	22-47.07	18.64	2.4	2.3	159.9	2.5	0.94
26	85 430	2355 38.62	39-13.68	22-50.07	9.82	1.9	0.4	158.1	0.4	0.21
27	85 5 1	055 14.15	39-13.91	22-50.27	9.09	2.1	3.4	216.9	1.5	0.89
32	85 5 1	244 38.95	39-14.64	22-51.50	12.95	2.0	1.3	183.0	0.9	0.45
33	85 5 1	3 7 15.21	39-13.35	22-47.13	15.62	2.1	6.0	190.3	3.8	1.82
35	85 5 1	433 43.59	39-12.61	22-46.21	9.08	2.2	1.2	207.5	0.6	0.30
38	85 5 1	5 2 29.82	39-18.05	22-53.15	18.05	2.5	7.3	266.1	1.7	1.11
39	85 5 1	518 35.53	39-13.54	22-51.26	9.65	2.7	15.3	375.3	1.3	0.45
40	85 5 1	633 17.65	39-12.96	22-48.53	7.93	2.0	1.2	171.7	1.0	0.48
41	85 5 1	714 52.00	39-14.02	22-50.32	14.12	2.3	3.3	207.7	1.6	0.86
42	85 5 1	739 11.71	39-14.63	22-39.92	12.29	1.9	1.7	301.8	0.3	0.29
44	85 5 1	751 40.08	39-16.56	22-53.15	10.71	2.3	2.1	192.5	1.3	0.64
45	85 5 1	8 2 9.38	39-14.52	22-50.09	9.07	1.8	2.0	205.4	1.0	0.50
46	85 5 1	8 5 8.31	39-14.50	22-49.77	17.38	1.7	1.3	144.4	1.9	0.79
47	85 5 1	810 39.82	39-15.19	22-48.40	12.86	2.1	23.4	412.0	1.5	0.13
48	85 5 1	820 37.07	39-15.33	22-50.44	18.08	1.9	1.2	206.6	0.6	0.36
49	85 5 1	829 26.84	39-13.07	22-47.36	13.64	2.3	3.7	242.0	1.1	0.77
50	85 5 1	834 50.36	39-14.70	22-50.55	14.23	2.5	7.7	249.3	2.2	1.31
53	85 5 1	1146 34.70	39-14.75	22-50.93	9.92	1.7	1.1	156.5	1.2	0.59
55	85 5 1	1333 32.64	39-16.05	22-51.07	7.78	2.9	17.4	444.6	0.9	0.95
56	85 5 1	1359 39.43	39-15.92	22-47.01	19.62	1.7	1.0	227.0	0.4	0.23
57	85 5 1	1432 2.95	39-15.38	22-53.15	10.09	2.2	5.3	282.0	1.0	0.76
58	85 5 1	1442 13.30	39-16.11	22-50.15	15.96	2.7	8.5	186.4	5.7	2.69
60	85 5 1	15 7 54.79	39-13.13	22-47.47	6.32	2.2	2.0	183.4	1.4	0.61
61	85 5 1	1514 14.44	39-13.86	22-47.86	8.37	2.5	6.7	270.3	1.5	1.00
65	85 5 1	1815 16.19	39-13.01	22-46.34	18.55	1.7	1.4	223.2	0.5	0.32
69	85 5 1	1956 51.99	39-13.89	22-50.45	9.59	1.9	0.8	225.0	0.3	0.23
70	85 5 1	2001 58.69	39-13.43	22-43.68	12.12	2.2	3.5	234.8	1.2	0.76
73	85 5 1	2029 53.34	39-15.58	22-50.76	7.44	2.6	6.7	251.2	1.8	1.15
75	85 5 1	2122 57.62	39-12.22	22-44.56	10.00	1.7	0.7	219.5	0.3	0.19
77	85 5 1	2235 20.34	39-17.60	22-49.14	17.63	2.4	7.6	325.3	1.0	0.82
78	85 5 1	23 1 47.62	39-15.31	22-48.71	17.67	1.9	1.8	291.7	0.3	0.25
79	85 5 2	016 41.27	39-18.70	22-42.37	20.55	2.3	2.2	258.2	0.6	0.33
80	85 5 2	122 4.30	39-14.40	22-51.86	0.66	2.1	0.8	142.5	1.2	0.49
81	85 5 2	130 44.55	39-15.17	22-54.22	13.78	2.2	3.3	213.6	1.5	0.81
87	85 5 2	820 40.11	39-15.25	22-44.43	5.00	1.8	1.1	363.1	0.1	0.12
92	85 5 2	1056 42.38	39-18.67	22-41.21	18.39	1.7	1.2	249.0	0.3	0.26
94	85 5 2	1151 54.20	39-16.48	22-52.49	18.78	1.8	1.3	134.5	2.3	0.89
96	85 5 2	1552 38.34	39-15.55	22-53.50	9.57	1.7	0.9	316.8	0.1	0.12
97	85 5 2	17 7 6.96	39-15.48	22-51.47	9.25	2.0	1.1	150.6	1.4	0.54
99	85 5 3	017 24.16	39-14.89	22-53.12	13.08	1.8	0.5	137.6	0.8	0.39
100	85 5 3	5 8 30.67	39-14.15	22-50.53	9.70	1.7	1.0	198.2	0.6	0.31
101	85 5 3	647 54.05	39-15.82	22-52.66	9.67	1.7	0.3	165.7	0.3	0.14
102	85 5 3	1047 55.16	39-13.58	22-50.14	7.45	2.4	4.8	222.3	1.9	1.08

The small magnitude earthquakes showed low stress drops and small average slips, and even lower are the stress drops of the analysed aftershocks. Gagnepain-Beyneix (1985) found low values of Δσ for events below the order of 10^{13} Nm of seismic moment, and decreasing Δo between foreshocks and aftershocks. This was also observed in the present study, by comparing the values of

Δσ and s inferred from events of the same magnitude but belonging to the two different data sets, with the aftershocks having systematically lower Δσ and s values (table 3).

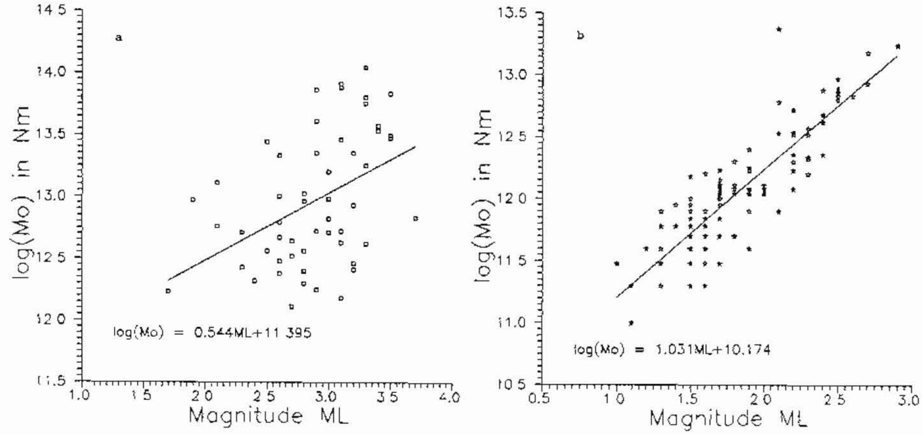

Fig.4. Moment-magnitude relationship for a) N.Sporades events b) 1985 aftershocks in Pagassitikos gulf

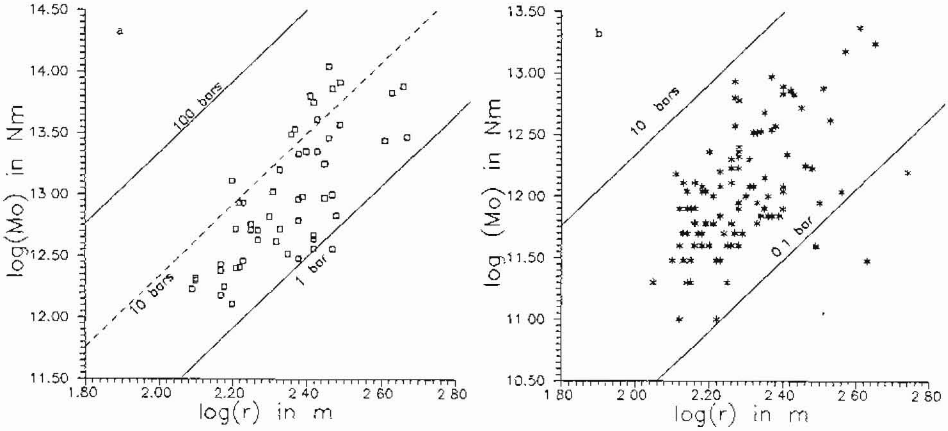

Fig.5. Moment-source radius relationship for a) N.Sporades events b) 1985 aftershocks in Pagassitikos gulf

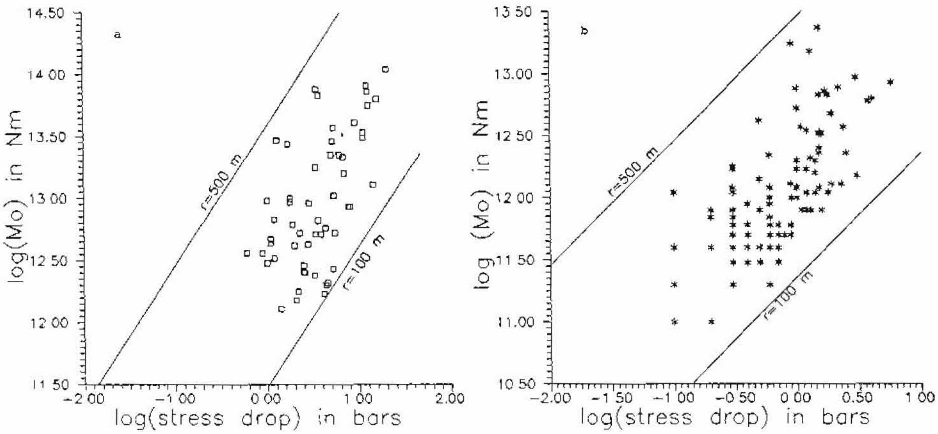

Fig.6. Moment-stress drop relationship for a) N.Sporades events
b) 1985 aftershocks in Pagassitikos gulf

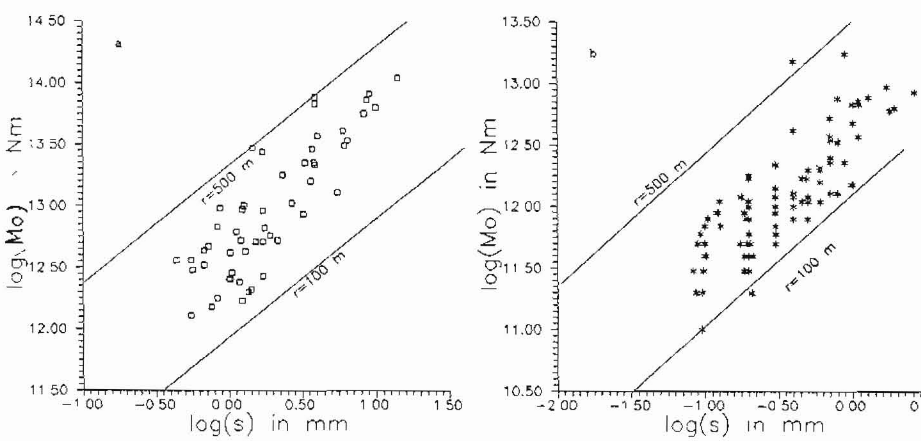

Fig.7. Moment-fault slip relationship for a) N.Sporades events
b) 1985 aftershocks in Pagassitikos gulf

Table 3. Calculated mean values of stress drop and fault slip for events of the same magnitude from the two data sets.

	N.Sporades		Pagassitikos	
MAG	Δσ	s	Δσ	s
1.7	4.2	1.23	0.6	0.35
1.9	1.8	1.24	0.5	0.39
2.1	9.5	3.72	2.0	0.83
2.3	4.6	1.69	1.4	0.73
2.4	4.6	1.41	1.5	0.81
2.5	1.1	1.08	2.5	1.41
2.6	2.6	1.46	1.8	1.15
2.7	1.2	0.64	3.5	1.57
2.9	7.1	4.31	0.9	0.95

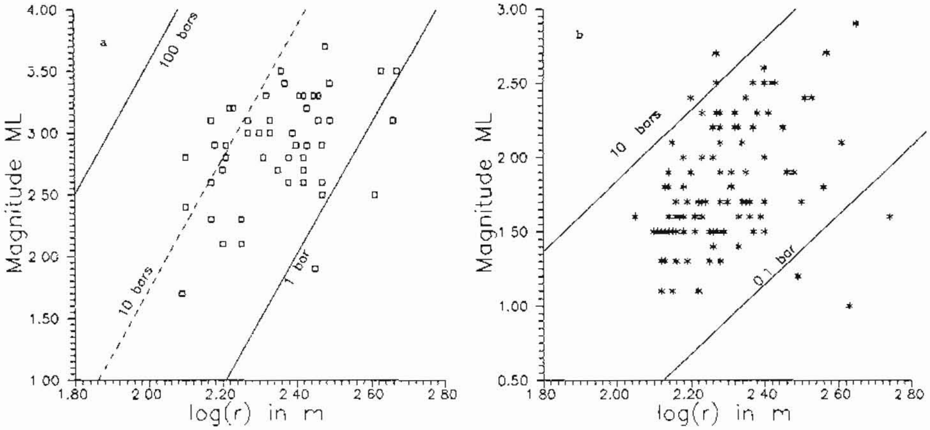

Fig.8. Magnitude-source radius relationship for a) N.Sporades events b)1985 aftershocks in Pagassitikos gulf.

The linear relationship between $\log M_0$ and local magnitude for the events of the two groups studied here is shown in figure 4a,b. The theoretical line, for earthquakes with magnitude less than 6.0, gives a gradient of 1.0 (Kanamori and Anderson, 1975). However, Tselentis et al., (1988) for Greek earthquakes with $M_s>5.0$ in the western Hellenic arc, estimated a gradient of B=1.16, which is considered to be in a fairly good agreement with the least squares results for the aftershock data (figure 4b) and shows that a correlation between large and small earthquakes might be possible. The N.Sporades data are very scattered (figure 4a), and the obtained value of B is considered very low.

For the moment-radius relationship, it is known that the corner frequencies of large magnitude events are lower than the small, and therefore according to equation (2) smaller radii are expected for the small magnitude events. The sensitivity of the recording system allows corner frequencies of up to 16 Hz to be measured, but in fact the highest f_c measured for the aftershocks did not exceed 11 Hz, and it corresponds to a minimum radius of 125 m.

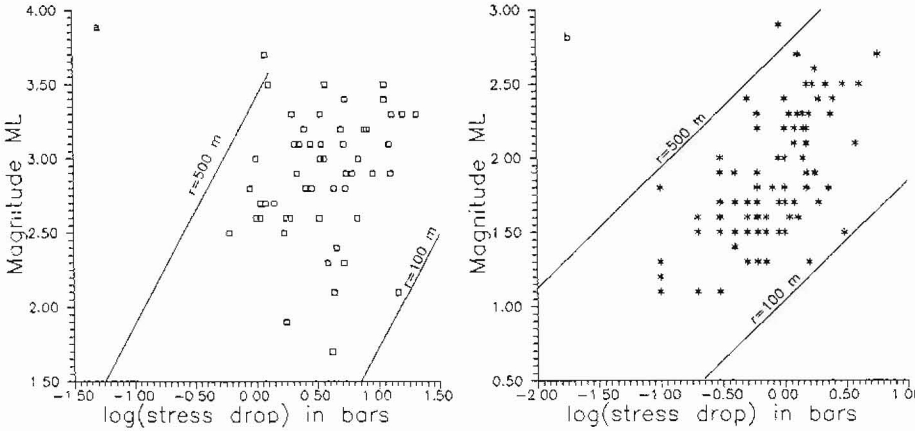

Fig.9. Magnitude-stress drop relationship for a) N.Sporades events b) 1985 aftershocks in Pagassitikos gulf

Additionally, since $\Delta\sigma > M_0 > M_L$, larger magnitude events correspond to higher values of stress drop. Therefore the N.Sporades events fall within values of stress drop of 1 and 100 bars, whilst the Pagassitikos aftershocks, which presented lower values of M_0, fall within 0.1 and 10 bars (figure 5a,b). In spite of the scatter, the moment-radius relationship shows a consistent pattern for both data sets.

The log-log plots of seismic moment vs. stress drop (figure 6a,b) show that, according to equation (3), their relationship is linear with gradient 1 and the events of both data sets fall within the values of source radius between 100 and 500 m. An almost similar pattern as in figure 5a,b emerges again.

The log-log relationship between moment-fault slip is plotted in figure 7a,b. The data fall again within 100 and 500 m source radii for both data sets, its gradient is 1, as implied from equation (4), and the data are following the same consistent pattern as in the above relationships, with considerably smaller scatter. Therefore, observed links between M_0 and r are now found to be significantly weaker than those between M_0 and s.

The seismic moment is related to magnitude through the formula $M_0=10^{A+BM}$, from which relationships between source parameters and magnitude can be extracted. In figures 8a,b and 9a,b, magnitude vs. logr and log$\Delta\sigma$ respectively are plotted. The comparison of these figures to figures 5a,b and 6a,b reveals that the first ones show a greater scatter, a fact which indicates that the seismic moment is more capable to describe the 'size' of an earthquake instead of the magnitude.

Summarizing, the relationships applied for the N.Sporades events and the Pagassitikos aftershocks showed similarities as far as their trend and the range of constant fault radius are concerned. However, the fact that for the same magnitude they showed significant differences in the actual values of stress drop and fault slip, shows that most probably a different tectonic process is taking place in the two areas. Therefore the earthquakes of these relatively close to each other areas should not be considered as one data set, since combining their data would only serve to increase the scatter and hence to conceal details concerning their tectonic regime. As far as the Pagassitikos sequence is concerned, a study of the source parameters relationship between foreshocks and aftershocks is expected to produce more quantitative results.

In conclusion, the results of this study stress the fact that the careful delineation of seismic zones is of great importance in revealing specific tectonic characteristics, thus leading to a more realistic aseismic design and hazard assessment.

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