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Local and Duration Magnitude Determination for the Italian Earthquake Catalog, 1981–2002

by B. Castello, M. Olivieri, and G. Selvaggi

Abstract In the present work, we update magnitude estimates of the instrumental catalogue of 99,780 Italian earthquakes that occurred during 1981–2002. The catalog contains a large data set of *P*- and *S*-arrival times and accurate earthquake locations. We derive duration magnitude estimates from linear regression between local magnitude calculated from Mediterranean Very Broadband Seismographic Network (MedNet) and the corresponding seismic-signal durations at the national network Rete Sismica Nazionale Centralizzata (RSNC). We introduce a station correction factor Sc_j because of most of the stations located in southern Italy show large residuals that appear to be of regional importance. The relation obtained:

$$M_{d_{ij}} = 2.49 \cdot \log(T_{ij}) - 2.31 + Sc_j.$$

Log $M_0 - M_L$ and $M_W - M_L$ relations are also computed in the range of 3.5–5.8 from regional centroid moment tensor estimation of medium-strong Italian earthquakes, by linear regressions. We obtained best least-square fits for:

$$\text{Log } M_0 = 1.18(\pm\ 0.06) \cdot M_L + 10.92.$$
$$M_w = 0.79(\pm\ 0.4) \cdot M_L + 1.20.$$

Introduction

A catalog of relocated Italian earthquakes over the past 22 years (1981–2002) is now available at Istituto Nazionale di Geofisica e Vulcanologia (INGV) web site (Italian Seismic Catalogue, CSI 1.0, Castello *et al.*, 2005). The catalog includes locations and *P*- and *S*-wave arrival times at the national and several regional seismic networks operating on Italian territory. The location procedure and velocity model are described in Chiarabba *et al.* (2005). They relocated the earthquakes with a homogeneous procedure, adapting and optimizing location parameters.

Chiarabba *et al.* (2005) compiled a catalog of *P*- and *S*-wave arrival times from bulletins for the period 1997–2002, including data from the INGV national network Rete Sismica Nazionale Centralizzata (RSNC) and several regional networks (Fig. 1). All the arrival times were associated, based on those by individual networks and propagation times for *P* waves, and carefully reanalyzed to find possible errors or inconsistencies. This catalog was added to the pre-existing 1981–1996 associated arrival times (ICWG, 2001). The final dataset consists of about 1,407,000 *P*-wave arrivals and 609,013 *S*-wave arrivals for the whole period. Locations have been obtained with an optimized 1D velocity model, cautiously selecting the location-weighting parameters, both using sharp weighting parameters to enhance the information at close stations or using smooth weighting parameters to locate events recorded only at a few and distant seismic stations. The work of Chiarabba *et al.* (2005) does not explore magnitude determination. That is the goal of this article.

In this work, we propose an updated version of log of duration versus local magnitude scale by regression analysis for the catalog. The regression coefficients have been calibrated from 1996–2000 revised local magnitude from broadband stations recordings and the corresponding duration estimates from national network (RSNC) short-period stations data. Since 1996, Mediterranean Very Broadband Seismographic Network (MedNet) data have been used to compute automatic simulated Wood–Anderson magnitude and regional centroid moment tensor estimation (Pondrelli *et al.*, 2002) for medium-strong earthquakes of the Mediterranean area. More than 5000 revised local magnitudes for Italian earthquakes from MedNet seismic network are available for the period 1996–2000. The magnitude range covered by the revised M_L estimates varies from 0.8 to 5.6.

The regression coefficients and station corrections have been applied to the entire catalog 1981–2002 of relocated earthquakes. The threshold of applicability is limited up to 4.9 M_L, because signal durations for stronger earthquakes are usually not estimated. For $M_L > 4.9$, local magnitude is taken from the available catalogs. The completeness of $M_L > 4.5$ is checked on the basis of International Bulletins

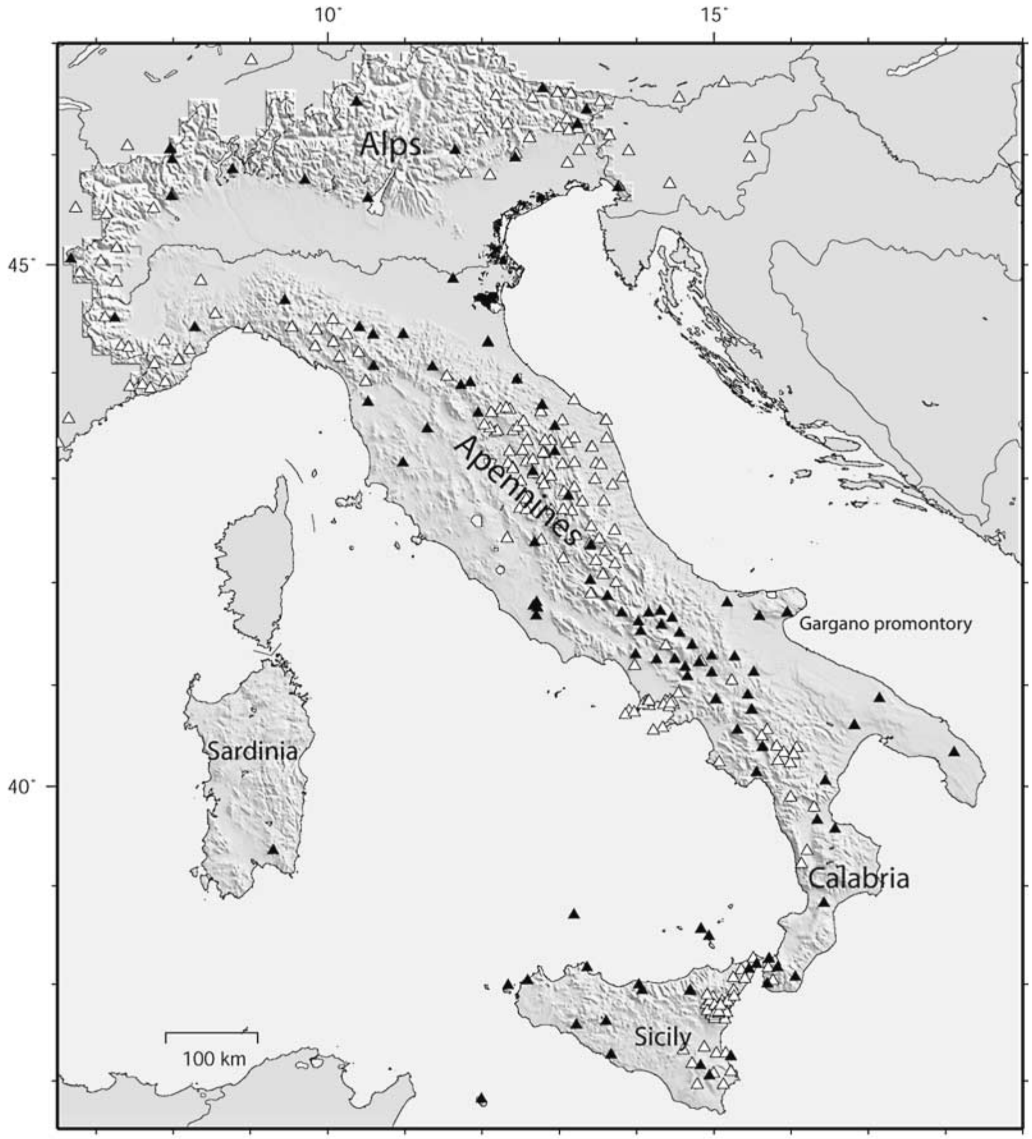

Figure 1. Distribution of permanent seismic stations managed by different Italian and European institutions (filled triangles = RSNC stations managed by INGV; open triangles = other institutions).

by the National Earthquake Information Center (NEIC) and the International Seismological Centre (ISC).

Finally, we performed regression analysis to obtain M_L versus log M_0 and M_L versus M_w calibrations using the M_L data set collected and the 1997–2000 Italian earthquakes database from regional centroid moment tensor estimation for medium-strong earthquakes of the Mediterranean area (Pondrelli *et al.*, 2002).

Duration Magnitude Scale for Italian Earthquakes

A general formulation for the duration magnitude scale is

$$M_d = a \cdot \log(\tau) + b \cdot \Delta + c, \qquad (1)$$

with τ = duration observations and Δ = epicentral distance in kilometers. Several authors (Real and Teng, 1973; Bakun, 1984; Michaelson, 1990; Eaton, 1992; Mouayn *et al.*, 2004) proposed different duration magnitude models, including hypocentral distance factor, site correction, and instrument correction.

The magnitude duration scale used at INGV computed by Console *et al.* (1988) was not calibrated on M_L Wood–Anderson magnitude but derived from the Lee *et al.* (1972) formula. The scale accounts for epicentral distance and is

$$M_d = a \cdot \log(\tau + b \cdot \Delta) + c, \qquad (2)$$

with $a = 2.0$, $b = 0.082$, and $c = -0.87$. Malagnini *et al.* (2000) and Gasperini (2002) noticed that M_D provided by

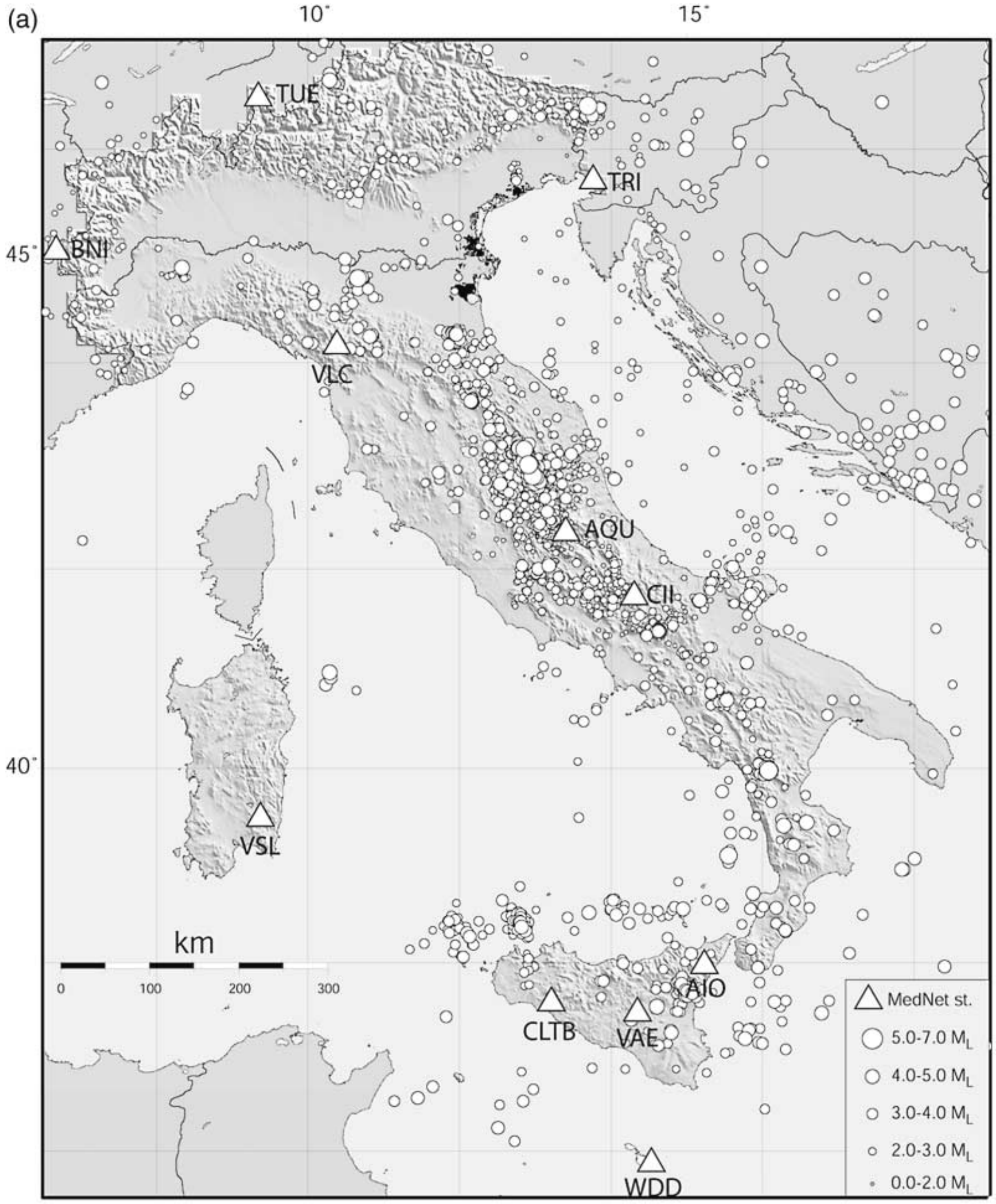

Figure 2. (a) 1996–2000 Italian earthquakes with M_L computed by MedNet Data Centre. Open triangles are for MedNet network seismic stations. (*continued*)

INGV underestimates the magnitude for events larger than 3.4. Moreover, in Gasperini (2002) a clear overestimation of magnitude by using Console *et al.* (1988) formula for smaller earthquakes is observed.

Data

The M_L–MedNet Data Set

Since 1996 an automatic system (MUSCLES) interacts with stations of MedNet providing reliable and real-time local magnitudes for the strongest earthquakes ($M_L > 3.8$) in the Mediterranean region (Mazza *et al.*, 1998). The automatic procedure, routinely used at INGV, operates the deconvolution of the velocity-response spectrum of the VBB seismometer to obtain the ground displacement and subsequently the convolution of the latter with the response of the Wood–Anderson seismometer. The maximum amplitude is automatically detected for each time series as well as the arithmetic average of the amplitude of the two horizontal components of each station to determine the local magnitude according to the Richter definition. Distance corrections correspond to Richter attenuation function parameters computed for California, because they satisfy the attenuation function characteristics of Italy (Gasperini, 2002). The final

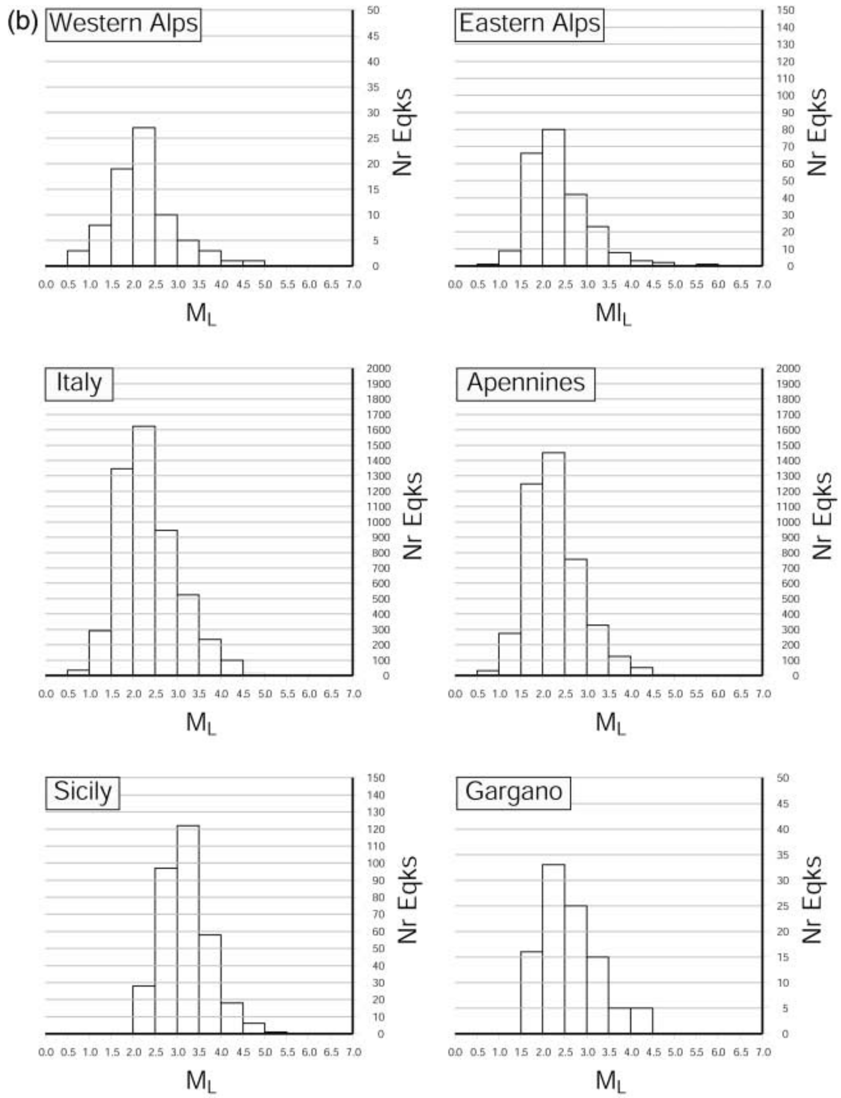

Figure 2. (*continued*) (b) Frequency distribution of 1996–2000 Italian earthquakes with M_L computed by MedNet Data Center: entire data set (left middle); regional subsets (all others). For geographical references see Figure 1.

M_L is derived from the average values obtained at different stations and the standard deviation is also computed.

MedNet data are available since 1990 with a few stations, but the network expanded during the past fourteen years and at present counts 21 stations. This created the capability to produce a catalog of 5068 revised local magnitude earthquakes from 1996 up to 2000 estimated with accuracy. The magnitudes were computed using all available recordings for each event, discarding data with bad signal-to-noise ratios. Distance factors are improved by using the more accurate hypocentral location of the INGV Bulletin. The 1996–2000 M_L-MedNet data set covers the Italian region well, with a concentration in the Central Apennines, where the M_w 6.0 1997 Colfiorito sequence occurred (Fig. 2a). M_L ranges from 0.8 to 5.6; the most representative class of magnitude corresponds to $2.0 < M_L < 3.0$ (Fig. 2b).

Duration Estimates

Duration estimates of Italian earthquakes are available from bulletins of each Italian seismological observatory that manages national or regional permanent networks. The estimate of event duration is visually defined by the analysts from *P*-onset time until the point when the signal envelope decays down to the pre-event noise level. Nevertheless, definition of event duration is not homogeneous at each observatory. Because the visual determination produces some bias in the earthquakes catalogs, we have preferred to select only durations coming from RSNC stations to avoid summation of different catalog biases, which means seismic events recorded exclusively by regional permanent networks are not included in the 1996–2000 M_L durations data set. The data set consists of 4929 earthquakes with 21,995 RSNC duration estimates: 21% of earthquakes have five or more duration

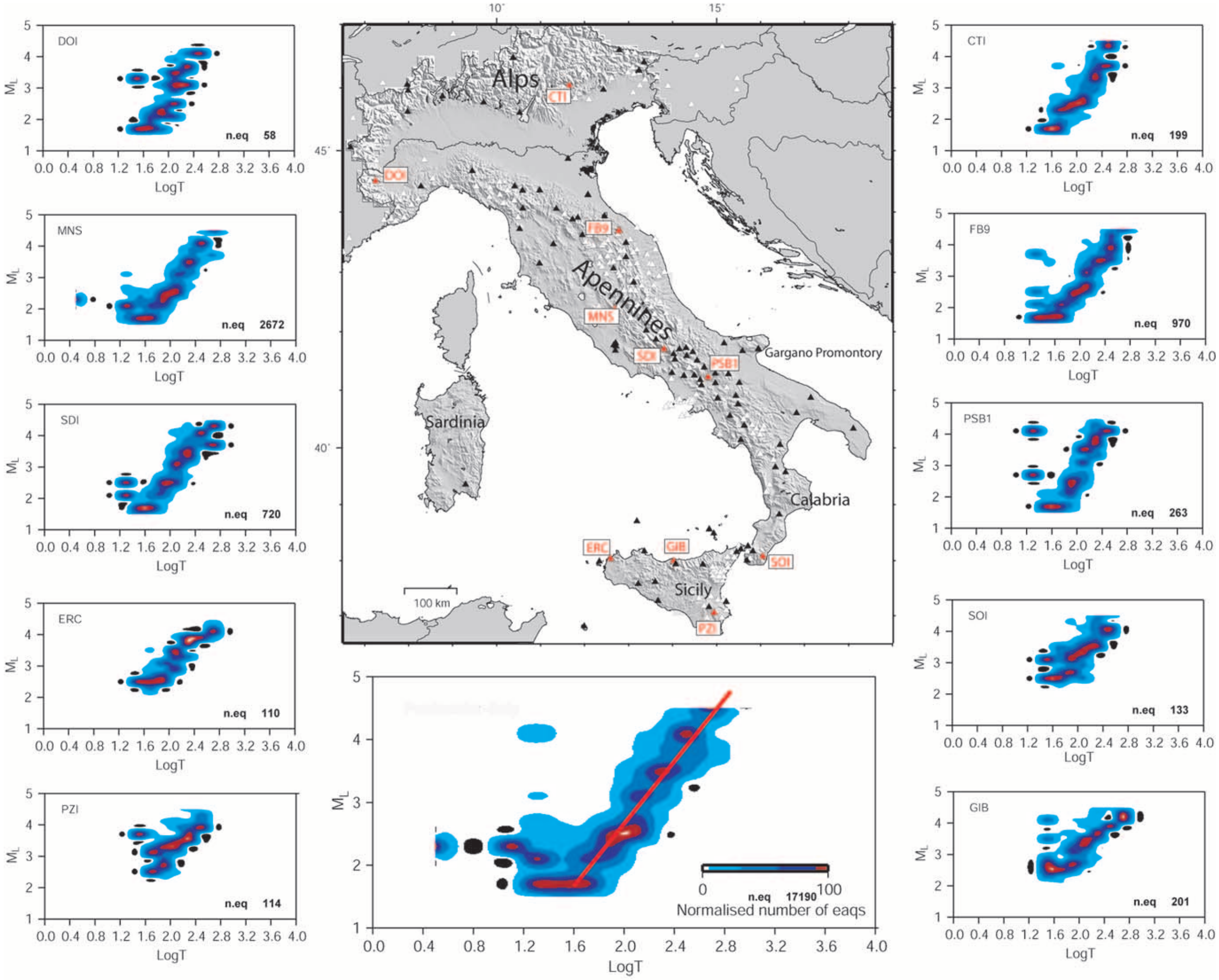

Figure 3. M_L versus logarithm of duration (T) observations at seismic stations located along the Italian Peninsula and Sicily. Duration observations are plotted by frequency per magnitude normalized to 100. Plots show a different trend at Sicilian and Southern Calabria stations (ERC, PZI, SOI, GBM). (bottom center) The M_L versus logarithm of duration plot for the Peninsular Italy stations recordings only. The red line corresponds to equation (3).

estimates. The data set is mainly contained within the first 100 km of station distance from the epicenter. This implies that the estimate of a regression coefficient associated with distance will not be well constrained. Besides, shallow crustal earthquakes are most of the data set.

We then analyzed the data set station by station. Figure 3 shows some representative samples of M_L versus log of duration distribution for Italian stations. The data, though largely scattered, show a similar trend for stations located in the Alps and in the Apennines. Stations in Sicily and in Southern Calabria clearly have a different trend, suggesting that attenuation properties of the crust may differ considerably across Italy (Scognamiglio *et al.*, 2005, and references therein). Accordingly, we calculated the coefficients of the model (1) by using linear least-squares multiple regression and dividing the data set in two subsets taking into account the observations from Figure 3. A least-squares regression method implies that the independent variable is not affected by error, and the dependent variable has errors normally distributed. Duration estimates and M_L are both affected by error and variance is difficult to estimate. In any case the error in the log of duration derived from duration estimate is approximately four times less in percentage than the M_L estimate error. Thus we avoid the use of orthogonal regression methods (Carrol and Ruppert, 1994). Furthermore, for the same reason, the choice of the dependent variable as Log of duration is justified and we did not investigate a maximum-likelihood parameter estimation (Stroymer *et al.*, 2004).

Table 1
Regression Results and Analysis of Variance

	Network Subset: Weighted and Limited Data Set					
	a	c	Standard Error	R^2	*F* Test	No. of Degrees of Freedom
Peninsular Italy and Sardinia	2.485253	−2.31379	0.347566	0.779386	5468.774	1548
Sicily and Messina Strait	1.313947	0.614009	0.392016	0.596361	2895.829	1960

Table 2
Station Corrections for 82 of the 99 RSNC Stations of 1996–2000 M_L MedNet Durations Data Set

Station Code	$dSta_j$	δ_j	*N*	Station Code	$dSta_j$	δ_j	*N*
AQU	−0.0248	0.0116	1042	MDI	0.1877	0.0563	38
ARV	0.0765	0.0105	1366	MEU	0.7768	0.0528	72
ASS	0.0114	0.0067	2796	MGR	0.1904	0.0466	108
ATN	0.5483	0.0487	58	MNO	0.5919	0.0359	162
AU9	0.6172	0.0384	122	MO9	0.5319	0.0337	142
BAI2	−0.0734	0.0411	67	MPG	0.2278	0.063	23
BDI	0.2155	0.0398	118	MSI	0.7669	0.0933	29
BR9	0.0528	0.0399	98	MU9	0.1108	0.0259	260
BRT	0.4657	0.0442	80	NRCA	−0.1171	0.0107	995
BS9	0.3819	0.1381	10	ORI	0.3229	0.0467	101
CA9	0.1524	0.0416	80	PGD	0.1266	0.0406	90
CI9	0.1634	0.0353	179	PII	0.2615	0.0501	86
CLTB	0.4303	0.0524	32	PLI2	0.1356	0.05	77
CRE	0.0903	0.0233	363	PQ9	0.0355	0.0152	523
CRV1	−0.055	0.0368	167	PSB1	−0.0755	0.0259	230
CS9	0.6198	0.0429	97	PTCC	−0.0992	0.0306	168
CSNT	0.26	0.038	207	PTS	0.5467	0.0546	17
CTI	−0.0351	0.0275	199	PZI	0.6081	0.039	114
DSB1	0.0981	0.0578	40	RDP	0.1476	0.0346	89
DUI	−0.1101	0.0258	160	RFI	0.0726	0.0306	170
EB9	0.0968	0.0418	126	RGNG	0.217	0.0653	61
ERC	0.4187	0.0304	106	RMI2	0.0609	0.0521	52
FAI	0.5951	0.0792	26	RMP	0.1587	0.0478	58
FAVR	0.5744	0.079	36	RNI2	−0.1757	0.0502	58
FB9	0.0351	0.0104	936	RSM	0.1678	0.03	125
FG2	0.178	0.0333	122	RV12	−0.1476	0.0282	117
FG3	0.2039	0.039	94	SAI	0.6472	0.0704	62
FG4	0.2254	0.0571	57	SAL	0.193	0.0539	90
FG5	0.0956	0.032	141	SC9	0.6382	0.0656	46
FVI	−0.0355	0.0298	206	SDI	−0.0406	0.0139	665
GE9	0.0797	0.0328	146	SFI	0.0651	0.0161	416
GIB	0.5121	0.0272	195	SGO	0.1968	0.0251	254
GMB	0.7706	0.0756	9	SL9	0.3176	0.0354	150
GRFL	0.3784	0.117	27	SMB1	−0.1729	0.0205	273
GRI	0.5934	0.0473	88	SNTG	−0.0234	0.0155	777
GU9	0.116	0.0457	118	SOI	0.5564	0.0362	131
LCI	0.8096	0.109	21	TDS	0.4563	0.0571	85
LT9	0.3694	0.045	88	TRI	0.1336	0.0451	93
LVI	0.5044	0.0323	77	USI	0.3616	0.0404	60
MAB1	0.0469	0.0421	71	VVI	0.1738	0.0735	35
MCT	0.5824	0.0927	9	ZC9	0.0946	0.0441	166

Data Analysis

Regression Analysis

Data have been differently selected, either limiting the duration observations to log (T) = 1.7 (T~50 sec) as minimum or weighting by the frequency of durations per magnitude, to prevent possible bias caused by the nonuniform data distribution. One general conclusion from these tests is the poor contribution of the distance factor b since most of the durations estimates come from stations with epicentral distance shorter than 100 km and the b factor is not very sensitive at this short distance range.

Results show (Table 1) a good fit for Peninsular Italy subset ($R^2 = 0.78$), whereas the coefficient parameters are not well constrained for Sicilian subset ($R^2 = 0.60$).

Model variance also did not improve for different Sicilian subnets, suggesting that a linear relationship as (1) is not valid for the data distribution. We infer that the presence of Mt. Etna volcano, as well as large crustal heterogeneities across this region, are responsible for this behavior. Therefore, we choose to adopt a conservative strategy for calculating station corrections, as described in the next section, to avoid the arbitrary further selection of the data set. In summary, the formula calculated for the whole data set is the following:

$$M_{d_{ij}} = 2.49\ (\pm\ 0.03)\cdot\log(T_{ij}) - 2.31\ (\pm\ 0.08), \quad (3)$$

where i and j represent the ith event recorded at the jth station, while a and c coefficients of model (1) correspond to Peninsular Italy regression analysis parameters.

Station Corrections

Station corrections were computed using equation (3). Given the arguments for representing the source by a scalar, the station corrections represent additional propagation path and seismograph effects (Bakun, 1984; Michalson 1990). They are introduced to reduce the particular effect of the site of each station. Sc_j is the station correction at jth station of the network and is defined:

$$Sc_j = \frac{\sum_i (M_L - M_{d_{ij}})}{N}. \quad (4)$$

σ_j is the standard deviation of the mean:

$$\sigma_j = \sigma \Big/ \sqrt{N}, \quad (5)$$

and N is the number of events recorded at each station. Stations with numbers of recorded events $N < 9$ are excluded from station correction estimates and station corrections with $|\sigma_j| > Sc_j$ are not considered.

The final formula adopted is:

$$M^*_{d_{ij}} = 2.49(\pm\ 0.03)\cdot\log(T_{ij}) - 2.31(\pm\ 0.08) + Sc_j. \quad (6)$$

Station corrections range from -0.18 and 0.81 magnitude units with a maximum standard deviation of 0.14 units from the mean (Table 2); the highest values come from stations in Sicily and Southern Calabria (Fig. 4). The applications of the station corrections reduces the total rms from 0.44 to 0.40 for $M^*_{d_{ij}}$ estimates from equation (6). M_d of the event will be the arithmetic average of $M^*_{d_{ij}}$.

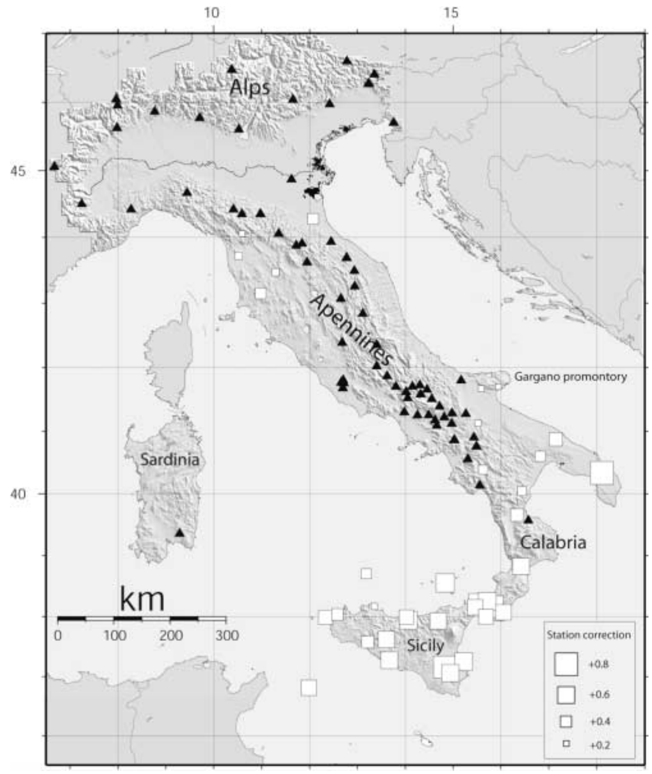

Figure 4. Station correction distribution for $Sc_j > +0.2$: negative values in this range were not found. Filled triangles are for stations without significant correction.

Residuals Analysis and Tests

We define the station residual as the difference between $M^*_{d_{ij}}$ and the mean M_d for an individual station. We plot all the station residuals versus epicentral distances Δ and log (T) (Fig. 5a,b). This allows us to check if station residuals are correlated with log (T) or epicentral distances Δ. The misfit is small and normally distributed within twice the standard deviation ($2\sigma = 0.28$), and are clearly uncorrelated with respect to both quantities.

We then compared M_d with M_L MedNet in the same interval (1996–2000). The best fit would be represented by a 1:1 trend. Figure 6a and b shows the expected trend, with a slight improvement when using stations correction (Fig. 6b). This result was expected as the regression coefficients have been obtained from the same data set. 1727 M_L MedNet of Italian earthquakes that occurred during 2001–2002 and computed in this study were used as an independent data set. When an independent data set is used for the same test, the fit is not as good, but the use of station corrections strongly improves the M_L estimate, at least in the interval covered by the data (Fig. 7a,b).

Finally, Figure 8 shows the same test using the present-day formula used at INGV (Console *et al.*, 1988), where the already stated overestimation at low magnitude is clearly visible.

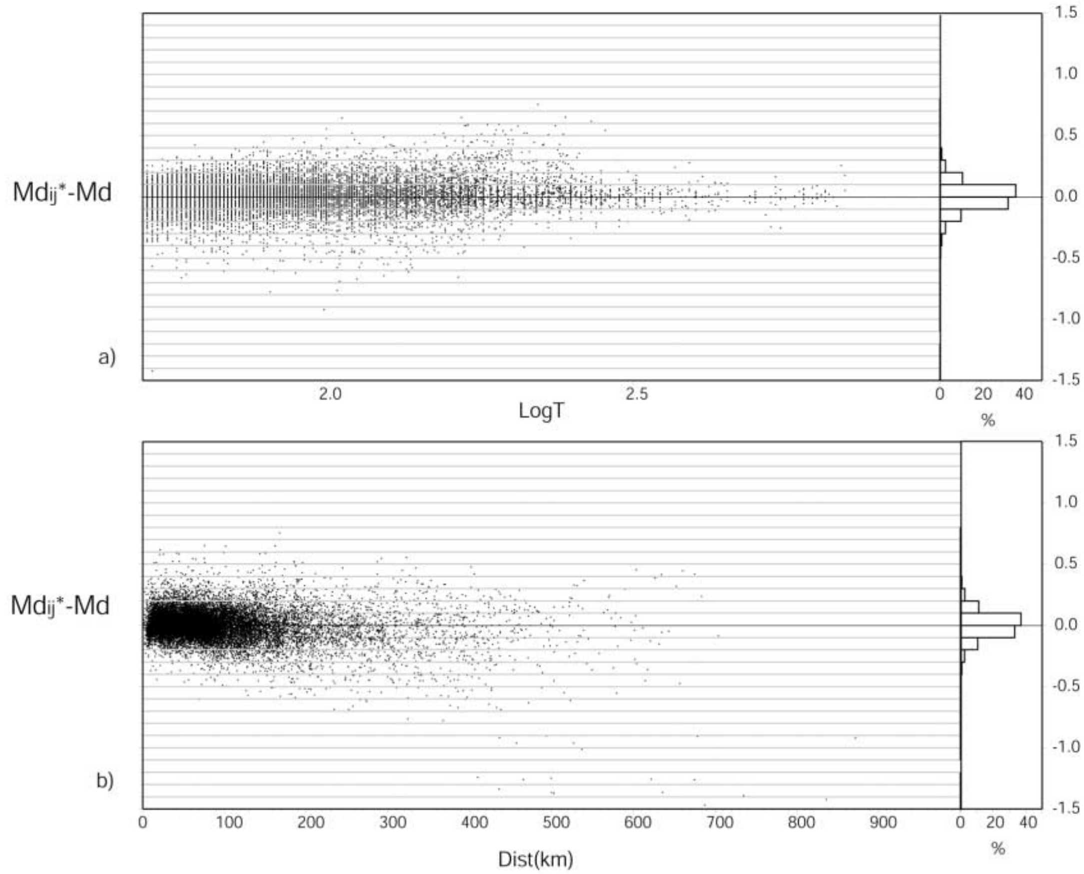

Figure 5. Residual values $M^{*}_{d_{ij}} - M_d$ versus log(T) (a) and versus epicentral distances $\triangle$ (b). Residuals are distributed between twice standard deviation ($2\sigma = 0.28$) (histograms on the right).

Revised Local and Duration Magnitude Catalog

M_D scale parameters calibrated with station corrections are applied to the duration estimates of the Italian relocated earthquake catalog 1981–2002 to obtain an Italian seismicity catalog with revised magnitudes. The range of applicability is 1.5–2.9 for log(T), that corresponds to 1.6–4.9 M_L, where T is the signal duration in seconds at stations. within 100 km from the epicenter. We could estimate 37,653 magnitudes of the 99,780 earthquakes contained in the catalogue. For earthquakes with magnitude M_L larger then 4.9, thus out of applicability of our regression, local magnitudes come from M_L MedNet (complete after 1996) and from the ICGW catalog (ICGW, 2001). For strongest ($M > 4.5$) deep earthquakes ($z > 35$ km) we use M_b from the International Seismological Centre (ISC). For some of these events there is a M_w calculation from CMT Harward or from RCMT if available (Pondrelli *et al.*, 2002).

There are, 44,151 magnitude estimates in the revised catalog, which represents 44% of the total number of located earthquakes. This percentage is due to several factors, including that during the first years of the catalog, duration estimates were not systematically computed and earthquakes were recorded only at regional networks. These events have not had magnitude estimates and are probably very small. Finally, the magnitude threshold of 1.6 M_L drastically reduces the numbers of earthquakes with magnitude estimates.

The cumulative frequency-magnitude distribution (Gutenberg–Richter relation), as shown in Figure 9a, is used to portray the most direct visualization of completeness of the catalog. The cutoff magnitude M_c corresponds to 1.6 and the b-value is 1.0. The 4.5–5.4 magnitude range is biased by the strongest aftershocks of the 1997 Colfiorito sequence (Central Apennines). We plotted also the cumulative distribution for only Sicilian earthquakes to test the method used for computing magnitudes for this region. The higher cutoff magnitude (M_c 2.2) is the result of the higher detection magnitude threshold for stations in that region, due to an intrinsic high-noise signal (Fig. 9b).

Regression Log $M_0 - M_L$

We performed linear regressions for scalar seismic moment M_0 and M_w versus M_L. Seismic-moment values are derived from regional centroid moment tensor estimates (Pondrelli *et al.*, 2002). We extracted from this catalog 110 earthquakes located in Italy between 1997 and 2002, ranging

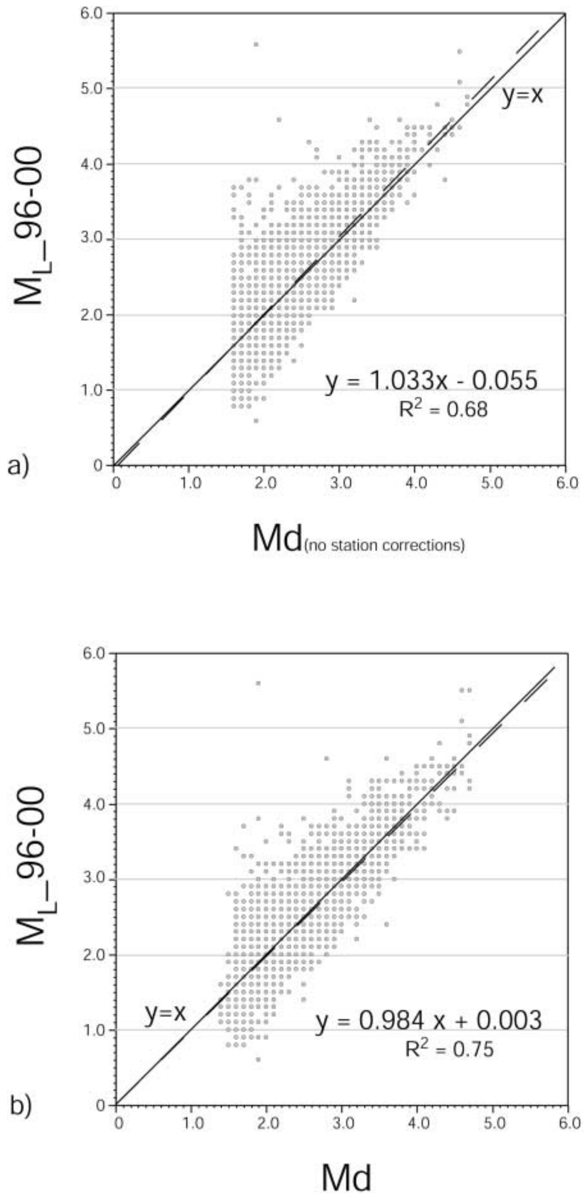

Figure 6. 4929 M_d computed with this study scale (equation 3), without and with stations corrections, respectively, against M_L MedNet (1996–2000) (a, b). Black lines correspond to $y = x$, and dashed lines represent the best least-squares fit.

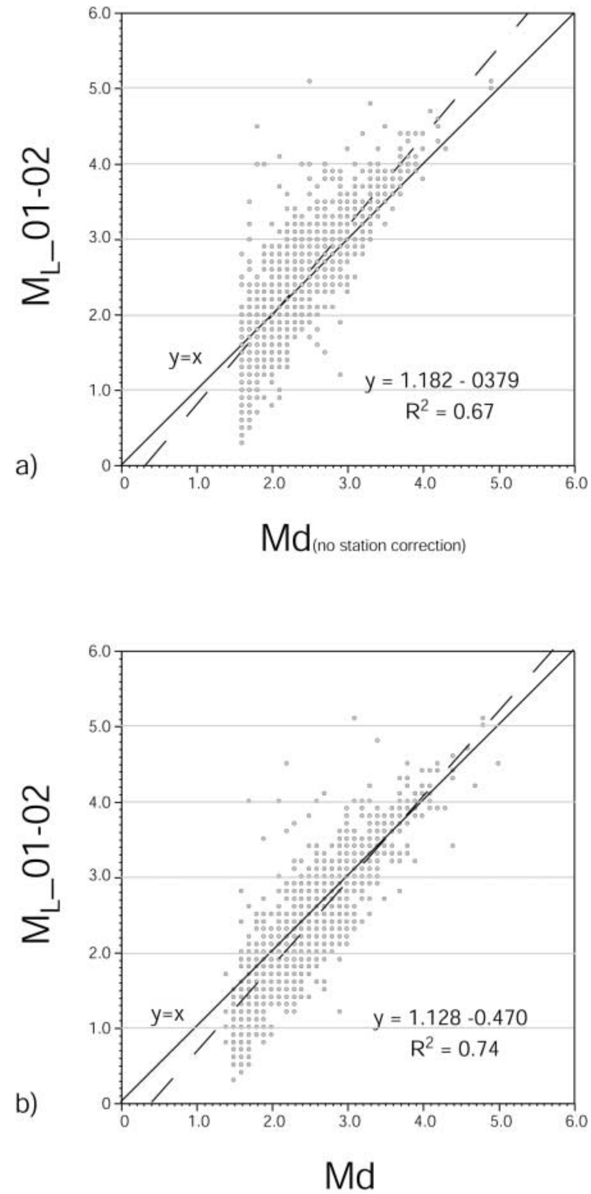

Figure 7. 1727 M_d computed in this study plotted against M_L Med-Net (2001–2002), without and with stations corrections, respectively, as a test data set. Figure shows that our study M_D scale (b) strongly reduces the bias of the previous M_D scale (Console *et al.*, 1988) (Fig. 8), corresponding well with M_L MedNet.

from 10^{15} to 10^{18} N m, with M_L MedNet from 3.5 to 5.8. Seismic moment M_0 versus M_L and M_w versus M_L plots are shown in Figure 10; the best least-squares fits are:

$$\text{Log } M_0 = 1.18(\pm 0.06) \cdot M_L + 10.92\ (\pm 0.28), \qquad R^2 = 0.76 \quad (7)$$

$$M_w = 0.79\ (\pm 0.4) \cdot M_L + 1.20\ (\pm 0.19) \qquad R^2 = 0.76 \quad (8)$$

Selvaggi *et al.* (1997) calculated the M_0 versus M_L relationship from 42 earthquakes located in Apennines (Italy) with magnitude range from M_L 1.5 to 3.5. Regression coefficients are different from those of equation (7) but similar to the Log $M_0 - M_L$ relationship parameters obtained from northwestern Italy earthquakes of the same range of magnitude by Bindi *et al.* (2005). Braumiller *et al.* (2005) found parameters of M_L versus M_w regression similar to that of equation (8) in the same range of magnitude. The lack of linearity of Log $M_0 - M_L$ relationships for a large range of magnitude is well known (Bakun, 1984; Hanks and Boore, 1984; Ben-

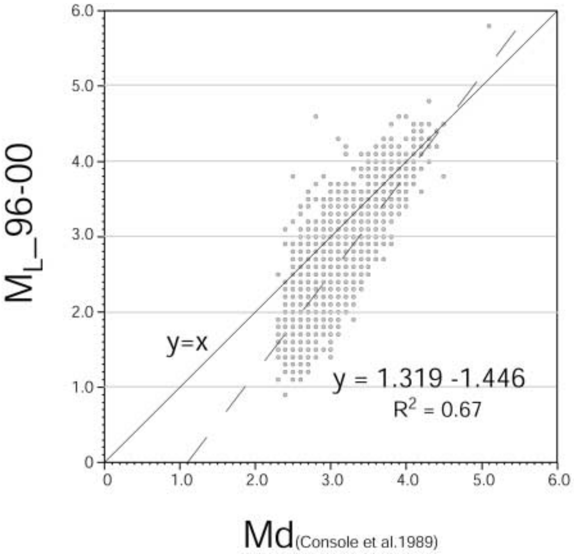

Figure 8. M_d computed with previous M_D scale (Console *et al.*, 1988) against M_L MedNet (1996–2000).

Zion and Zhu, 2002), corresponding in general to a quadratic relation. We noted that the range of our data set ($3.5 < M_L < 5.8$) falls in a region where the data distribution is well represented by a linear relation.

Conclusions and Discussion

This work likely represents the final stage of calculating local magnitude estimates by regression analysis for the Italian earthquake catalog. Presently, local magnitude is directly determined from the growing number of broadband calibrated seismometers of the RSNC network in Italy. Nevertheless, the need to compare magnitude estimates back in time has required the work presented in this article. The M_D scale calibrated in this work reduces the previous bias between M_D and M_L estimates for Italian earthquakes recorded by the Italian seismic network (RSNC). This allows us to compile a homogeneous magnitude catalog for Italian instrumental seismicity with a completeness greater than 1.6 (the revised earthquake catalog is on the web: Italian Seismic Catalogue, CSI 1.0, Castello *et al.*, 2005).

We have also introduced station corrections computed for RSNC seismic stations to decrease the large residuals due to the different wave propagations across Italy, such as in Sicily and Southern Calabria. Recent articles on different ground-motion scaling in Italy (Scognamiglio *et al.*, 2005, and references therein) confirm the necessity for further investigation

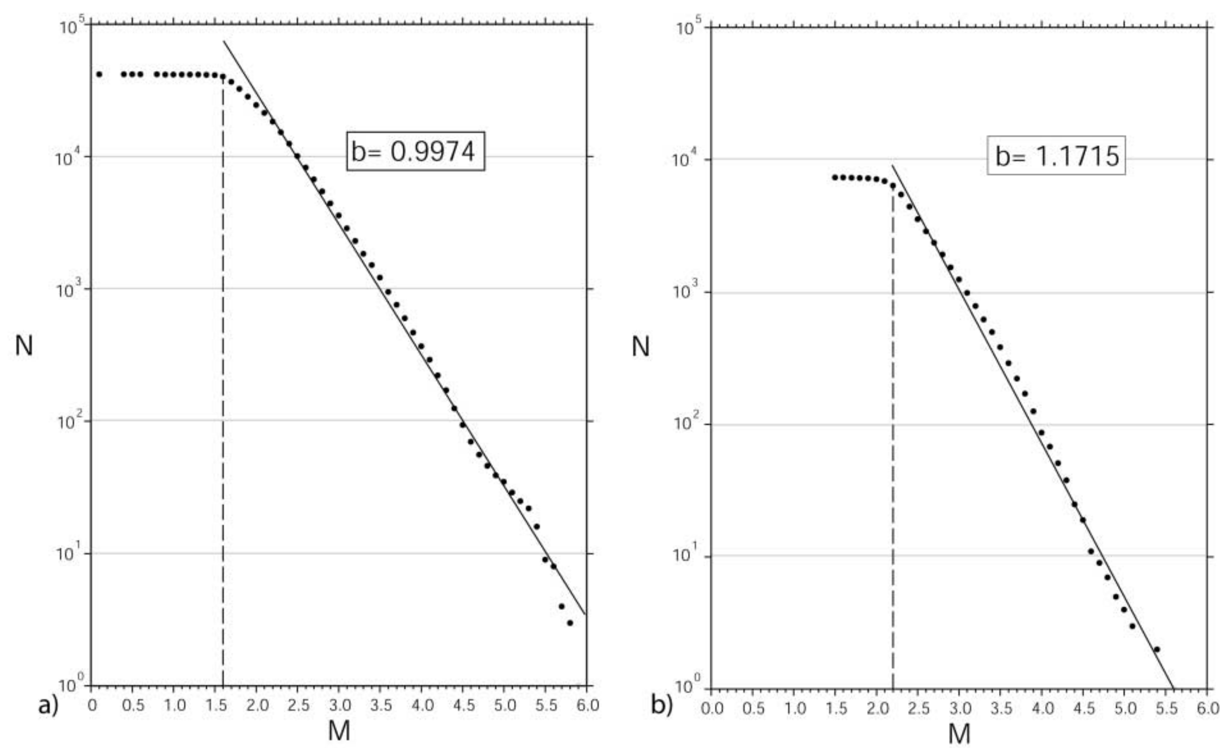

Figure 9. Cumulative distribution plot of the entire catalog (a) and cumulative distribution plot for only Sicilian earthquakes (b) as an estimation of agreement with the Gutenberg–Richter law.

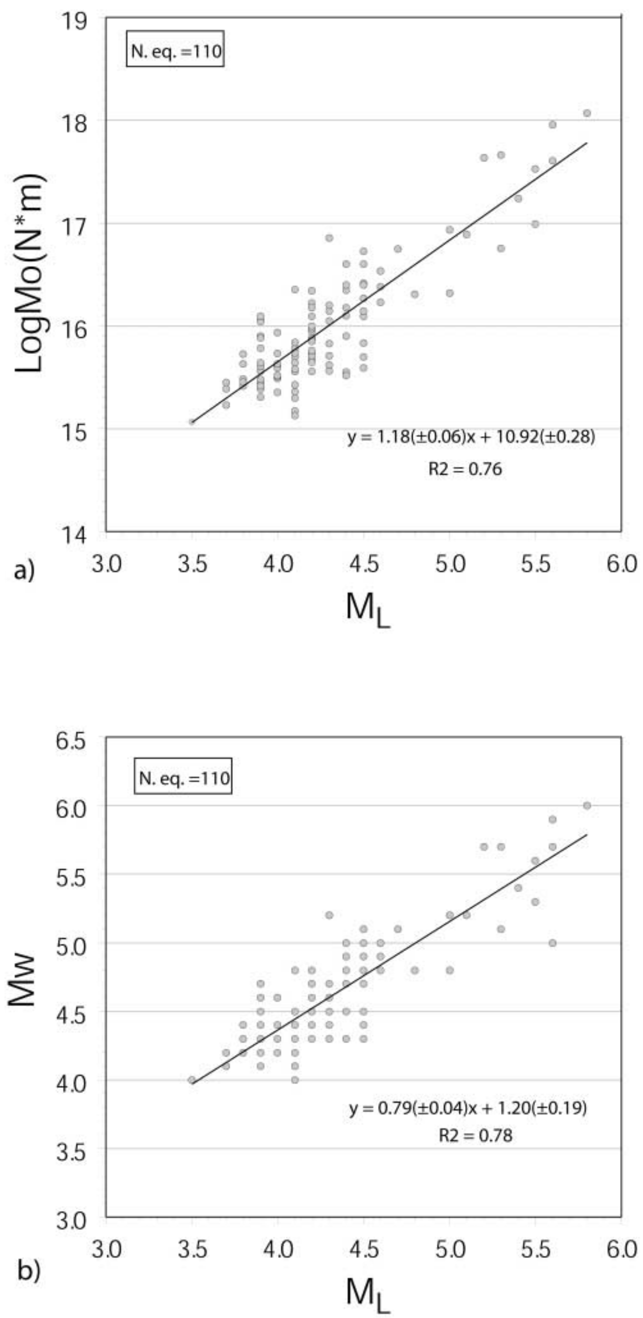

Figure 10. Log M_0 and M_W versus M_L. Seismic moment and M_w of 110 earthquakes located in Italy between 1997 and 2002 are from regional centroid moment tensor estimation (Pondrelli *et al.*, 2002) M_L MedNet computed in this study.

on attenuation functions, with the aim of improving the local magnitude estimates of Italian earthquakes.

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Istituto Nazionale di Geofisica e Vulcanologia
Centro Nazionale Terremoti
Via di Vigna Murata, 605
00176 Rome, Italy
(B.C., M.O.)

Istituto Nazionale di Geofisica e Vulcanologia
Centro per la Sismologia e l'Ingegneria Sismica
Via Castello d'Aquino 13
83035 Grottaminarda (AV), Italy
(G.S.)

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