S-WAVE SPECTRAL ANALYSIS AND ESTIMATION OF SPECTRAL PARAMETERS IN NORTHWESTERN GREECE

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Abstract

During a 12-month period (August 1998 - June 1999), a dense microseismic network of 44 portable seismographs, was installed in Epirus - Northwestern Greece, by the Seismological Laboratory, of the University of Patras and recorded 1368 earthquakes. We selected a subset of 200 well recorded events, with duration magnitude ranging from 1.61 to 2.92 and focal depths ranging from a few hundred meters to 35km; the majority was in the 0-10km range. This study uses this high quality dataset to (i) calculate the earthquake spectra and source parameters; (ii) perform linear regression between Seismic Moment (M_0) and the source parameters Source Radius (r), Stress Drop (Δσ) and Displacement (s); (iii) correlate source parameter's distribution with the tectonics of the area. Finally, we compare the derived empirical laws with similar studies.

***Keywords**: Microseismicity, source parameters, Epirus, stress drop, Brune model.*

Περίληψη

Κατά το χρονικό διάστημα Αύγουστος 1998 - Ιούνιος 1999, εγκαταστάθηκε στην Ήπειρο, από το Εργαστήριο Σεισμολογίας του Πανεπιστημίου Πατρών, φορητό μικροσεισμικό δίκτυο, αποτελούμενο από 44 σταθμούς, το οποίο κατέγραψε 1368 σεισμούς. Από αυτούς, επιλέχθηκαν 200 σεισμοί με μέγεθος από 1.61 έως 2.92 και εστιακό βάθος από μερικές εκατοντάδες μέτρα έως 35km, με την πλειοψηφία των σεισμών να εντοπίζεται στα 0-10km βάθος. Στην παρούσα εργασία πραγματοποιείται (i) υπολογισμός του σεισμικού φάσματος και των σεισμικών παραμέτρων; (ii) εφαρμογή γραμμικής παλινδρόμησης μεταξύ της Σεισμικής Ροπής M_0 και των σεισμικών παραμέτρων Ακτίνα Ρήγματος (r),Πτώση Τάσης (Δσ) και Μετατόπιση (s); και (iii) εκτίμηση της κατανομής των σεισμικών παραμέτρων σε σχέση με την τεκτονική της περιοχής. Τέλος, οι εμπειρικές σχέσεις που προέκυψαν συγκρίνονται με αυτές από αντίστοιχες εργασίες.

Λέξεις κλειδιά:

1. Introduction

The estimation of source parameters is a critical task in seismology and can be accomplished with various methodologies. This study uses high quality data in order to (i) calculate spectral parameters of earthquake source, namely low frequency displacement spectral level (Ω_0), corner frequency (fc), cut-off frequency above which the acceleration spectra shows a sharp decrease with increasing frequency (fmax) (Boore, 1983) and the rate of decay above fmax (N); (ii) estimate source parameters namely seismic moment (M_0), source radius (r), stress drop (Δσ) and displacement (s)

for each earthquake; (iii) develop a linear regression of the source parameters and (iv) correlate the source parameters distribution with the tectonic characteristics of the region.

Epirus extends from the Ionian Sea and belongs to External Hellenides, where three isopic zones, are formed. Starting from the eastern end, the Pindos zone is thrusted on the Gavrovo zone and the latter on the Ionian zone (Avramidis *et al.*, 2000; Kiratzi *et al.*, 1987; Waters, 1994; Hatzfeld *et al.*, 1995), performed microearthquake studies in Epirus, which have shown an ENE-WSW shortening which agrees with the continental convergence west of Corfu and a NNW extension, close to the Pindos foothills, further east. Taymaz *et al.* (1991), asserted that the E-W shortening generates thrust belts that trend N-NW and are cut by almost perpendicular strike slip or normal faults. King *et al.* (1983), based on a boundary-element model proposed a substantial left lateral strike-slip component in addition to the compressional motion. In agreement with this idea are the results of the geological and geomorphological research performed by IGSR and IFP (1966) and King *et al.* (1993) and the crustal deformation study of the Aegean area performed by Papazachos and Kiratzi (1996). At the Epirus area the extensional inner Aegean regime switches to the compressional outer Aegean. According to Hatzfeld *et al.* (1995), the compressional regime in Epirus is caused by the jump of active thrusting from the Pindos to the Ionian zone, which is still active at the present time. The focal mechanisms from earthquakes located in Epirus, denote thrust and strike slip to normal geological structures (Mercier *et al.*, 1972; King *et al.*, 1983; Doutsos *et al.*, 1987; Underhill, 1989; Waters, 1994; Hatzfeld *et al.*, 1995). Additional information derived from Martakis (2003), Tselentis *et al.* (2006) and Stavroulopoulou *et al.* (2013) seismotectonic studies in Epirus, agree with a thrust belt zone at the west, combined with an extensional regime at the eastern end.

In this article, we analysed earthquake source spectra calculated from high quality seismological data from the area of Epirus, in order to estimate the spectral parameters and correlate them with the tectonics of the area.

2. Seismograph Network and Data

For this study, we used high quality seismological data, which were recorded during a 12-month period (August 1998 - June 1999) by a dense microseismic network of 44, three component portable seismographs. During the aforementioned 12-month operation period 1368 earthquakes were recorded.

From this dataset, 200 well recorded events, which were relocated within the area of interest from Stavroulopoulou *et al.* (2013), were selected and analysed in this paper. The duration magnitude of this subset ranges from 1.61 to 2.92 and the focal depth ranges from a few hundred meters to 35km. The majority of focal depths were in the 0-10km range. In the same study of Stavroulopoulou *et al.* (2013), the area was divided into ten clusters of events based on their spatial distribution. The spectrum analysis was applied per cluster, in order to correlate the estimated source parameters with the seismotectonic characteristics of each smaller structural area (cluster), extending the work of Stavroulopoulou *et al.* (2013).
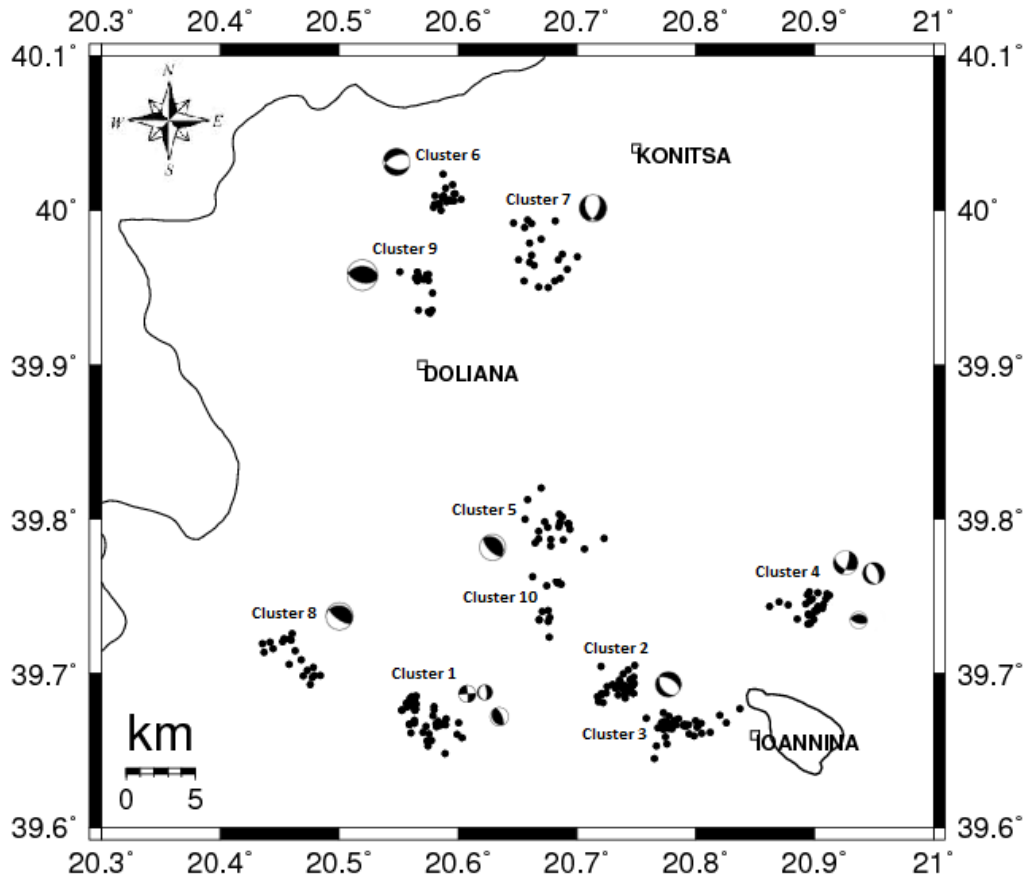
Figure 1 - The distribution of the 200 relocated epicentres for which source parameters were determined and the representative focal mechanisms of each cluster (Stavroulopoulou *et al*., 2013).

3. Method of analysis

To estimate earthquake spectral and source parameters, the EQK_SRC_PARA software was applied, (Kumar *et al*., 2012). The time histories are first corrected for instrument response using the transfer function and then rotated according to their azimuth to obtain the SH-component of ground motion. EQK_SRC_PARA is performing the spectral analysis on the SH-component. Spectrum is obtained from Fast Fourier Transform and is corrected for attenuation due to path. The software EQK_SRC_PARA, automatically picks the spectral parameters, (i) low frequency displacement spectral level (Ω_0), (ii) corner frequency (fc), (iii) the (fmax) frequency and (iv) the rate of decay above fmax (N). For the calculation of seismic moment (M_0) value, the Brune's source model was assumed, (Brune, 1970, 1971).

The values of the source parameters are estimated using the following equations:

Equation 1 - Seismic Moment (M_0) for the S seismic waves, (Brune, 1970, 1971):

$$Mo = \frac{4\pi\rho\beta^3 R\Omega_0}{R_{\theta\varphi}S_\alpha}$$

Where ρ is the average density (=2.67 g/cm^3), β is shear wave velocity in the source zone (=3.2 km/s), R is the hypocentral distance, R$_{\theta\varphi}$ is the average radiation pattern (=0.63), Sα is free surface amplification (=2).

Equation 2 - Moment Magnitude (Mw):

$$M_W = \frac{2}{3}\log(M_0) + 10.7$$

Equation 3 - Source Radius (r), (Brune, 1970):

$$r = \frac{2.34\beta}{2\pi f_c}$$

Equation 4 - Stress Drop (Δσ), (Keilis-Borok, 1959; Kanamori and Anderson, 1975):

$$\Delta\sigma = \frac{7M_o}{16r^3}$$

Equation 5 - Displacement (s), (Brune, 1968):

$$s = \frac{M_o}{\mu\pi r^2}$$

A time window over the S-wave is selected and a standard Fourier spectral analysis is applied. In order to determine the best duration for the S-wave window, several tests with different durations were performed. The time window duration with the most robust results was 2.5 sec.

The S-wave log-displacement spectrum is divided in two sections: (i) a flat section with amplitude level Ω$_0$ up to a frequency fc, and (ii) a roll-off linear decay. On the displacement spectrum, two intersecting lines are defined optically, which determine the source characteristics of each event analysed: (i) the overall mean trend of the low-frequency spectral asymptote and (ii) the high-frequency roll-off. (Brune *et al.*, 1986; Melis, 1992; Burton *et al.*, 1995).

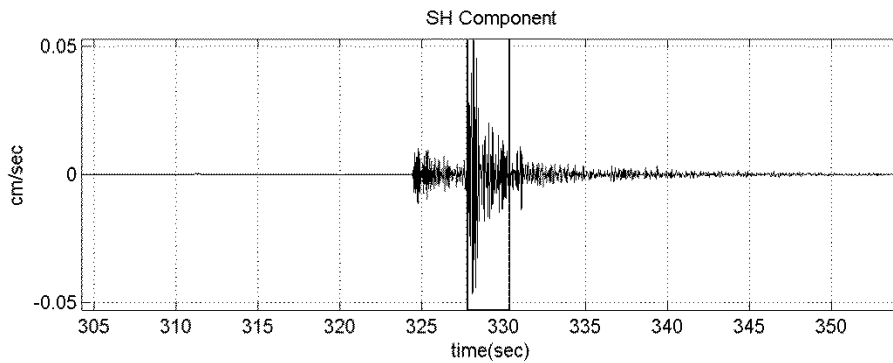An example of the analysis is shown in Figure 6 and Figure 3 taken from the March 7th 1999, 10:10:00 UTC, earthquake.

Figure 2 - The selected time window over the S-wave, for the March 7th, 1999, 10:10:00 UTC, earthquake.
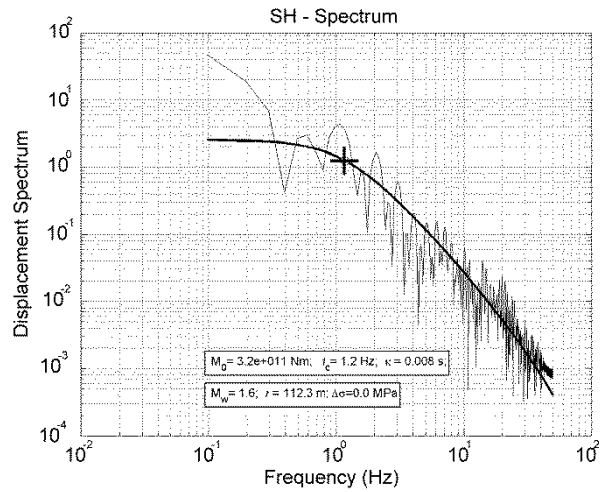
Figure 3 - The displacement spectrum for the March 7th 1999, 10:10:00 UTC, earthquake. Cross symbol defines fc; thin line represents the displacement spectrum; thick line represents the fitted Brune spectrum.

4. Results of the spectral analysis

In the following paragraphs we discuss in detail the results of the S-wave spectral analysis obtained within each cluster and the relationship between seismic moment (M_0) and the source parameters, source radius (r), stress drop ($\Delta\sigma$) and displacement (s), in order to investigate crustal deformation in Epirus.

Totally, 200 events were analysed and the range of the values of the source parameters determined are shown in Table 1:

Table 1 - Range of the seismic parameter's values.

Cluster No	Events	Mo (Nm)		r (m)		Δσ (bars)		s (mm)		Ωo (cm)		fc (Hz)	
		min	max	min	max	min	max	min	max	min	max	min	max
1	34	6,0E+10	8,2E+12	8,5E+01	1,6E+02	3,4E-01	9,2E+00	7,58E-02	3,25E+00	7,5E-05	5,7E-03	7,95	15,3
2	30	2,2E+11	4,8E+12	1,3E+02	3,1E+02	1,7E-01	1,1E+00	7,51E-02	6,00E-01	1,4E-04	1,9E-03	4,2	9,75
3	30	1,1E+11	1,7E+12	9,5E+01	3,7E+02	8,6E-02	1,6E+00	3,92E-02	5,12E-01	9,0E-05	8,0E-04	3,5	13,7
4	14	6,0E+10	6,3E+13	7,8E+01	3,9E+02	8,2E-02	2,6E+01	3,92E-02	1,85E+01	2,7E-04	1,5E-02	5,2	11,4
5	18	2,1E+11	7,1E+12	9,1E+01	1,9E+02	6,3E-01	1,7E+01	1,16E-01	5,03E+00	1,8E-04	6,7E-03	6,8	14,4
6	19	4,0E+11	2,4E+13	9,8E+01	2,6E+02	5,1E-01	2,5E+01	1,04E-01	5,27E+00	2,3E-04	1,1E-02	5,1	13,3
7	15	1,7E+11	5,9E+12	1,0E+02	2,3E+02	2,9E-01	6,1E+00	7,87E-02	2,25E+00	1,3E-04	3,4E-03	5,8	12,6
8	13	9,8E+10	8,5E+12	8,0E+01	1,7E+02	3,9E-01	9,7E+00	1,21E-01	4,20E+00	1,4E-04	6,7E-03	7,7	16,2
9	15	1,7E+11	1,6E+13	1,0E+02	2,2E+02	6,5E-01	6,7E+00	1,61E-01	3,50E+00	1,8E-04	8,4E-03	5,9	12,5
10	12	1,2E+11	2,6E+12	9,4E+01	1,4E+02	2,8E-01	1,1E+01	1,20E-01	3,17E+00	1,3E-04	3,2E-03	9,1	13,9
ALL	200	6,0E+10	6,3E+13	7,8E+01	3,9E+02	8,2E-02	2,6E+01	3,9E-02	1,8E+01	7,5E-05	1,5E-02	3,5	16,2

Pairs of ($\log M_0$ - $\log r$), ($\log M_0$ - $\log\Delta\sigma$) and ($\log M_0$ - $\log s$) values were analysed for the 10 cluster subsets and for the whole data set. Since the derived regression laws, per cluster, were similar we will discuss the results for the whole dataset only. The regression coefficients obtained using the whole data set, are presented in Table 2:

Table 2 - Regression of source parameters for the whole dataset.

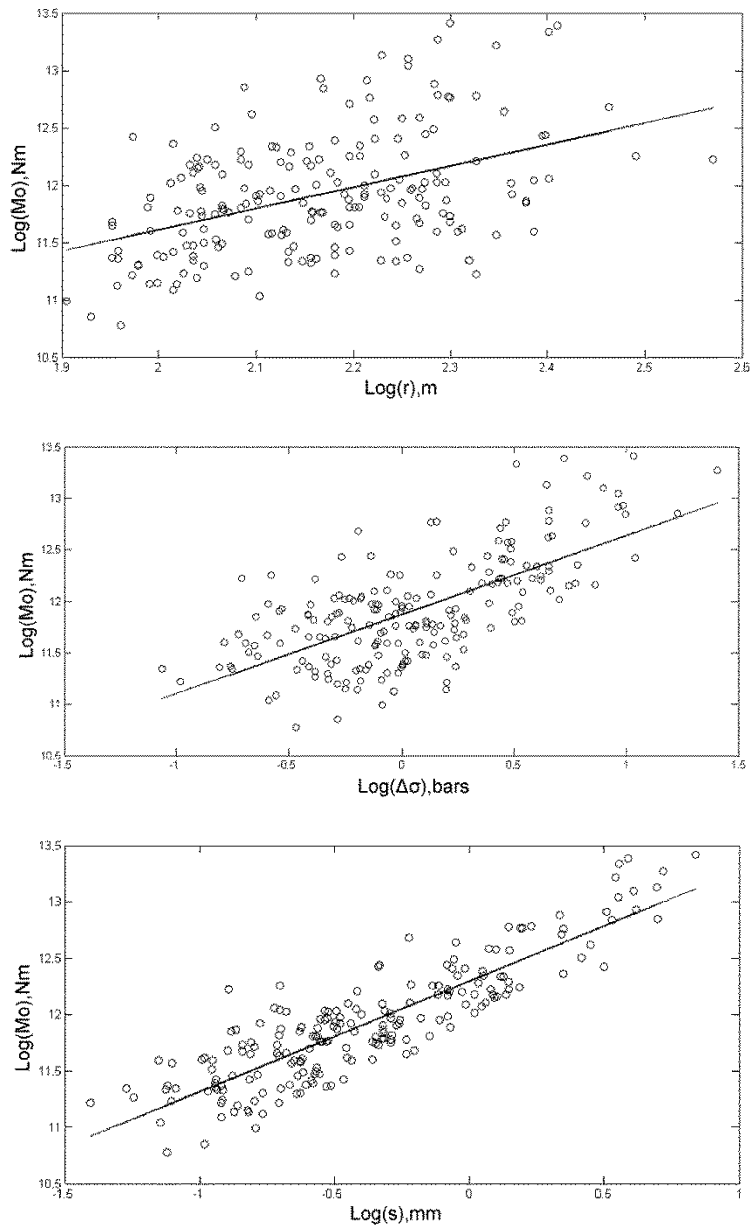| Regression (M_0-r)		Regression (M_0-$\Delta\sigma$)		Regression (M_0-s)	
Equation	R^2	Equation	R^2	Equation	R^2
logMo = 1,85logr + 7,89	0,20	logMo = 0,76log$\Delta\sigma$ + 11,86	0,46	logMo = 0,97logs + 12,29	0,77

Figure 4 - Linear regression between seismic moment (M_0) and source radius (r), stress drop ($\Delta\sigma$) and displacement (s), for the whole data set.

The relationship between seismic moment (M_0) and displacement (s) was quite strong for almost all of the clusters, with the R^2 equal 0.77 for the case of whole dataset. Similarly, the relationship

between seismic moment (M_0) and stress drop ($\Delta\sigma$) was moderate, with the median of R^2 equal 0.46. Furthermore, the values of stress drop are low, ranging from 0.1 bars to 25.4 bars, which is in agreement with the low stress drop character of Greek earthquakes (Kiratzi *et al.*, 1985). The relationship between seismic moment (M_0) and source radius (r), was quite poor, with R^2 equals 0.20 for the whole dataset.

The stress drop variation with moment and source radius is examined in Fig.4. Seismic moment (Mo) versus source radius (r) values for the whole dataset, are plotted with lines of constant stress drop determined from Equation 4. A linear dependence between seismic moment (Mo) and source radius (r) is observed, for the studied moment and source radius range, suggesting constant stress drop.
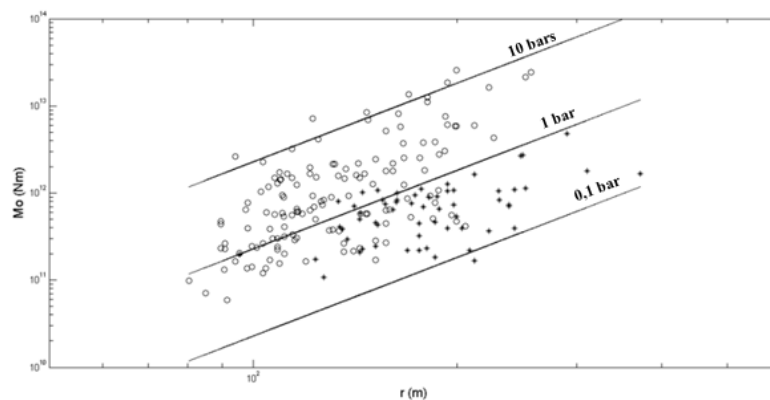

Figure 5 - Seismic moment versus source radius. Star symbols indicate values from cluster 2 and cluster 3; circle symbols indicate the other clusters. Lines of constant stress drop determined from Equation 4, are also indicated.

Specifically, cluster 2 and cluster 3 which are located west of Ioannina, show very poor correlation between the calculated source parameters. This area was referred by King *et al.* (1993) as Ioannina basin and is located over an evaporate dome (Tselentis *et al.*, 2006). The majority of the earthquakes, which were used for the spectral analysis, occurred at shallow depths up to 5km. This special characteristic of these events, which separate them from the whole dataset, lead us to remove these clusters from the analysis. Omitting cluster 2 and cluster 3 from the regression produced a significant improvement in the regression analysis, between the source parameters, as shown in Table 3:

Table 3 - Regression from the whole dataset omitting cluster 2 and cluster 3.

Regression (M_0-r)		Regression (M_0-$\Delta\sigma$)		Regression (M_0-s)	
Equation	R^2	Equation	R^2	Equation	R^2
logMo = 3,38logr + 4,79	0,43	logMo = 1,11logΔσ + 11,7	0,60	logMo = 1,16logs + 12,26	0,87

5. Conclusions - Discussion

In this paper we present empirical relations of source parameters using a high quality dataset from Epirus. A dataset of 200 events was analysed using an S-wave spectral fitting technique and Brune model, to estimate seismic moment, stress drop, displacement and source radius. The initial dataset was divided in ten clusters according to seismotectonic characteristics of the area (Stavroulopoulou *et al.*, 2013). Then, the regression analysis was applied to each cluster and to the whole dataset separately. The calculated moment magnitude for the whole dataset ranges from 1.2 to 2.9. Since the regression results were similar among the examined clusters, we restrict our analysis to the whole dataset only. The spectral analysis provided a quite good correlation between seismic moment and

displacement and a moderate correlation between seismic moment and stress drop, for most of the clusters and for the whole dataset. The poor correlation obtained between seismic moment and source radius precludes its further use. In the Ioannius Basin area (clusters 2 and 3), the very poor correlation between the calculated source parameters is probably due to the shallow depth of the seismicity. This seismicity is connected with the presence of an evaporite body in the area (Tselentis *et al.*, 2006).
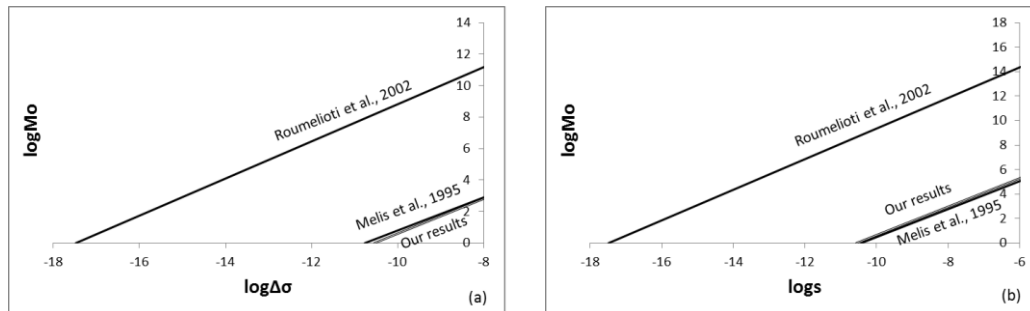

Figure 6 - Comparison between a) seismic moment (M_0) and stress drop ($\Delta\sigma$) and b) seismic moment (M_0) and displacement (s), proposed by Roumelioti *et al.*, 2002; Melis *et al.*, 1995; and our results omitting cluster 2 and cluster 3.

A comparison of the empirical laws derived in this study, for Epirus (Table 3), with the ones proposed by Roumelioti *et al*. (2002) and Melis *et al*. (1995) for Kozani and Corinth gulf respectively is presented in Fig. 6. The magnitude range examined in Roumelioti *et al*. (2002) was the highest ($\sim$3-4.5M_L), while the datasets of this paper and Melis *et al*. (1995) are comparable in magnitude range ($\sim$1.5-3.5M_L). The empirical laws derived in this study, are very close to Melis *et al*. (1995) and depict a similarity with Roumelioti *et al*. (2002).

6. Acknowledgments

7. References

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