Focal parameters of the micro-earthquakes in the Hyblean area (South-eastern Sicily) during the period from September 2000 to October 2002

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The geodynamic features of South-Eastern Sicily play an important role in the central Mediterranean area. In fact, several earthquakes have produced even serious damages to the people living in that area, in particular the 1169 and the 1693 earthquakes, with M = 7 (Azzaro & Barbano, 2000) and, more recently, the 1990 earthquake, with M = 5.4 (Amato et al., 1995) and the epicentre located in the Malta Escarpment between Augusta and Catania (fig.1). Due to the high seismic hazard in this area, the Regional Province of Ragusa, together with the University of Catania, has realized a digital seismic network for the seismic monitoring. Many local events (200) with low magnitudo (M<3.3) have been recorded in the period from September 2000 to October 2002. At this moment, the physical features of the sources in the mentioned area are scarcely known; plus, there is no information in other papers about the spectral parameters such as the seismic moment, the stress drop and so on (Giampiccolo et al., 2003). Aky (1967) was one of the first researchers who tried to give parameters to the source by using the S-wave spectrum and by computing the scale laws. Some papers (Archouleta et al., 1982; Haar et al., 1984; McGarr, 1986; Centamore et al., 1997) highlight that the scale relations between the seismic moment and the stress drop -or the fault dimension- are not univocal for the earthquakes with M0 ≤ 1014 Nm. Many authors ascribe these phenomena to propagation effects (Frankel, 1982; Fletcher et al., 1986); on the contrary, many others consider the site-effects as more important (Cranswick et al., 1985; Malin and Waller, 1985). Finally, according to some authors, the physical processes at the source are due to the independence of the corner frequency from the seismic moment (Aky and Papageorgiou, 1983; Dysart et al., 1988). The aim of this paper is to characterize the source of the earthquakes occurring in the South-Eastern Sicily, and particularly in the Hyblean Area after having calculated the attenuation laws at several seismic stations. The source parameters have been obtained by applying the Brune model (1970, 1971) to the displacement density spectrum SH. This one better fits with the analyzed data than the Madariaga model (1976). The performed correlations agree with the other studies applied both to the tectonic environment (Bindi et al., 2001) and to the volcanic one (Centamore et al., 1997).

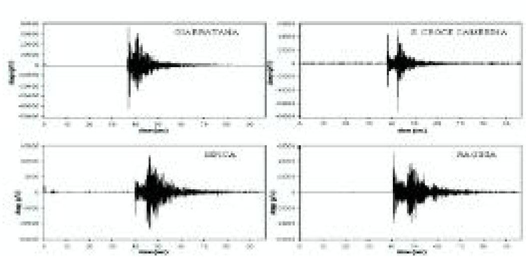
STRUCTURAL FEATURES OF THE HYBLEAN AREA & DATA SEISMIC NETWORK

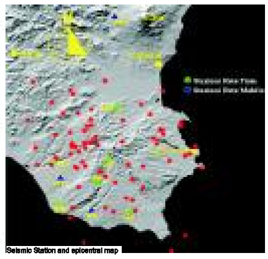
The Structural setting of the studied area is very complex and it is related to the tectonic setting of the Mediterranean area, which is characterized by a compressive regime between the African and the Euro-Asian plate. There are three main structural units in Sicily, going southwards: the Apennines-Maghrebide chain, the Gela-Catania foredeep and the Hyblean foreland.

The Hyblean foreland represents the more northern border of the African plate. It has been weakly deformed in the collision with the Euro-Asian plate during the Alpine orogenetic phase. (Grasso et al., 1979). It is made of limestones with intercalations of clay levels and Plio-Pleistocenic volcanics for the first 6 km (Bianchi et al., 1987). The eastern border of the Hyblean foreland is the Hybleo-Maltese Escarpment, which is one of the most important structural directrices in the central Mediterranean. It is 300 km long and it represents the morphological evidence of a system of NNW-SSE oriented normal faults, with an immersion towards ENE. According to Ghisetti et al. (1982) and to Monaco et al. (1995), the trans-current component of the Malta Escarpment is towards the right direction; on the other hand, according to others (Grasso et al., 1993), it is directed to the left (Fig.1). The age and the genesis of the escarpment are still under debate. According to Lentini et al. (1994), the Malta Escarpment had been a Mesozoic genesis, and it has mainly been re-activated during the Plio-Pleistocenic times by normal dislocations. The Hyblean Area underwent through a moderated uplift, being fractured during the Alpine orogenesis. It is thus characterized by a NE-SW oriented graben, whose NW border coincides both with the Gela trench and with a system of NE-SW oriented faults with an age of 400 ky. On the eastern side of such a graben there is a system of NNW-SSE oriented trans-extensional faults. This system can be seen on the field along the coast from Augusta to Siracusa and those faults could represent the natural, internal appendix of the Malta Escarpment (Carbone et al., 1982). According to Carbone et al. (1982), the northern part of this system generates the Timpa system in the eastern sector of the Mt.Etna. Recent papers (Hirn et al., 1997) would confirm this continuity between the two structures. A further contribution to a deeper knowledge of the Hyblean foreland has been given by the several seismic studies on the crust, thanks to which the space variations of the P-wave velocity in the Hyblean foreland crust has been defined (Cassinis et al., 1969). Continisio et al. (1997) have developed two refraction seismic profiles which detect a refractor at depth ranging between 25 and 30 km, with Vp = 8 Km/sec which is probably related to the Moho discontinuity.

Structural Framework

The data used in this paper have been recorded both by an analogical monitoring seismic station located in the town of Scordia (SCD) and equipped with a vertical seismometer and by the seismometric network of Ragusa Province. This one includes 5 fixed digital stations with a short period (1 Hz) 3D seismometer and a sensitivity which is equal to 400V/m/sec in a frequency range from 0.5 to 100 Hz. The sampling frequency of the seismic signal is 125 Hz; besides, the signal has been filtered by an anti-aliasing filter with cut-off frequency at 25 Hz. Such stations are located respectively in Giarratana (GIA), S. Croce Camerina (SCR), Ispica (ISP), Ragusa (RAG) and Acate (ACT). The network has been recently completed by adding three further mobile seismic stations with the same features as the others. They are located in Vittoria (VTT), Scicli (SCL) and Bronte (BRT). The geometric features of the network are shown in Fig.2, where the black triangles represent the seismic stations that have been used to calculate the source parameters of the earthquakes. Such stations have been chosen for the high signal/noise ratio; the data stored in each site have been transmitted to the collecting centre through the GSM network. About 200 local seismic events have been recorded during the period from September 2000 up to October 2002; Fig.3 shows a typical signal, recorded by some stations. Hypocenter localization has been calculated using both the Hypo 71 (by Lee and Lahr, 1975)





Seismic Station and epicentral map

ANALYSIS OF DATA

The Attenuation Laws

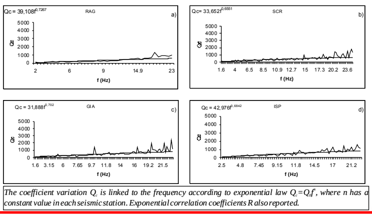
The anelastic absorbance of the Hyblean crust is determined through the analysis of the quality coefficient Q. In particular, Q_c is determined by the study of the coda waves. In this paper, a method based on the fitting of the seismograph coda has been used. The amplitude decrease of the coda waves with respect to the passing of time is explained by Aky & Chouet (1975), through a "single-scattering" model. In the "single-scattering" model, the amplitude of the coda wave A(f,t) of a seismogram, where f is the frequency and t the time interval, decreases according to this formula:

$$A(f,t) = A_0(f)\, t^{-\alpha} e^{-\pi f t / Q_c}$$

Here, $A_0(f)$ is to be considered as a constant factor; is a function of the geometric spreading and Q_c is the quality factor deduced from the analysis of the coda waves. This quality factor includes both the intrinsic and the scattering attenuation. Q_c has been estimated through the "direct method" (Del Pezzo et al., 1987; Del Pezzo et al., 1990). All the frequencies of the signal have been filtered at a single station, in order to obtain a Qc which is as homogeneous as possible. The filtered signal has been fitted -in the time domain- through a straight line, whose equation is:

$$\ln A(f|t) * t = \ln A_0 - \pi f t / Q_c$$

The angular coefficient of this equation allows obtaining the value of Qc corresponding to a given frequency, for each event and for each station.



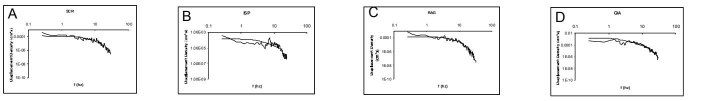
The coefficient variation Q_c is linked to the frequency according to exponential law $Q_c = Q_0 f^n$, where n has a constant value in each seismic station. Exponential correlation coefficients R also reported.

Spectral Analisis

The FFT of the S-waves for every earthquake have been performed to obtain the source parameters of the earthquakes in the Hyblean area. The spectrum of the displacement densities has been corrected for the anelastic attenuation by multiplying its value by the factor: $D = \exp\left(\frac{\pi f \Delta}{Q V_s}\right)$ with as the hypocentre distance (km); V_s is the velocity of the S-wave (km/sec), calculated as discussed above, $Q = Q_0 f^n$. According to Brune's model (1970, 1971), the equation of the far-field displacement spectrum can be written as:

$$\langle \Omega(f) \rangle = \frac{2 < \Omega_0 >}{1 + \left(\frac{f}{f_0}\right)^2}$$

where Ω_0 is the value of the spectral density, corresponding to the characteristic angular frequency f_0. Last equation can be also written as y = Ax + B, where y = 1/Q(f), $x = f^2$, $A = 1/(2\,\Omega_0 f_0^2)$, $B = 1/2\,\Omega_0$.



After having calculated the values of f_0 and Ω_0, it is possible to calculate the values of the focal parameters, hypothesizing that a stress decay is equal to 100 % (Brune, 1979; 1971; Centamore et al., 1997).

$$r = \frac{2.34}{2\pi}\frac{V_S}{f_0} = 0.37\frac{V_S}{f_0} \qquad \Delta\sigma = 445.89\Delta f_0^3 \Omega_0 / b \qquad M_0 = 52.86 \Delta V_S^3 \Omega_0 / b \qquad E_s = (1/2\rho V_S^2)\Delta\sigma M_0$$

where Vs , S-wave velocity (m/sec); *b* is a factor depending on the site amplification; is the Hypocenter distance (m). The parameter *"b"*, as introduced in the previous equations, is a function of the site amplification and it plays an important role, being important to calculate the focal parameters of the local events (Frankel, 1982; Hanks, 1982; Centamore, 1997; Feignier, 1991).). The equivalent Wood-Anderson Magnitudo has been calculated through Aki & Richards's method (1980), where: $A(\omega,\Delta) = A_s(\omega)\Delta^{-n}\exp\left(-\frac{\omega\Delta}{2QV_S}\right)$ Through several simplifications we gain the general equation MWAeq that can be used to every station:

$$MWAeq_{(GIA)} = \log_{10}\left[\frac{2800 A_{max}(\omega,\Delta)}{\langle R_{\vartheta\varphi}\rangle 0.98}\right] + (2.59\log_{10}\Delta + 2.17)$$

$$MWAeq_{(SCR)} = \log_{10}\left[\frac{2800 A_{max}(\omega,\Delta)}{\langle R_{\vartheta\varphi}\rangle 0.90}\right] + (-2.90\log_{10}\Delta + 2.80)$$

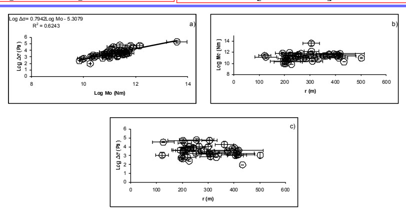
$$MWAeq_{(ISP)} = \log_{10}\left[\frac{2800 A_{max}(\omega,\Delta)}{\langle R_{\vartheta\varphi}\rangle 1.21}\right] + (3.01\log_{10}\Delta + 3.03)$$

$$MWAeq_{(RAG)} = \log_{10}\left[\frac{2800 A_{max}(\omega,\Delta)}{\langle R_{\vartheta\varphi}\rangle 0.69}\right] + (-2.90\log_{10}\Delta + 2.80)$$

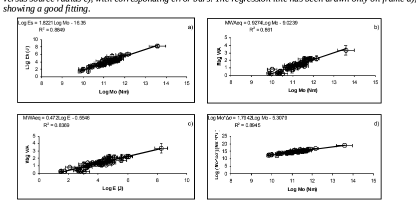
The analysis of the wave forms, related to 72 micro-earthquakes occurred inside or near the seism metric network along the period 20002002, has provided a preliminary picture of the seismic nature of this sector of the South-eastern Sicily. Only 41 seismic events satisfy the conditions to locate the epicentres and the signal/noise ratio

Table: Source parrameters (mean values) and associated standard deviation of the 41 events selected for spectral analysis

N°	Date	Hour	Depth (Km)	MWAeq	Mo (Nm)	Δσ (Pa)	E (J)	R (m)	Δ MWAeq	ΔMo (Nm)	Δ Δσ (Pa)	Δ E (J)	Δ R (m)
3	01/10/00	22 43 26,34	14.1	0.26	6.974E+09	2.55E+02	3.18E+01	227.00					
4	03/10/00	05 30 11.91	11.91	1.41	2.035E+11	1.31E+03	4.14E+03	416.84		1.07E+11	1.53E+02	2.66E+03	63.64
7	11/11/00	01 31 46.21	22.48	0.26	9.045E+09	4.69E+02	5.55E+01	202.27		6.66E+08	6.50E+01	1.17E+01	4.41
8	12/11/00	08 08 26.73	28.86	1.40	2.684E+11	9.65E+03	3.55E+04	225.59	0.30	1.05E+11	2.23E+03	2.06E+04	20.79
9	13/11/00	04 20 04.94	12.97	1.90	3.786E+11	9.55E+03	5.17E+04	299.65	0.37	2.26E+11	9.88E+03	5.74E+04	
11	02/07/01	04 22 11.34	15	0.81	5.419E+10	6.33E+02	6.15E+02	331.90					
12	10/08/01	16 42 50.77	3.56	2.21	5.449E+11	3.80E+03	4.89E+04	418.56	0.09	3.25E+11	2.16E+03	3.63E+04	94.00
13	14/08/01	11 38 35.01	13.74	0.74	9.133E+10	1.14E+03	1.39E+03	501.94	0.39	3.76E+10	1.19E+03	9.07E+02	
15	27/08/01	11 07 59.67	14.04	1.40	1.391E+11	3.28E+04	9.28E+04	126.68	0.14	1.04E+11	5.35E+03	5.88E+04	41.87
17	02/09/01	01 02 58.23	19.23	1.19	1.985E+11	1.07E+03	7.21E+03	406.03	0.01	2.48E+11	1.16E+03	1.17E+04	31.90
18	07/09/01	18 27 21.91	14.93	0.81	1.019E+10	5.60E+02	1.22E+02	196.68		7.22E+09	3.68E+02	1.36E+02	4.32
19	08/09/01	15 22 41.50	0.35	0.25	1.789E+10	9.39E+01	3.06E+01	433.38					
21	12/10/01	09 21 39.28	13.47	2.17	5.531E+11	1.15E+04	1.25E+05	265.36	0.32	1.97E+11	8.89E+03	9.74E+04	49.00
22	12/10/01	22 07 37.40	18.17	0.59	2.615E+10	8.02E+02	3.58E+02	309.47	0.18	8.10E+09	7.25E+02	2.98E+02	40.59
26	05/11/01	00 25 11.29	18.28	2.25	1.436E+12	5.19E+04	1.16E+06	305.96	0.34	5.15E+11	5.40E+04	9.36E+05	29.32
27	24/11/01	07 28 02.77	16.49	1.65	4.397E+11	3.51E+03	1.90E+04	375.28	0.19	1.38E+11	3.67E+02	1.37E+04	51.50
28	30/11/01	04 47 46.53	12.37	1.13	1.917E+11	7.57E+03	3.56E+04	241.95		1.36E+11	7.87E+03	4.55E+04	44.09
30	05/12/01	17 37 23.19	19.79	1.02	8.893E+10	1.78E+03	2.43E+03	318.68	0.21	3.90E+10	7.94E+02	1.14E+03	62.50
31	08/12/01	19 27 27.59	36.46	1.38	7.460E+10	4.03E+03	1.99E+03	284.81		6.01E+10	4.91E+03	1.61E+03	
32	09/12/01	23 16 32.22	11.41	3.34	3.788E+13	2.00E+05	1.83E+08	305.25	0.65	5.58E+13	1.06E+05	2.99E+08	32.79
33	19/12/01	03 42 54.49	14.75	0.22	3.182E+10	1.49E+03	1.14E+03	209.59		2.59E+10	1.23E+03	1.39E+03	1.61
35	23/12/01	23 21 15.49	25.33	1.39	2.079E+11	4.04E+03	1.20E+04	363.51	0.29	3.35E+10	4.57E+03	1.51E+04	35.27
38	10/01/02	03 21 49.90	10	1.55	1.166E+11	1.79E+04	4.09E+04	202.86	0.17	1.69E+10	2.27E+04	5.28E+04	
40	11/01/02	18 19 37.38	19.27	1.24	6.243E+10	2.71E+03	4.50E+03	221.29	0.14	5.37E+10	2.32E+03	5.98E+03	24.21
41	13/01/02	10 54 41.65	16.43	1.11	8.274E+10	6.06E+03	1.73E+04	204.80	0.24	8.46E+10	8.23E+03	2.84E+04	30.30
42	15/01/02	01 49 48.32	14.53	1.21	1.269E+11	3.76E+03	1.20E+04	243.63	0.33	1.14E+11	3.39E+03	1.54E+04	0.25
43	15/01/02	05 04 45.35	13.3	2.18	3.656E+11	7.43E+03	5.85E+04	255.34	0.38	3.59E+11	3.06E+03	6.79E+04	66.29
46	24/01/02	02 29 42.62	11.31	1.72	2.471E+11	5.98E+04	3.67E+05	122.41	0.21	1.90E+11	4.92E+04	5.07E+05	24.82
47	30/01/02	21 38 19.97	18.48	0.36	1.929E+10	1.14E+03	4.48E+02	214.21	0.14	5.95E+09	1.05E+03	4.83E+02	55.60
49	26/02/02	14 53 59.70	26.85	1.43	1.478E+11	4.40E+03	9.75E+03	253.18	0.31	3.56E+10	2.18E+03	5.99E+03	42.07
50	14/03/02	01 49 21.76	14.51	0.97	5.476E+10	1.92E+03	1.89E+03	209.45	0.28	3.17E+10	1.72E+03	1.84E+03	26.49
51	17/03/02	23 21 04 37	19.93	2.13	7.858E+11	2.76E+04	4.04E+05	219.80	0.38	2.76E+11	2.15E+04	4.05E+05	32.46
52	01/04/02	00 15 42.85	13.76	0.79	9.984E+10	6.85E+02	1.71E+03	412.92		8.18E+10	6.68E+02	2.20E+03	35.88
53	08/05/02	16 56 54.51	18.71	1.25	6.671E+10	1.23E+03	1.11E+03	273.83	0.21	5.11E+10	4.34E+02	1.51E+03	45.09
56	21/05/02	01 35 24.42	11.41	1.92	4.544E+11	3.15E+03	2.57E+04	394.02		8.75E+10	2.68E+01	5.16E+03	24.33
57	24/05/02	15 43 59 93	18.66	1.60	3.264E+11	6.08E+03	4.22E+04	303.90	0.24	1.58E+11	4.57E+03	4.09E+04	41.15
59	29/06/02	16 14 13.37	11.4	1.47	3.160E+11	2.19E+03	1.36E+04	376.17	0.40	1.39E+11	1.73E+03	1.45E+04	36.08
60	05/07/02	06 19 44.20	9.25	1.23	3.724E+11	2.38E+03	1.83E+04	403.04		2.18E+11	1.24E+03	1.75E+04	10.44
61	07/07/02	03 57 18 65	14.8	1.72	3.734E+11	7.37E+03	5.74E+04	408.62	0.32	1.38E+11	9.29E+03	7.40E+04	70.85
63	25/07/02	18 03 52 13	24.79	0.29	2.339E+10	1.85E+03	6.44E+02	202.85	0.16	4.51E+09	1.20E+03	4.41E+02	59.18
65	27/08/02	06 42 15.17	7.28	2.23	6.344E+11	5.00E+04	8.23E+05	192.55	0.23	4.02E+11	5.31E+04	1.18E+06	29.16
66	05/09/02	23 56 40.52	19.98	1.54	2.189E+11	4.12E+03	1.13E+04	355.98	0.19	1.70E+11	3.48E+03	9.06E+03	62.65



Plots of stress drop versus seismic moment a), seismic moment versus source radius b), and stress drop versus source radius c), with corresponding error bars. The regression line has been drawn only on frame a), showing a good fitting.



Plot of energy versus seismic moment a), MWAeq versus seismic moment b), and MWAeq versus energy c). Error bars and regression straight lines are superimposed. In d) frame, there is the product stress drop by seismic moment versus the seismic moment, with corresponding error bars and linear trend superimposed.

According to Dysart et al. (1988), the large variation of M_0 -with respect to the source radius- is not function of the site-effects or of the sources directionality. According to Aky (1967), the above described behaviour suggest a self-similarity violation. Papageorgiou & Aky (1983), Dysart et al. (1988) and Centamore et al. (1997) have made similar considerations in some researches on the seismic aspect of the Etnean area and of tectonically active zones; the obtained data are ascribed to the presence of barriers on the fault plane. Finally, variations due to the breakdown in self similarity do not influence the relation between MWAeq and M_0, as these two parameters are only function of the spectral amplitude.

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