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The attenuation of seismic intensity in the Etna region and comparison with other Italian volcanic districts

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Abstract
A detailed analysis of the intensity attenuation in the Etna and other Italian volcanic districts, was performed using the most recent and complete intensity datasets. Attenuation laws were derived through empirical models fitting ΔI (the difference between epicentral I_0 and site I_x intensities) average values *versus* hypocentral site distances by the least-square method. The huge amount of data available for the Etna area allowed us to elaborate bi-linear and logarithmic attenuation models, also taking source effects into account. Furthermore, the coefficients of the Grandori formulation have been re-calculated to verify the ones previously defined for seismic hazard purposes. Among the tested relationships, the logarithmic one is simple and fairly stable, so it was also adopted for the other volcanic Italian areas. The analysis showed different attenuation trends: on the one hand, Etna and Ischia show the highest decay of intensity ($\Delta I = 4$) in the first 20 km; on the contrary, the Aeolian Islands and Albani Hills present a slight intensity attenuation ($\Delta I = 2$) at 20 km from the hypocentre; finally, Vesuvius seems to have an intermediate behaviour between the two groups. The proposed regionalization gives a significantly better image of near-field damage in volcanic regions and is easily applicable to probabilistic seismic hazard analyses.

Key words *macroseismic intensity – attenuation – Mt. Etna – Italian volcanic areas*

1. Introduction

In active volcanic areas the attenuation of macroseismic intensity with distance is usually higher than in tectonic zones. This behaviour of seismic energy propagation is due both to physical properties of the medium, which is strongly fractured and with a very marked anisotropy at short distances (Del Pezzo *et al.*, 1987; Mayeda *et al.*, 1992; Bianco *et al.*, 1999; Ciccotti *et al.*, 2000; Martinez-Arevalo *et al.*, 2003; Novelo-Casanova and Martínez-Bringas, 2005), and to features of the seismicity itself, characterised by moderate magnitudes and shallowness of foci (Vilardo *et al.*, 1996; Del Pezzo *et al.*, 2004; Patanè and Giampiccolo, 2004). In the Etna region, for instance, earthquakes producing severe damage or even destruction (epicentral intensity up to X EMS-98) are associated with magnitudes less than 4.8 and depths above 3 km (Azzaro, 2004). As a result, the highest intensity areas are very small – usually narrow zones up 5 km long and 1 km wide astride the seismogenic source – and the effects disappear quickly in some twenty kilometres, with a strong attenuation of the seismic energy in a direction orthogonal to the fault. So, the attenuation relationships of macroseismic intensity used in Italy for purposes of seismic hazard assessment (Grandori *et al.*, 1987; Gasperini, 2001; Albarello and D'Amico, 2004) cannot be applied

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in volcanic districts, since they predict a lower attenuation rate with epicentral distance, inducing an overestimation of the expected intensities.

In general, formulas proposed to define the attenuation of ground-shaking parameters with distance are based on seismic wave propagation or empirical models. Most relationships derived from empirical approaches use logarithm and root functions (*e.g.*, Blake, 1941; Cornell, 1968). A comprehensive review of studies on attenuation laws is reported in Gasperini (2001).

In Italy, the Grandori *et al.* (1987) relationship has been used for seismic hazard assessment (Slejko *et al.*, 1998). In this framework, Peruzza (2000) calculated different coefficients of Grandori relationship using just one reference earthquake for each seismogenic zone of Italy defined in the ZS4 model (Meletti *et al.*, 2000), volcanic areas included. This approach has, however, the weakness of being based on a restricted dataset for every single seismogenic zone (*i.e.* the intensity distribution of the reference earthquake), with possible biases due to source mechanism, radiation pattern, site response etc. Berardi *et al.* (1994) proposed another empirical law, the Cubic Root Attenuation Model (CRAM), employed in some software to compute seismic hazard using site observations (Magri *et al.*, 1994). Lately, Albarello and D'Amico (2004) elaborated a new attenuation relationship taking into account both epicentral intensity and hypocentral distance.

The aim of this paper is to obtain intensity attenuation laws derived from empirical models that best fit data using the difference between epicentral and site intensities (ΔI), to be applied at a local scale in Italian volcanic districts (fig. 1), referring to the latest Italian seismogenic zone ZS9 (Gruppo di Lavoro, 2004). For the Etna area, in particular, the large amount of intensity data has allowed us to analyse in detail variations in the attenuation behaviour according to different laws.

2. Dataset

2.1. *Etna area*

The intensity data, used to calculate *ad hoc* intensity-distance relationships, were extracted from the macroseismic catalogue specifically compiled for the Mt. Etna region by Azzaro *et al.* (2000, 2002, 2006). It provides an extensive and homogenous dataset including in all 1778 earthquakes occurring from 1832 to present, 195 of which are above the damage threshold ($I \geq$ V-VI EMS-98). For our analysis, only the events characterised by epicentral intensity $I_0 \geq$ VII and by a number of macroseismic observations $N_{ip} \geq 10$ were selected, obtaining a subset of 24 earthquakes (table I). The intensity database used in this study consists of 813 site observations.

Figure 2 shows the epicentral distribution of the selected earthquakes with the relative intensity data points in the ZS936. The destructive and severely damaging events, with macroseismic magnitude $M_m \geq 3.7$ according to Azzaro and Barbano (1997), are mostly located in the eastern flank of the volcano which is crossed by the main seismogenic faults of the area (Azzaro, 2004), whereas only a few shocks occur outside this sector. As shown by instrumental data, the major seismicity (duration magnitude $M_d \geq 3.4$) occurring in the eastern flank of Etna is extremely shallow, with hypocentres less than 2 km in depth (fig. 3).

2.2. *Other volcanic districts (Aeolian Islands, Ischia, Vesuvius and Albani Hills)*

Specific earthquake catalogues for the other Italian volcanic areas have not been compiled so far and therefore we referred to the national seismic catalogue (CPTI Working Group, 2004). For the investigated districts this catalogue reports several earthquakes, but the events whose dataset of macroseismic observations is indeed suitable for studying attenuation is rather limited, so we have integrated data with earthquakes not included in the seismic catalogue.

For the Aeolian Islands only the earthquakes originating inside the volcanic sector (in bold in fig. 1) have been considered, discarding the tectonic events located in the Gulf of Patti and the Peloritani Mts. For this reason, we have not included in our analysis the 1978 earthquake which was chosen by Peruzza (2000) as a reference for calibrating the attenuation law of this area. As a result, we have selected 6 earthquakes with $I_0 \geq$ VI and $N_{ip} \geq 10$ (table II), 5 reported in the DOM database (Monachesi and Stucchi, 1997) and one

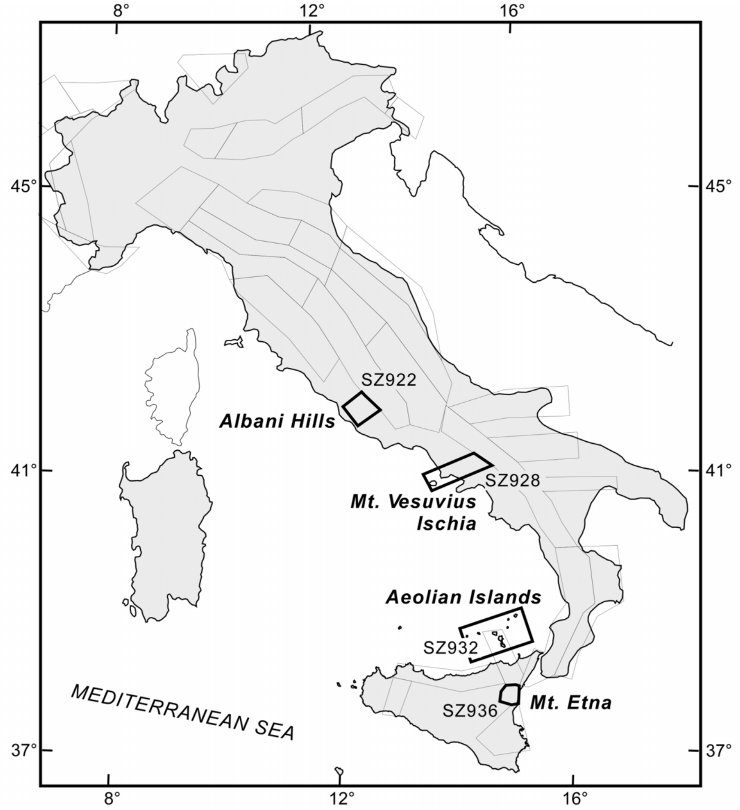

Fig. 1. Location of the studied volcanic areas (thick boxes) in the framework of the seismogenic zoning (thin polygons) used in the latest Italian seismic hazard map (Gruppo di Lavoro, 2004).

Table I. Dataset of the earthquakes selected for the Etna area. N_{ip}, number of intensity data points; I_0, epicentral intensity; M_m, macroseismic magnitude, calculated by the intensity-magnitude relationship from Azzaro and Barbano (1997); M_{aw}, moment magnitude from CPTI Working Group (2004); $*$ magnitude from surface waves *Ms* (Margottini, 1993). Source of data: 1) Azzaro *et al.* (2000); 1a) Azzaro *et al.* (2006).

Year	Month	Day	Hour	Min	N_{ip}	I_0	M_m	M_d	M_L	M_{aw}	Epicentral area	Lat	Long	Ref.
1865	7	19	01	00	31	IX	4.5			5.0	Fondo Macchia	37.702	15.153	1
1865	8	19	12	30	15	VIII	4.1				S. M. Ammalati	37.641	15.165	1
1879	6	17	06	50	25	VIII-IX	4.3			5.0	Bongiardo	37.678	15.143	1
1889	12	25	17	23	25	VII-VIII	3.9			4.8	S. M. Ammalati	37.651	15.156	1
1894	8	8	05	16	43	VIII-IX	4.3			5.2	Mazzasette	37.653	15.110	1
1898	5	14	04	45	20	VII-VIII	3.9			4.9	S. M. Licodia	37.615	14.889	1
1907	12	7	21	28	18	VII-VIII	3.9			4.8	Fiandaca	37.632	15.134	1
1909	10	21	16	48	13	VII	3.7			4.3	S. G. Bosco	37.655	15.162	1
1911	10	15	08	52	41	VIII-IX	4.3		4.5*	5.3	Fondo Macchia	37.699	15.154	1

Table I (*continued*).

Year	Month	Day	Hour	Min	N_{ip}	I_0	M_m	M_d	M_L	M_{aw}	Epicentral area	Lat	Long	Ref.
1914	5	8	18	01	79	IX-X	4.7		4.9*	5.3	Linera	37.659	15.149	1
1920	9	26	02	56	15	VII-VIII	3.9			4.6	Codavolpe	37.713	15.161	1
1952	3	19	08	13	98	VII-VIII	3.9		4.9*	5.2	Linera	37.660	15.147	1
1971	4	21	16	30	11	VIII	4.1	3.5	4.0	4.2	Fondo Macchia	37.714	15.148	1
1973	8	3	19	49	35	VII	3.7	3.9		4.2	S.M. Ammalati	37.650	15.157	1
1973	8	18	22	38	18	VII	3.7	3.7			Guardia	37.666	15.165	1
1984	6	19	15	19	46	VII	3.7	3.4		4.4	Fiandaca	37.636	15.131	1
1984	10	19	17	43	102	VII	3.7	4.2	3.5		Zafferana Etnea	37.694	15.103	1
1984	10	25	01	11	105	VIII	4.1	3.9		4.7	Fleri	37.660	15.095	1
1985	12	25	02	39	10	VII	3.7	3.3			Piano Provenzana	37.805	15.048	1
1986	2	2	16	10	55	VII	3.7	3.5			S.G. Bosco	37.653	15.163	1
1986	10	29	23	18	35	VII	3.7	4.0		4.4	Piano Provenzana	37.806	15.051	1
1989	1	29	07	30	68	VII	3.7	4.1	3.3	4.5	Codavolpe	37.705	15.165	1
2002	10	27	02	50	17	VIII	4.1	4.2	4.8		Piano Provenzana	37.803	15.055	1a
2002	10	29	10	02	38	VIII	4.1	4.4	4.5	4.8	Bongiardo	37.674	15.143	1a

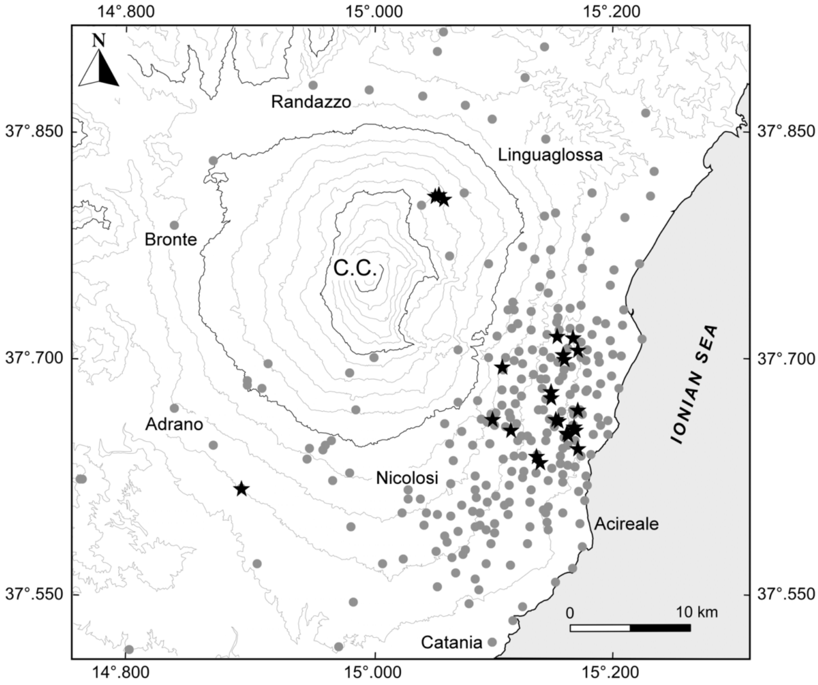

Fig. 2. Distribution of the epicentres (black stars) and related 813 site intensity observations (grey circles) of the 24 earthquakes used for the Etna region (listed in table I).

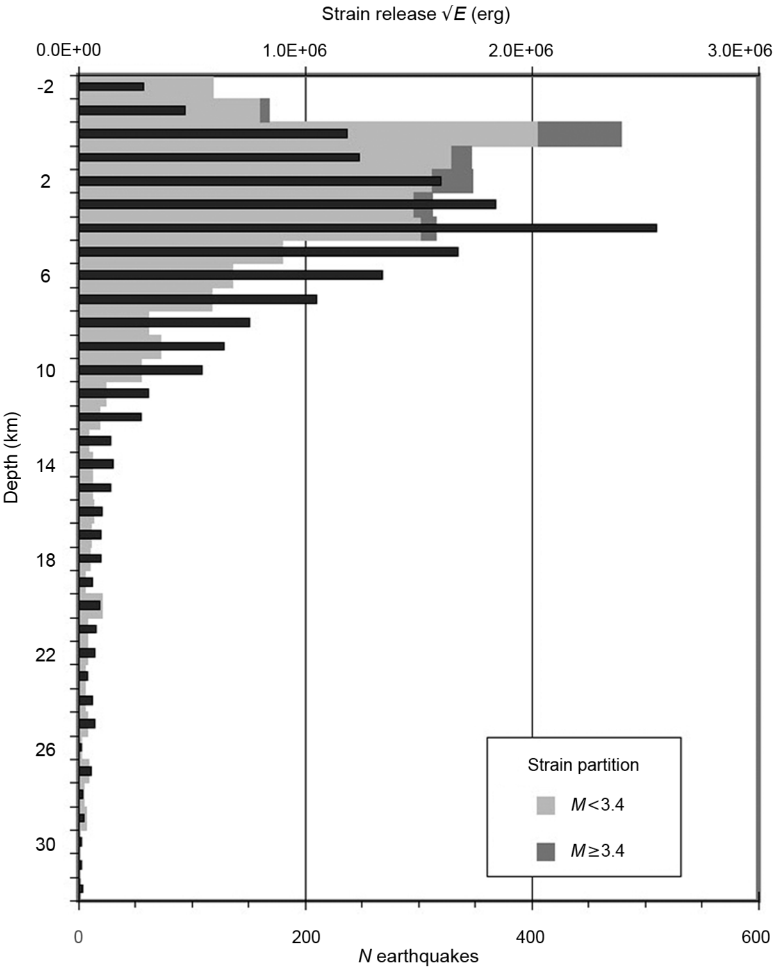

Fig. 3. Distribution of strain release *versus* depth (km below sea level) on Etna's eastern flank obtained from instrumental data (1999-2005, from Gruppo di Lavoro Analisi Dati Sismici, 2005).

Table II. Dataset of the earthquakes selected for the Aeolian Islands. M_{aw}, moment magnitude from CPTI Working Group (2004). Source of data: 2) Monachesi and Stucchi (1997); 3) Azzaro (1995).

Year	Month	Day	Hour	Min	N_{ip}	I_0	M_L	M_{aw}	Epicentral area	Lat	Long	Ref.
1892	3	16	12	38	28	VII-VIII		5.4	Alicudi	38.556	14.590	2
1894	12	27			12	VII		5.2	Filicudi	38.562	14.570	2
1916	7	3	23	21	18	VI-VII		5.1	Stromboli	38.812	15.237	2
1926	8	17	01	42	44	VII-VIII		5.3	Salina	38.567	14.825	2
1930	3	26	10	52	11	VII-VIII		5.0	Filicudi	38.548	14.467	2
1995	7	23	18	44	117	VI	4.8		Filicudi	38.567	14.583	3

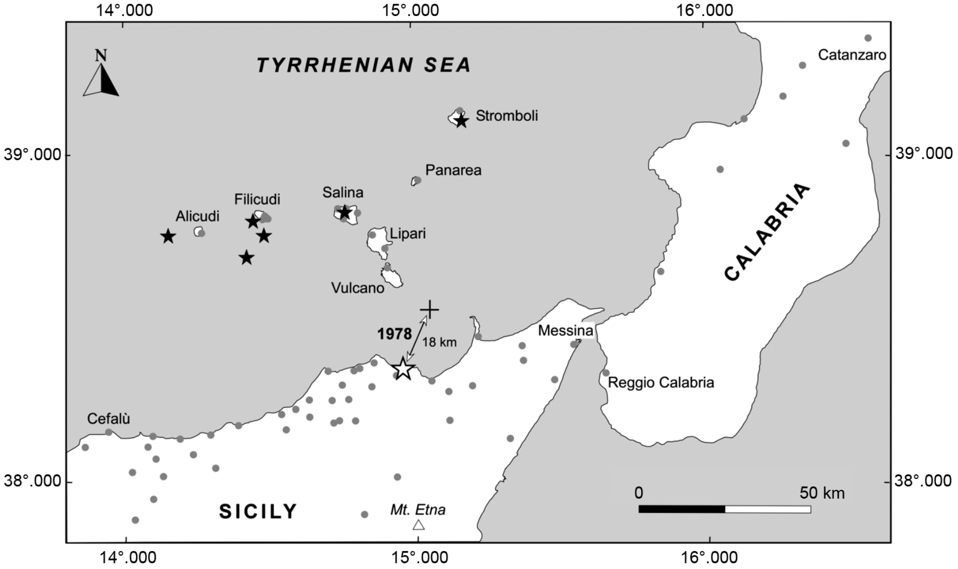

Fig. 4. Distribution of the epicentres and related 117 intensity site observations concerning the 6 earthquakes used for the Aeolian Islands (listed in table II). Symbols as in fig. 2. The white star and the cross represent, respectively, the macroseismic and instrumental epicentres of the 1978 Gulf of Patti earthquake.

Table III. Dataset of the earthquakes selected for the Vesuvius-Ischia district. M_{aw}, moment magnitude from CPTI Working Group (2004). Source of data: 4) SGA (2002); 5) Boschi *et al.* (2000); 6) Cubellis and Marturano (2002).

Year	Month	Day	Hour	Min	N_{ip}	I_0	M_L	M_{aw}	Epicentral area	Lat	Long	Ref.
1881	3	4	12		9	VIII		5.4	Casamicciola	40.750	13.917	4
1883	7	28	20	25	28	IX		5.8	Casamicciola	40.750	13.880	5
1999	9	10	07	41	48	VI	3.6		Vesuvius	40.825	14.411	6

retrieved from Azzaro (1995), obtaining a dataset of 117 macroseismic observations (fig. 4).

The availability of data for the Neapolitan volcanic district (ZS928) is scant. For Ischia Island only two shock (with $I_0 \geq$ VIII) that are appropriate for the analysis were found (table III), one reported in the DOM database (Monachesi and Stucchi, 1997) and the other one in SGA (2002), for a total of 37 intensity data. For Vesuvius, just one earthquake of I_0=VI (Cubellis and Marturano, 2002) is available, with 48 macroseismic observations (fig. 5).

Finally, for the Albani Hills (ZS922) the dataset consists of 5 earthquakes with $I_0 \geq$ VI-VII (table IV), all characterised by a significant number of intensity data points retrieved from the DOM and CFTI databases (Monachesi and Stucchi, 1997; Boschi *et al.*, 2000). On the whole, 190 macroseismic observations are available (fig. 6).

3. Data analysis and results

In the following, we analyse the presented datasets by plotting, for each volcanic district, the hypocentral distances *D* of the points *versus* ΔI, the difference between epicentral I_0 and site I_x intensities. The I_0 values are retrieved from the aforementioned catalogues, and in most cases correspond to the maximum observed intensity. Then some attenuation relationships are compared in order to find the law that empirically best fits data.

3.1. *Etna area*

The intensity data points are not uniformly distributed throughout the Etna area, most of them being located in the eastern sector of the volcano (fig. 2), the most intensively urbanised one. The focal depth used to calculate the hypocentral distance *D* was defined at 1 km b.s.l., as indicated by instrumental data (fig. 3). Considering that intensity data are much denser at short distances from the epicentres than at longer ones, we calculated the arithmetic average of ΔI and the corresponding 95% confidence intervals, within intervals of 1 km up to 10 km of distance, 5 km up to 20 km whereas at distances larger

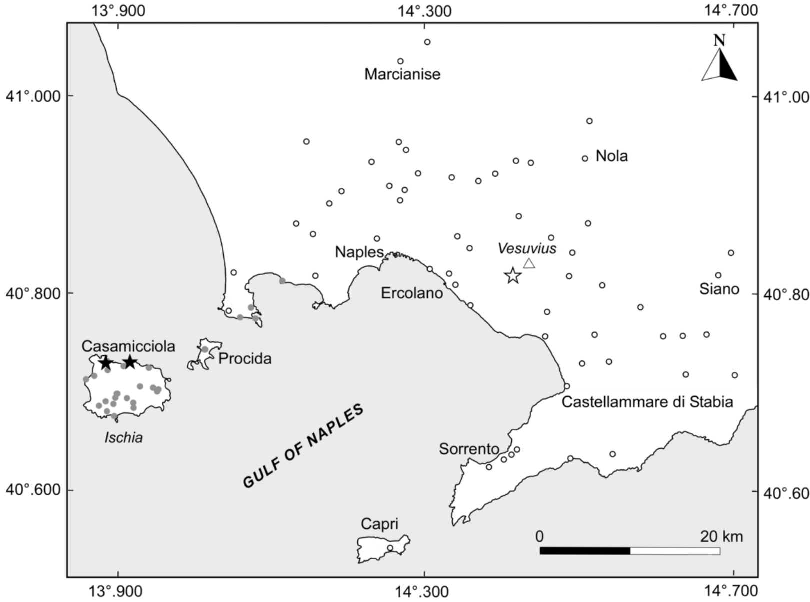

Fig. 5. Distribution of the epicentres and related site intensities of the earthquakes used for the Neapolitan volcanic district (listed in table III). Symbols as in fig. 2: Ischia (black star), 2 earthquakes for 37 site observations; Vesuvius (white star), 1 earthquake for 48 site observations.

Table IV. Dataset of the earthquakes selected for the Albani Hills. M_{aw}, moment magnitude from CPTI Working Group (2004). Source of data: 2) Monachesi and Stucchi (1997); 5) Boschi *et al.* (2000).

Year	Month	Day	Hour	Min	N_{ip}	I_0	M_{aw}	Epicentral area	Lat	Long	Ref.
1806	8	26	07	35	35	VII-VIII	5.5	Albani Hills	41.720	12.730	5
1876	10	26	14	18	29	VI-VII	5.0	Palestrina	41.827	12.784	2
1892	1	22			81	VI-VII	5.2	Albani Hills	41.725	12.712	2
1899	7	19	13	18	125	VII	5.2	Albani Hills	41.800	12.680	5
1927	12	26	15	06	38	VII	5.0	Albani Hills	41.700	12.700	5

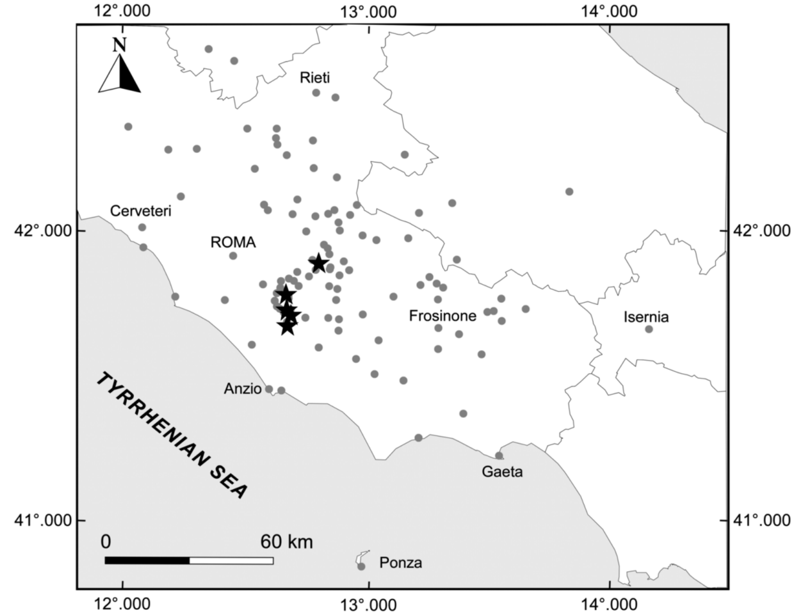

Fig. 6. Distribution of the epicentres and related 190 intensity site observations of the 5 earthquakes analysed for the Albani Hills (listed in table IV). Symbols as in fig. 2.

than 20 km the step has been increased to 10 km (fig. 7a).

Since sampling at low intensity sites (I_x<IV) may be incomplete, data with I_x≤III-IV were removed. Therefore, a test to investigate the influence of low-degree incompleteness in the sample, was performed by plotting the average residuals as a function of predicted intensity. The bias is evidenced by systematically negative ΔI average residuals at low predicted intensities and positive ones at large intensities. The obtained results show that data are incomplete for ΔI values ≥5, which have been excluded from the analysis.

On average there are more than 75 intensity data in each ΔI class in the near field (≤10 km), and about 20 in the far field (>10 km).

Figure 7b shows the typical pattern of the shallow Etnean shocks with respect to deeper crustal events such as the 1818 one, the largest (M_{aw}=6.2) known earthquake located in the area but not related to the shallow volcano-tectonic structures (Azzaro, 2004). In such a case the attenuation is much lower – damage extending up to 50 km far from the epicentre and the felt area is some hundreds kilometres wide – similarly to that of the regional events.

In order to test the best attenuation model, the ΔI average values were fitted by least-square method using a bi-linear relationship, as done by Gasperini (2001) for the whole Italian dataset, and a logarithmic law (fig. 8a). Furthermore, the coefficients of the Grandori *et al.* (1987) relationship were re-calculated to verify probable variations with respect to those computed by Peruzza (2000) using a very limited dataset.

The obtained bi-linear relationship is

$$\Delta I = 0.81 + 0.34\ D \text{ for } D \leq 8 \text{ km}$$

$$\Delta I = 0.81 + 0.34 \times 8 + 0.02\ (D - 8) \text{ for } D > 8 \text{ km}$$

$$R^2 = 0.95$$

where D is the hypocentral distance.

The logarithmic regression is

$$\Delta I = 0.98 \ln(D) + 1.01 \quad R^2 = 0.92 \quad \text{for } D \geq 0.4 \text{ km.}$$

The Grandori *et al.* (1987) relationship is

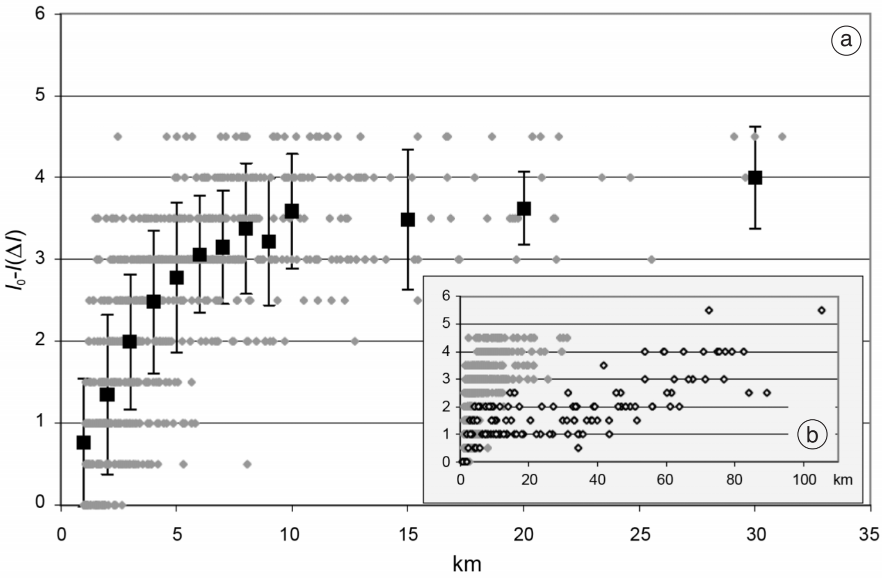

Fig. 7a,b. Etna area. a) Hypocentral distances *versus* ΔI (difference between epicentral and site intensities) for the earthquakes used in the analysis (grey diamonds); black squares indicate the arithmetic average of ΔI and relative standard deviation. b) Comparison between the 1818 earthquake intensity data (black diamonds) with respect to the dataset (grey diamonds).

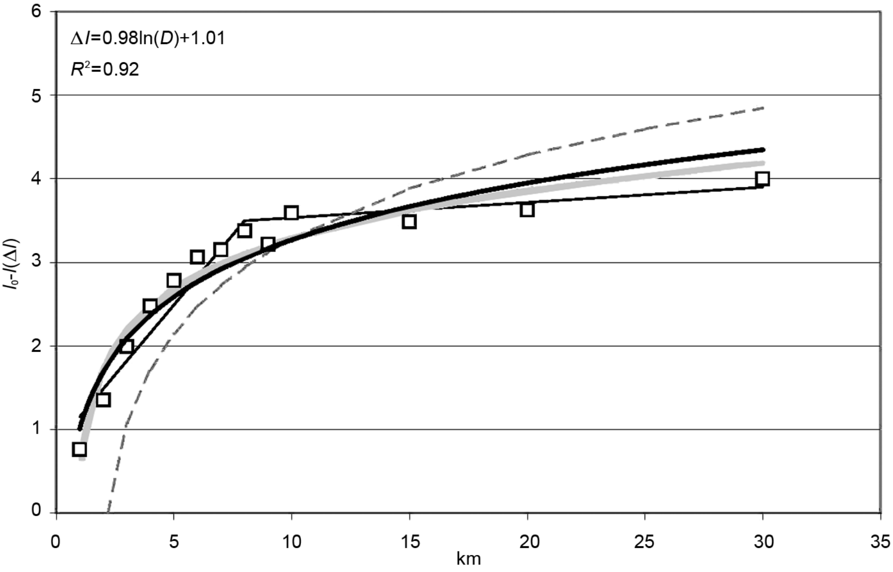

Fig. 8a. Different intensity attenuation relationships for the Etna area: bi-linear (thin line), logarithmic (thick line), Grandori *et al*. (1987) (grey), Peruzza (2000) (dashed); squares show the arithmetic average of ΔI in fig. 7a.

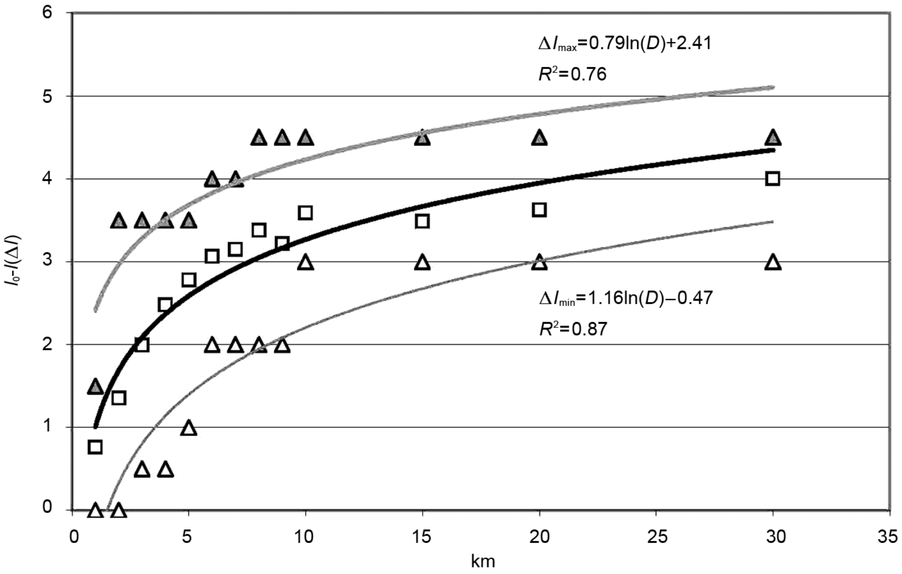

Fig. 8b. Best fits of the logarithmic relationships for maximum, minimum (grey and white triangles) and average values of attenuation; squares show the arithmetic average of ΔI in fig. 7a.

$$\Delta I = \frac{1}{\ln \Psi} \ln\left[1 + \frac{\Psi - 1}{\Psi_0}\left(\frac{D}{D_0} - 1\right)\right]$$

where $\Psi=3.556$, $\Psi_0=0.460$ and $D_0=0.804$, $R^2=0.95$.

For all the tested relationships the R^2 values are comparable. In terms of expected ΔI, there is no great difference between the results obtained from the three relationships. The bi-linear model shows a significant change in coefficients around 8 km of distance from the epicentre and requires three coefficients to be defined. The Grandori relationship is strongly dependent on three coefficients strictly related to each other and to the epicentral intensity (I_0). Differences in the attenuation trend (fig. 8a) between the Grandori relationship and our logarithmic regression are evident in the near- and far-field (around 10 km) as a result of the diverse dataset used by us and Peruzza (2000). So we propose to adopt the logarithmic law as intensity attenuation model in the Etna region because it is simpler, as it requires only two coefficients to be defined and it corresponds to a basic attenuation law valid at any distance. For this reason hereafter it was adopted as an appropriate attenuation law also for the other volcanic Italian districts.

The trend of logarithmic regression in fig. 8a does not take into account the source effect. In fact, the attenuation pattern of heavily damaging earthquakes is characterised by a highest intensity area distributed along the fault strike and a rapid decrease of the intensity in the perpendicular direction (fig. 9). Therefore we computed the maximum and minimum values of ΔI for each distance class, at the corresponding 75% confidence intervals, obtaining the related logarithmic curves of maximum and minimum attenuation (fig. 8b). In the near and far fields they are parallel to the average attenuation regression but shifted by about 1 intensity degree. These relationships can be adopted to better model hazard scenarios at a local scale of the volcano but for probabilistic assessment at a larger scale (*i.e.* national seismic mapping), we retain that the use of the logarithmic attenuation regression deriving from the ΔI average values is more suitable.

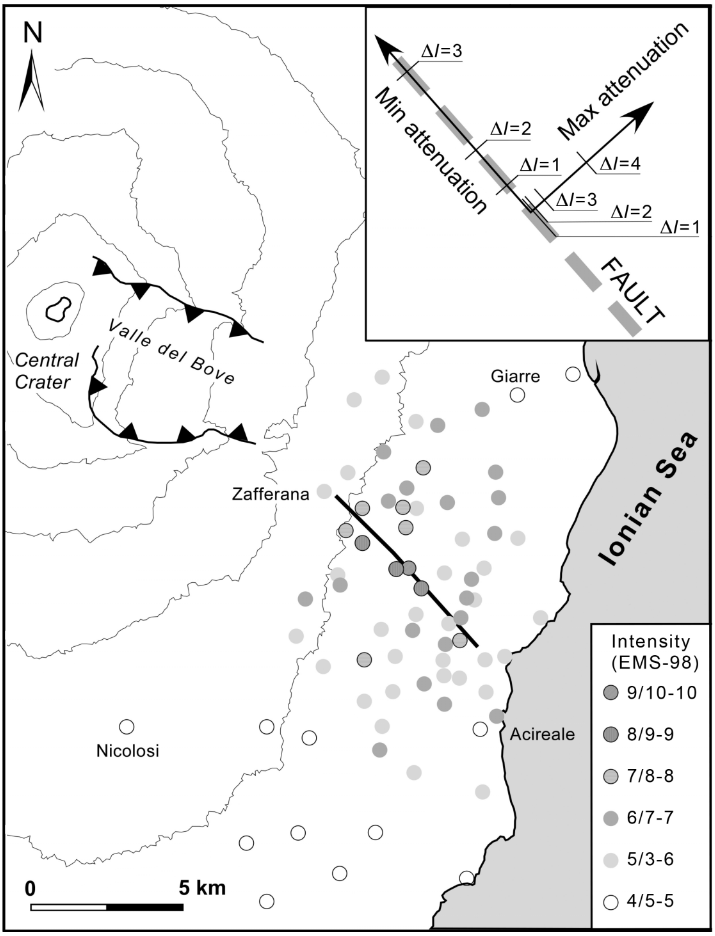

Fig. 9. Intensity map of the 1914 destructive earthquake (I_0=X EMS-98), from Azzaro *et al.*, (2000). Note the maximum intensities elongated astride the causative fault (line in bold), which corresponds to the minimum attenuation. Inset represents the minimum and maximum attenuation trends resulting from the curves of fig. 8b.

3.2. *Aeolian Islands*

The distribution of the intensity data throughout the Aeolian Islands suffers from a lack of points in the near field due to the presence of the sea and the shape of the archipelago itself (fig. 4). The dataset of this area was filtered by removing all intensity data with $\Delta I \geq 5$ and distance >150 km from the epicentre; with regard to the mean hypocentral depth, the value has been fixed at 10 km b.s.l, as adopted in the seismic zoning for the recent hazard map of Italy (Gruppo di Lavoro, 2004). Figure 10a shows the arithmetic average of ΔI for classes of hypocentral distances of 5 km up to 20 km of distance, whereas at distances larger than 20 km the step has been increased to 10 km, using the same procedure described above. Figure 10b shows the calculated logarithmic attenuation relationship

$$\Delta I = 1.28\ln(D) - 2.39 \quad R^2 = 0.89 \quad \text{for } D \geq 6.5 \text{ km.}$$

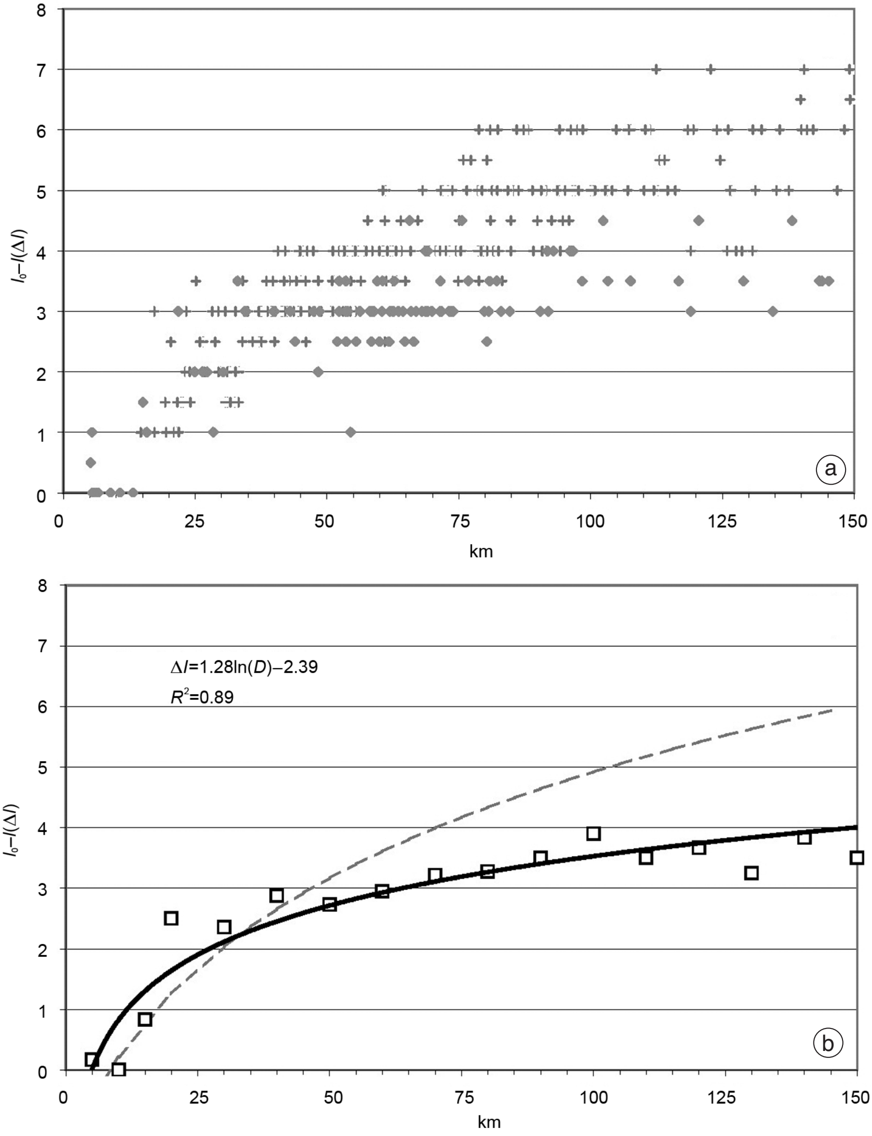

Fig. 10a,b. Aeolian Islands. a) Hypocentral distances *versus* ΔI for the earthquakes used in the analysis (diamonds) and comparison with the 1978 Gulf of Patti earthquake intensity data (crosses). b) Best fits (solid line) of the logarithmic relationship for the arithmetic average of ΔI (squares) and comparison with the Peruzza (2000) equation (dashed).

The R^2 is lower than that of the Etna area since the curve in the first 25 km is based only on the average of 4 data. By comparison, the data of the 1978 earthquake used by Peruzza (2000) to compute the attenuation model, are also represented. In this case, the epicentral distances are computed considering the instrumental epicentre, located in the sea in the Gulf of Patti. The regression obtained for the selected events differs from the attenuation pattern of the regional 1978 earthquake mainly in the far field, over 30 km of distance.

3.3. *Ischia and Vesuvius*

The distribution of the average values of Δ*I* for the Neapolitan volcanic district is shown in

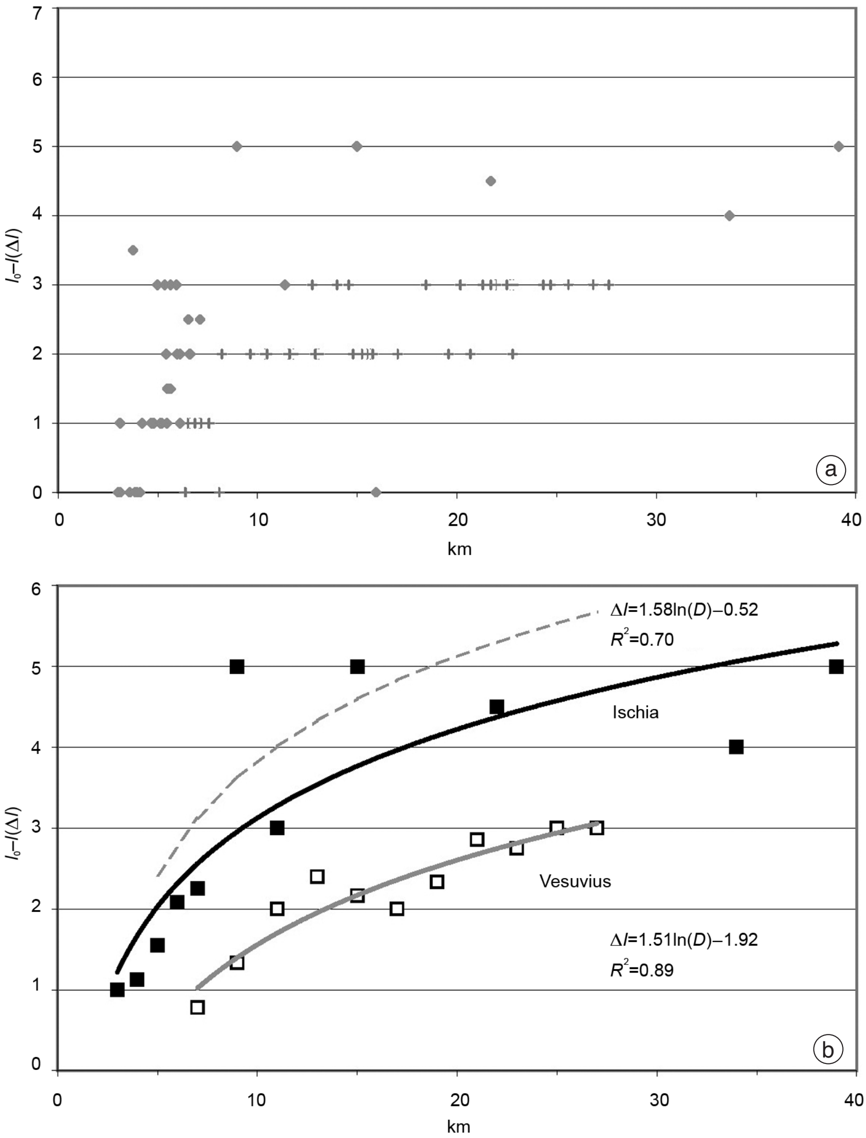

Fig. 11a,b. Neapolitan volcanic district. a) Hypocentral distances *versus* Δ*I* for the earthquakes used in the analysis: Ischia, diamonds; Vesuvius, crosses. b) Logarithmic relationships for the arithmetic average of Δ*I* (squares) for Ischia and Vesuvius and comparison with the Peruzza (2000) equation (dashed).

fig. 11a. The intensity dataset available for this area is rather poor, consisting of just two earthquakes for Ischia and one for Vesuvius (table III). In particular, only the 1999 event is known for this volcano (local magnitude M_L=3.6 and focal depth about 4 km b.s.l.), the largest event occurring since the last eruption in 1944 (Del Pezzo *et al.*, 2004). Intensity observations were

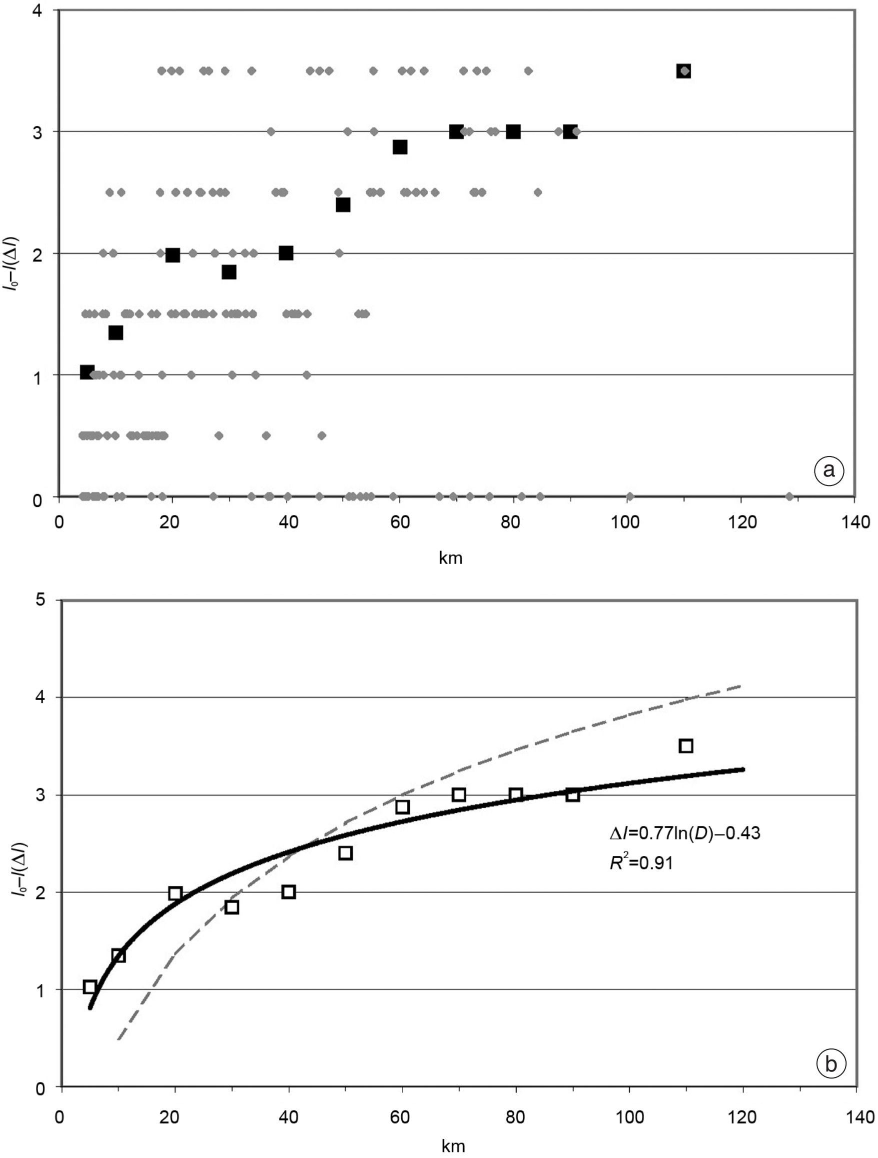

Fig. 12a,b. Albani Hills. a) Hypocentral distances *versus* ΔI for the earthquakes used in the analysis (diamonds) and arithmetic average of ΔI (squares). b) Logarithmic relationship for the average values and comparison with the Peruzza (2000) equation (dashed).

filtered by removing all data with $\Delta I \geq 5$ and the focal depth was fixed at 3 km b.s.l according to the recent seismogenic zoning (Gruppo di Lavoro, 2004). Given the small distances involved as on Etna, intervals of hypocentral distances of 1 km and 2 km, respectively, for Ischia and Vesuvius have been adopted. The results suggest probable differences in the attenuation pattern of the two areas, considered as one in the previous study by Peruzza (2000). Figure 11b shows the attenuation relationships resulting for Ischia and Vesuvius

$\Delta I = 1.58\ln(\mathrm{D}) - 0.52 \quad R^2 = 0.70$ for $D \geq 1.4$ km (Ischia)

$\Delta I = 1.51\ln(\mathrm{D}) - 1.92 \quad R^2 = 0.89$ for $D \geq 3.6$ km (Vesuvius).

Their significance from the statistical point of view is low compared with the other studied areas because of the few observations available. The relationship obtained for Ischia is fairly similar to that computed by Peruzza (2000) for the entire seismogenic zone of Ischia-Vesuvius, based on the 1883 Casamicciola earthquake. On the contrary, the intensity attenuation curve for Vesuvius appears very different, with a trend considerably lower than that of Ischia. Although based just on one earthquake, this result suggests that the macroseismic attenuation in the two areas should be treated separately.

3.4. *Albani Hills*

The distribution of the intensity data considered for the district of the Latium volcanoes is fairly dense. The dataset was filtered by removing all intensity data with $\Delta I \geq 4$ and the focal depth was fixed at 4 km b.s.l. according to Gruppo di Lavoro (2004). The computed arithmetic average of ΔI was done selecting classes of hypocentral distances of 5 km up to 10 km and of 10 km in the far field (fig. 12a).

The resulting regression is presented in fig. 12b

$\Delta I = 0.77\ln(D) - 0.43 \quad R^2 = 0.91$ for $D \geq 1.7$ km.

The value of the correlation coefficient is, among the studied cases, the highest one apart from that obtained for the Etnean dataset. With respect to the attenuation curve calculated by Peruzza (2000), our relationship shows a higher attenuation of macroseismic intensity within the first 50 km of distance and a lesser one beyond this value.

4. Concluding remarks

The analysis carried out allowed us to investigate the features of macroseismic attenuation in the Italian volcanic areas in detail, disclosing some differences among them but also analogies. Using an upgraded intensity dataset, more complete than the one adopted by previous studies, intensity attenuation laws have been derived from empiric models that fit data using the ΔI average values (difference between epicentral I_0 and site I_x intensities) by least-square method and results compared with those by Peruzza (2000), based on a «representative» event for each seismogenic zone. For the Etnean area, in particular, due to the large amount of data, it

Table V. Summary of intensity attenuation laws obtained in this study.

Area	Logarithmic regressions	R^2	Valid for D (km) ≥
Etna	$\Delta I = 0.98\ln(D) + 1.01$	0.92	0.4
Aeolian Islands	$\Delta I = 1.28\ln(D) - 2.39$	0.89	6.5
Ischia	$\Delta I = 1.58\ln(D) - 0.52$	0.70	1.4
Vesuvius	$\Delta I = 1.51\ln(D) - 1.92$	0.89	3.6
Albani Hills	$\Delta I = 0.77\ln(D) - 0.43$	0.91	1.7

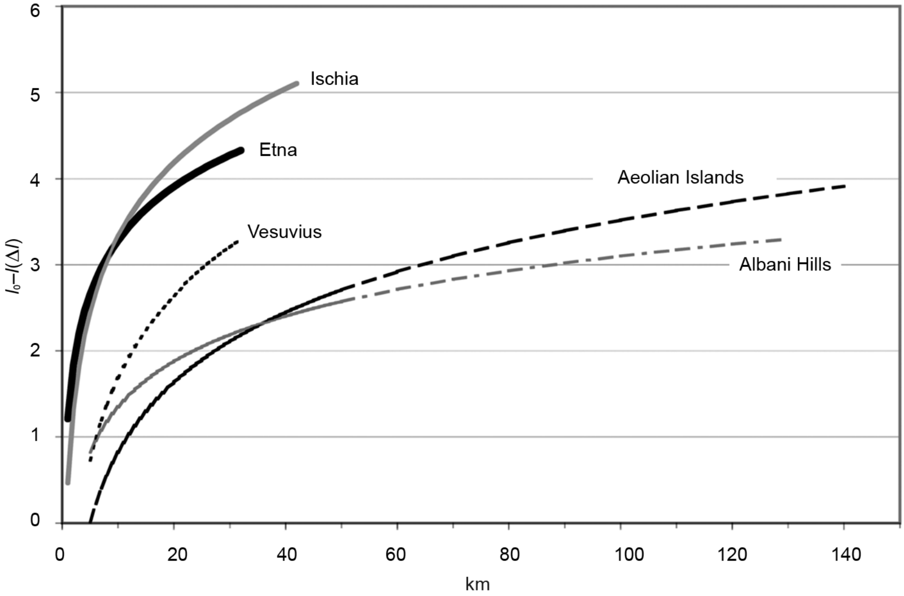

Fig. 13. Comparison of the intensity attenuation relationships obtained for the Italian volcanic districts.

was possible to test the best attenuation model using bi-linear and logarithmic regressions, to verify the source effect on the attenuation and to re-calculate the coefficients of the Grandori *et al.* (1987) relationship. Among the tested relationships the logarithmic one is simple and fairly stable, so it was adopted as a representative intensity attenuation law also for the other volcanic Italian districts.

By comparing the relationships (table V) computed for each volcanic area (fig. 13), the laws obtained for Etna and Ischia are very similar and show the highest intensity attenuation. This behaviour does not seem to be so evident for Vesuvius, whose curve on the average presents the same trend of the attenuation but over longer distances. A reason for the lower attenuation rate in this area may depend on the fact that the hypocentre of the earthquake used for calibrating the attenuation relationship is located underneath the volcanic edifice inside the carbonate basement (Del Pezzo *et al.*, 2004), a medium characterised by high rigidity. In the Etna region, most of the shallow earthquakes are located in the basement, but the occurrence of less compact rocks such as clayey and flyschioid terrains (Di Stefano and Branca, 2002) may account for a higher attenuation of the seismic energy in the medium.

Finally, the relationships obtained for the Aeolian Islands and Albani Hills (fig. 13) are clearly different from the others, presenting a very low intensity attenuation rate.

In general, all computed relationships show a higher attenuation rate in the near field and lower attenuation in the far field with respect to the laws used so far. The application of these laws should allow a more careful hazard assessment in Italian volcanic areas.

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