ANNALS OF GEOPHYSICS, 56, 4, 2013, S0439; doi:10.4401/ag-6445

Special Issue: Vesuvius monitoring and knowledge

Felt index, source parameters and ground motion evaluation for earthquakes at Mt. Vesuvius

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Article history
Received January 30, 2013; accepted June 2, 2013.
Subject classification:
Vesuvius, Felt index, Earthquake intensity, Source parameters, Ground motion.

ABSTRACT

Results of non-instrumental surveys carried out on recent and past seismicity at Vesuvius have been retaken in order to propose new analyses regarding source mechanisms and causative faults. We present the results of the October 9, 1999, earthquake, the most intense event since the 1944 eruption. The intensity was evaluated by utilizing integer values of the MCS Scale and the felt index as a continuous parameter. Values of magnitude and attenuation determinated by applying macroseismic models to data, and compared to instrumental ones, were utilized to assess the "size" of the historical Vesuvian earthquakes. A magnitude of M = 5.1±.3 was considered for the A.D. 62 earthquake, the largest one of the area that preceded the A.D. 79 famous eruption. By using the macroseismic field of October 9, 1999, the source mechanism of the earthquake was obtained, and synthetic isoseisms and causative fault of the A.D. 62 are also proposed.

1. Introduction

About 600,000 people live around Mt. Vesuvius, where the risk associated with a large eruption is very high, and its complete evaluation includes also the potential damage due to earthquakes foregoing and accompanying eruptions.

Low-moderate energy shallow earthquakes that produce high intensities in a small area generally characterize the seismicity. Also, the high housing density and economic exposed value make the Vesuvian area of considerable importance for mitigating the seismic risk. To evaluate the effects of earthquakes, data on the source parameters and damage levels of historical earthquakes are necessary. Data provided by fonts are rare and generally linked to eruptive phases emphasizing the peculiar role of volcanotectonic origin of vesuvian seismicity. Here we synthesize recent studies of Cubellis and Marturano [2002], Marturano [2006] and Cubellis et al. [2007] in which complete bibliography is also reported.

The oldest seismic activity at Vesuvius was recorded by classical fonts, archaeological ruins and represented on marble reliefs [e.g. Marturano and Varone 2005]. The oldest known earthquake in the area of Mt. Vesuvius occurred in A.D. 37 ($M = 4 - 4.5$), while the strongest one occurred in A.D. 62, on February 5 ($M = 5.1\pm.3$); this damaged Pompeii, Herculaneum, Nuceria and Neapolis. The heaviest damage occurred in Pompeii, where the intensity reached the IX MCS degree (Figure 1). In A.D. 64 ($M = 3.5 - 4$) a seismic event occurred during a representation in the theatre in Naples when the roman emperor Nero was present. The theatre was damaged but Nero was unharmed (Figure 2). In Roman and Medieval times the poor sources record no significant seismic activity in the Vesuvian area; on the contrary, some large eruptions occurred. Explosive activity was inferred in the 3rd and 5th century [e.g. Alfano 1924, Principe et al. 2004]. From the 7th to 12th century the eruptions of the 685, 787, 1036 and 1139 represent the exceptional phenomena in a quasi-persistent explosive and effusive activity [Figliuolo and Marturano 1997, 1998]. All through the period, the seismic activity is to consider quite secondary. After a quiescent period, from 1631 to 1944 Mt. Vesuvius experienced a permanent activity characterized by numerous eruptive episodes interrupted from time to time by intensive eruptions [e.g. Arrighi et al. 2001]. The largest eruption in modern times occurred in 1631. There is reliable documentary evidence for seismic activity before the eruption mostly during the night between December 15 and 16 ($M_{max} = 4$) from primary sources in State and Ecclesiastical Archives (Figure 3) [Marturano and Scaramella 1995, Marturano 2006]. Probable deformation phenomena, landslides, variations in water chemistry and seismicity, linked to the 1631 eruption, have been recently reconstructed by Guidoboni [2008] by three contemporary treaties.

After this eruption up to recent times the earthquakes were generally of low-moderate energy and re-

Figure 1. Archaeological data: effects of A.D. 62 earthquake by relief of the Caecilius Jucundus House. The relief shows buildings (Vesuvius Gate) and objects in unstable equilibrium and mules fleeing in terror during the earthquake. The Castellum Aquae on the left appears undamaged.

lated to eruptive activity [Cubellis and Marturano 2002, Cubellis et al. 2007]. The most dangerous occurred on June 15, 1794 ($M \approx 4$) during the lateral eruption, which destroyed the town of Torre del Greco. The shocks caused damage to buildings in the Vesuvian area and shattered windowpanes in Naples. The magnitude of the most severe earthquake during the period (1631-1944), is the same as that of the strongest event prior to the 1631 eruption ($M \approx 4.0$) and close to those of October 9, 1999 ($M = 3.6$) [Gasparini and Musella 1991, Cubellis et al. 2007].

Since 1944 Vesuvius is quiescent and the seismicity has been marked by low-moderate energy earthquakes with a frequency of a few hundreds per year. Epicentres are concentrated in the caldera area and the depth of seismic events does not exceed 6 km below sea level [e.g. Del Pezzo et al. 2004, De Natale et al. 2006]. Among the earthquakes recorded in the period 1944-1970 the most significant earthquake occurred on May 11, 1964, located in the crater area. The felt area covered the whole Vesuvian region with maximum effects in the upper part of the volcanic structure (V MCS degree) and gradually decreasing effects towards the apron (II-III degree) [Imbò et al. 1964].

In the early 1970s the surveillance seismic network at Vesuvius was restructured and equipped with sensitive modern instruments. Periods of high seismic activity were recorded in 1989, 1990 ($M_{max} = 3.2$), 1995 ($M_{max} = 3.2$). Moreover on April 25, 1996, a $M_D = 3.4$ earthquake occurred at a depth of 2 km and was clearly felt all over the Vesuvian region, the town of Naples and some sites in the Campi Flegrei and in Capri island. The seismicity increased slightly in the early months of 1999 and a seismic sequence began in August, culminating in the most energetic event on October 9, 1999, with epicentre location at crater area, depth of 3.8 ± 0.3 km b.s.l.; $M_D = 3.6$ [Zollo et al. 2002, Del Pezzo et al. 2004, De Natale et al. 2004, De Natale et al. 2006]. For this earthquake it was possible to provide a reliable extended macroseismic field [Cubellis and Marturano 2002].

Comparison between present and historical earthquakes at Vesuvius can only concern the released energy level, because data about the source mechanism of the latter are unknown. The lack of high-energy

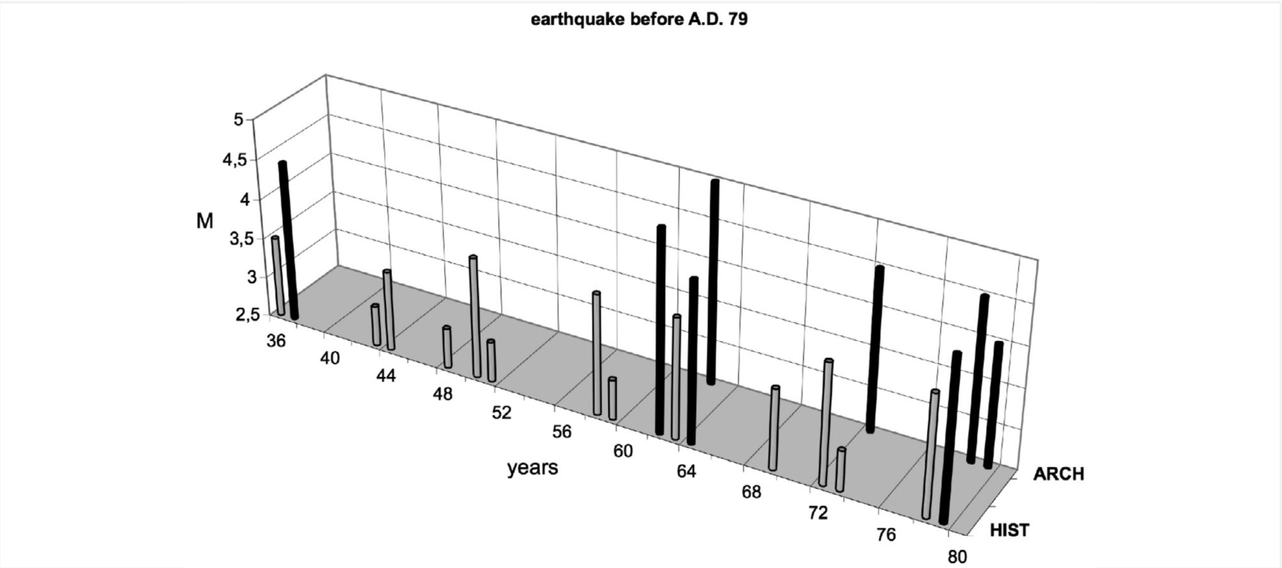

Figure 2. Earthquakes before the A.D. 79 eruption (modified from Marturano [2008]). HIST: earthquakes by historical sources occurred in A.D. 37, 62, 64 and 79 (full colour) and inferred but undatable seismicity; ARCH: earthquakes by archaeological sources; M: magnitude.

earthquakes at Vesuvius for two thousand years suggests that the strongest earthquake to be expected before an eruption would probably have an energy level similar to that of A.D. 62 or smaller. Therefore, the size of historical Vesuvian earthquakes, ground motion data and energy spreading must be evaluated in order to determine seismicity levels that can be associated with volcanic structures and eruptive phases. In order to achieve this aim, the data regarding the 1999 earthquake have been utilized as a test. Finally, synthetic intensity map and ground motion simulation are proposed for this event in order to validate reconstructions of older earthquakes.

2. Macroseismic study of the 1999 earthquake

In this section we synthesize the results obtained from the analysis of the macroseismic questionnaires sent out to schools in the Vesuvian and Neapolitan areas as well as surrounding towns in the provinces of Caserta and Salerno after the October 9, 1999, earthquake [Cubellis and Marturano 2002]. The earthquake was felt over a wide area, causing fear and anxiety among the people in the Vesuvian area and surrounding zones, not only for hazard associated to the ground shaking but also because the earthquakes in volcanic areas may be forerunners of eruptions. The questionnaires were designed to mark the limits of the felt area and analyze energy spreading. Such a study makes it possible to obtain empirical formulas for magnitude intensity and seismic energy attenuation laws in quake-stricken areas.

2.1. Felt index

The earthquake of October 9, 1999, was not only the most energetic since the last eruption in 1944 but also one of the most energetic of those occurring in the Vesuvian area as it was shown by an analysis of historical seismicity [Marturano and Rinaldis 1995, Marturano and Scaramella 1995, Marturano and Rinaldis 1998, Luongo et al. 2003, Marturano 2006, Cubellis et al. 2007]. After the earthquake, questionnaires were sent to all middle schools in the Vesuvian area, Naples and surrounding towns in the provinces of Caserta and Salerno in order to define the extent to which the earthquake had been felt (see Appendix: Table A1). The questionnaires, more than 10,000 in number, came from 92 sites, 18 of which were within the city of Naples.

For this earthquake and for the first time, the *felt index* parameter was utilized in order to give a measure of the earthquake intensity [Cubellis and Marturano 2002]. The *felt index* was introduced to overcome the quantifiers such as few, many or most usually utilized in intensity scales.

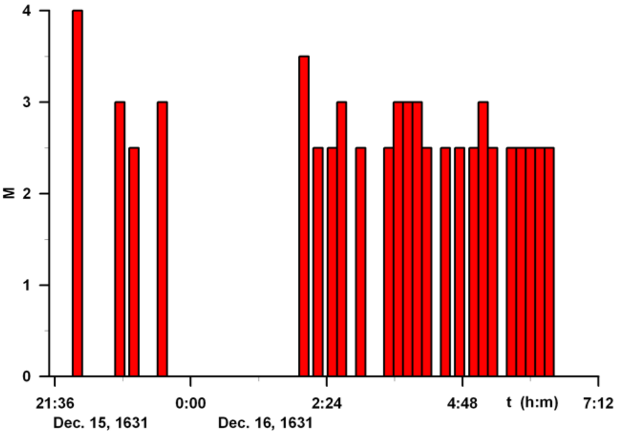

Figure 3. Earthquakes of December 15 and 16 preceding the eruption of the 1631 that began at 6:30 a.m. (modified from Marturano [2008]).

For each site – a town or a district in Naples – and for each of the 18 questions of the questionnaire, the ration between positive answers and total answers was computed. The percentage of affirmative response to Question 1 (*Did you feel the earthquake?*), called *felt index* (A), was used in later data processing. In Figure 4 is showed the *felt index* map, where isolines with differenced value are drawn. The *felt index* shows a maximum value for the volcanic edifice and radially decreasing values. In the area nearer Vesuvius (A > 66%) there appears a marked E and NE attenuation, which is confirmed in the second zone (44-30%). Attenuation can be also noted in Campi Flegrei area. The *felt index* thus obtained is a continuous parameter. This feature makes it possible, among other things, to relate it to ground motion parameters. So, the problem of the limits involved in using integer values of intensity utilized by the macroseismic

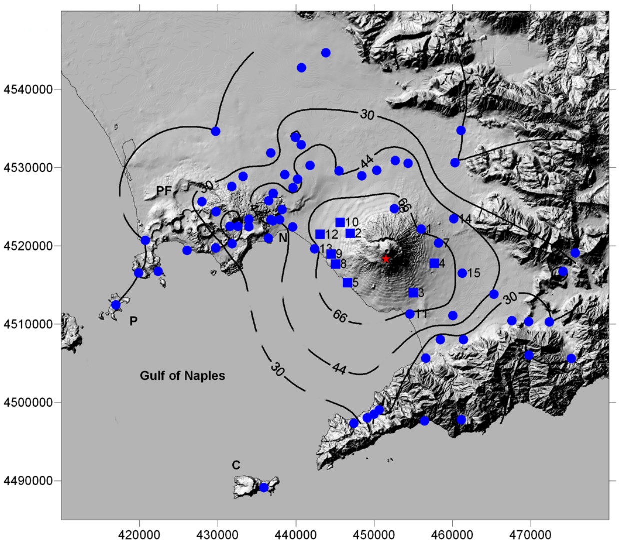

Figure 4. Earthquake of October 9, 1999: *felt index* map. Star = Epicenter; PF = Campi Flegrei; P = Procida; C = Capri; N = Naples. The numbers from 1 to 15 are localities as in Table 3 and Figure 10 (redraw by Cubellis and Marturano [2002]). Coordinates (meters) in UTM reference.

scales [e.g. Howell and Schultz 1975] is overcome.

Felt index data will also be used to calculate the quality factor and to compare synthetic isoseismals. The results enable comparison of values obtained for the same parameter by using completely independent data: instrumental and macroseismic. This is aimed to assess the 'size' of historical Vesuvian earthquakes in order to determine seismicity levels that can be associated with volcanic structures and eruptive phases in the light of the results from the analysis of the October 9, 1999, earthquake.

2.2. Intensity

The intensity plane for the October 9, 1999, earthquake is particularly dense of data. In the province of Naples, there is a survey point for each 15 km^2 of surface (54 towns). As far as 30 km from the epicentre, the radial distance between two consecutive points of the surveyed area is, on average, lower than 500 m. Such a high density is unusual for studies like this. Intensities (see Appendix: Table A2) were determined according to Karapetyan's frequency class subdivisions (Table 1) [Sponheuer and Grunthal 1981, Cubellis and Marturano 2002].

The maximum degree was V for sites at a mean distance of $R_V = 7\pm2.3$ km from the epicentre, the maximum intensity being found at Boscotrecase, Cercola and S. Sebastiano, where some intensity VI features were found, like "many people run outdoors" and "objects fell". Among the places analyzed, Ottaviano, Torre Annunziata and Somma Vesuviana, which are within 9.3 km from the epicenter, scored a lower fifth degree intensity. Places that were given IV and III degree are at an average distance of $R_{IV} = 15\pm4$ km and $R_{III} = 20\pm4$ respectively. As it will be emphasized in Section 4.2.1, where PGA, intensity and felt index are reproduced, to a rise of one degree of Intensity the PGA and the FI are 100% and 50% greater respectively. Therefore the isolines A = 66, 44 and 30 of Figure 4 represent the isoseisms of V, IV and III MCS degree respectively. This does not modify the Intensity determination and, to our knowledge, is the first logical association between experimental percentages and quantifiers such as few, many or most which are found in intensity scales.

Frequency class	Intensity
<12.5%	II
25%	III
50%	IV
75%	V
>87.5%	VI

Table 1. Intensity and frequency classes.

2.3. Magnitude and attenuation laws

There are few Vesuvian earthquakes that could be used to generalize the magnitude-intensity relation. The size of an historical earthquake is determined from macroseismic data by using intensity values, as well as the distances reached by intensities and/or the areas enclosed by isoseisms [Gutenberg and Richter 1942, Karnik 1968, Toppozoda 1975, Sibol et al. 1987, Bakun and Wentworth 1997]. More widely used relations of intensity *versus* epicentral distance take into account a linear term, for anelastic attenuation and a logarithmic one, for the geometrical spreading [e.g., Howell and Schultz 1975, Gupta and Nuttli 1976, Chandra 1979, Chandra et al. 1979]. In simplified formula, the linear term is eliminated and the coefficient of the logarithmic term is area dependent. In such models, the source is considered pointlike, the earth's surface is assumed horizontal, the medium homogeneous and isotropic, and spectra monochromatic.

For the simplified model 1 we used Blake's [1941] formula:

$$I_0\text{-}I_i = s \log [1+(\Delta_i/h)^2]^{1/2} \qquad (1)$$

where I_0 is the maximum value of intensity at the epicentre, h is hypocentral depth, Δ_i the epicentral distance of a place with intensity I_i and s is the attenuation coefficient allowing for geometrical spreading and the medium's physical properties.

For the model 2, Chandra's [1979] relation was used:

$$I_0\text{-}I_i = a+bR+c \log(R+h) \qquad (2)$$

where I_i is intensity at distance R from the epicentre with intensity I_0, h is the hypocentral depth, b is related to the absorption factor while c is associated with geometrical spreading. Cubellis and Marturano [2002] compared the two models and concluded that both of them provided good fits of the experimental data (Figure 5). However, a marked difference between the two models is found in the area at the epicenter, where no data from questionnaires were available. In addition, macroseismic observations rule out that the threshold of VII degree was likely at the epicenter. Though allowing for the increase in volcano elevation, which affects the hypocentral distance by up to 30%, model 2 still yields too high epicentral intensity. By contrast, model 1 does not consider VII degree. The values of I_0 associated with model 1 are therefore used in further data processing, but model 2 cannot be excluded for higher magnitude and/or different source parameters.

Applying relations for I_i and R usually utilized for active tectonic areas to the October 9, 1999, earthquake, all the calculated magnitudes appear higher than

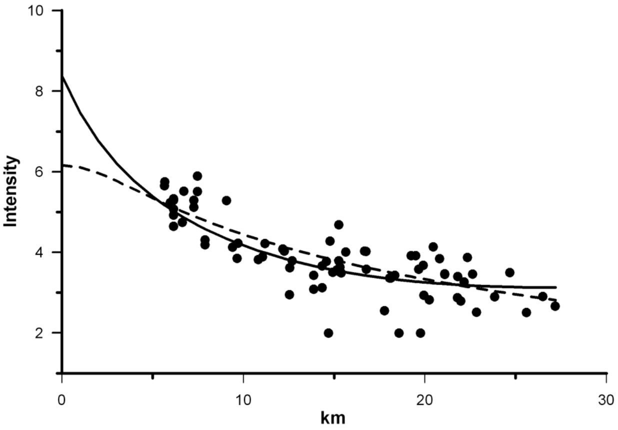

Figure 5. Intensity attenuation according to Blake's (dashed line, $R^2 = 0.62$) and Chandra's (solid line, $R^2 = 0.64$) models applied to the experimental data (circles) of the October 9, 1999, earthquake (redraw by Cubellis and Marturano [2002]).

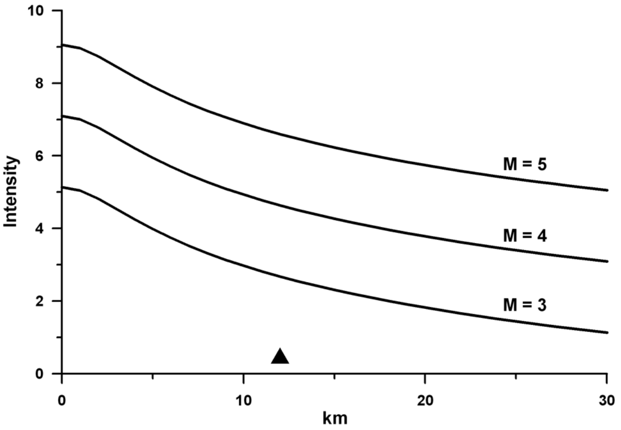

Figure 6. Intensity attenuation according to the Blake's model for events in the range M = 3 ÷ 5 and depth h = 3.8 km. The triangle represents the distance of centre of Naples from the crater axis.

the instrumental ones and the mean of the differences is $(M\text{-}M_L) = 0.5$.

(a) $M = (I_i + 1.72 + 0.0212\ Ri) / 1.4$ [Bakun and Wentworth 1997] a value of M = 4.2;

(b) $M = 0.66\ I_0 + 1$ [Gutenberg and Richter 1956] a value of M = 5-5.2 (model 1);

(c) $M = 0.51\ I_0 + \log(h) + 0.3$ [Karnik 1968] a value of M = 4.1 (model 1)

(d) $M = a + b\ I_0^2 + c \log^2 (AI)$ [Sibol et al. 1987] a value of M = 4.1-4.2.

The overestimate of the value of magnitude for data related to the October 9, 1999, earthquake is similar to that found for Campi Flegrei during the 1982-1984 bradyseismic crises $(M - M_l) = 0.4$ [Marturano et al. 1988]. Such result suggests that the epicentral intensity in volcanic areas is higher of about one degree than that observed in tectonic areas for the same value of magnitude. This condition has to be taken into account for the seismic hazard estimates. Therefore, the simple relation (c), that explicitly considers the focal depth (h), can be corrected as:

$$M = 0.51\ I_0 + \log(h) - 0.2 \qquad (3)$$

which will be in the following utilized by considering that an error of 0.5 degree for the intensity corresponds to a value of 0.3 for the magnitude.

In sum up, the relations obtained for the October 9, 1999, earthquake can be used to assess the energy of historical earthquakes in order to determine the level of seismicity and relate it to the volcano's seismogenetic structures. In Figure 6 the values of intensity *versus* distance for the 3 ÷ 5 Magnitude range are shown as obtained by combining relations 1 and 3 for h = 3.8 km. By using the same relation Cubellis and Marturano [2002] estimated the magnitude of earthquakes preceding the eruptions of A.D. 79 and 1631. So, the earthquakes from 1631 to 1944 do not appear to have exceeded the value of M = 4.5. Therefore taking into account this result and the magnitude of the A.D. 62 earthquake, the greatest magnitude pre-eruptive event may be estimated between 4.5 and 5.4 (Figures 2, 3), a value that exceeds those recorded in recent times, but not so far from the lower boundary.

2.4. *Quality factor (Q)*

To evaluate the quality factor (*Q*) Cubellis and Marturano [2002] utilized for the first time macroseismic data. They rely on the high density of the sampling and on the new felt index parameter employed for the 1999 earthquake survey. The quality factor *Q* for that earthquake was obtained considering the *felt index* (A), a parameter someway related to energy. In particular, since energy is proportional to the square of the amplitude, those authors utilized, the following relation for amplitude as a function of distance [Aki and Richards 1980, Lay and Wallace 1995]:

$$A(D) = A_o\, e^{-(f_\pi D / Q(f)\beta)} \qquad (4)$$

where f is the frequency, *D* is the hypocentral distance, β is the S-wave velocity and *A* the *felt index* expressed in percentage. Here, the spatial decay due to geometrical spreading (1/D) is also considered then, the *Q* is evaluated by determining the distribution slope *Log A*(*D*) relative to D in kilometres [$\log(A) = 1.99 (\pm 0.05) - 0.025 (\pm 0.003)\ D$] (Figure 7).

Q value increases with frequency. By assuming an average S-wave velocity $V_s = 2\ \text{km s}^{-1}$ [Scarpa et al. 2002], *Q* value in the range 50÷500 was estimated for frequencies usually investigated in earthquake engineering (f = 1÷10 Hz). Lower quality factor for coda waves (Qc) values in the same frequency ranges are obtained at Mount St. Helens, Campi Flegrei, Deception

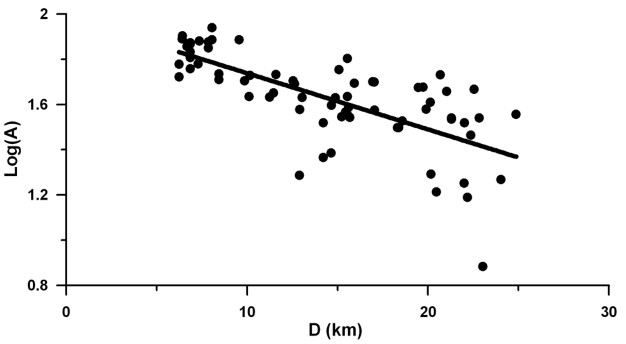

Figure 7. Linear regression Log (A) - hypocentral distance (D). A is the *felt index* expressed in %. [log (A) = 1.99 (± 0.05) − 0.025 (±0.003) D].

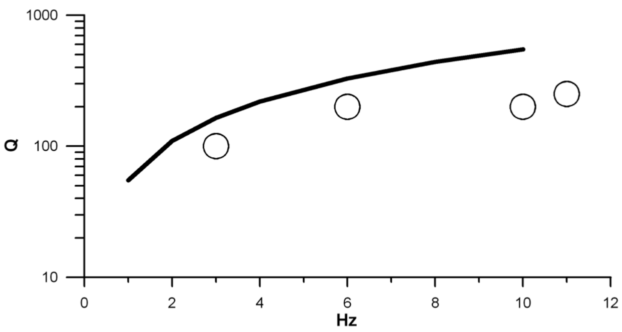

Figure 8. *Q* parameter at Mt. Vesuvius. *Q* values increasing with the frequency according Equation (4) (continuous line). Open circles: data obtained for frequency f(Hz) = 3, 6, 10, 11 [Bianco et al. 1999].

Island, Canary Island and at Mt. Vesuvius, where Qc results less dependent with the frequency [Bianco et al. 1999, Del Pezzo et at. 2006]. The correspondence of the macroseismic and instrumental *Q* values (Figure 8) emphasizes the ductility of the *felt index* as continuous parameter. By using the relation 4, and considering that the spectral density of the 1999 earthquake shows a peak around 2 ÷ 3 Hz [Del Pezzo et al. 2004], the average $Q = 150$ [Galluzzo et al. 2008] like calculated above, $\beta = 2$ km/s, the *felt index* values *versus* ipocentral distance can be calculated (Figure 9). This relation is to be considered like the attenuation of the perception of the shock with the distance by means the *felt index*, a non-instrumental experimental parameter, closely linked to the perceptible part of the seismic signal.

3. Macroseimic field, source parameters and ground motions

For the October 9, 1999, earthquake the *felt index* appeared to be an objective means of evaluation of shaking in one point and can be utilized to directly evaluate relations with other ground-motion data, thus getting round the difficulty caused by the use of discontinuous values typical of macroseismic scale degrees. Spatial distribution of macroseismic effects has been associated with source features (dimension, radiation pattern, rupture history) and/or anomalies in the travel path of seismic waves and/or ground conditions. All of those characteristics have been examined thoroughly [e.g., Shebalin 1972, Everdeen 1975, Vaccari et al. 1993, Sirovich 1996, Tosi et al. 2000, Molchan et al. 2002]. The earthquake of October 9, 1999, occurred near the crater axes, 3-4 km b.s.l., with source dimension of a few hundred meters [Zollo et al. 2002, Del Pezzo et al. 2004, De Natale et al. 2004]. Here the macroseismic field is modeled by point-source and synthetic peak ground acceleration (PGA) of finite fault.

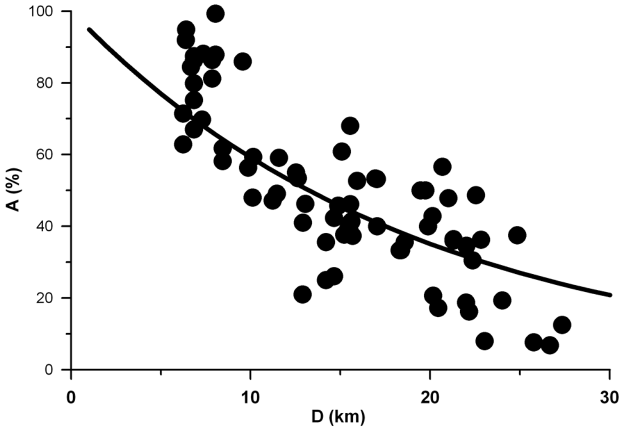

Figure 9. *Felt index* (A%) attenuation with the ipocentral distance D [A(%) =100 $e^{-0.059\,D}$; $R^2 = 0.6$].

3.1. The source parameters of the October 9, 1999, earthquake

The nearer macroseismic sites (numbered in Figure 4) are distant about 15 times the source dimension from hypocenter, thus justifying a pointlikesource model. For this model, only the far-field terms of the complete solution given by Aki and Richards [1980] are used, such an approximation working satisfactorily even at distances of the order of the wavelength [Spudich and Frazer 1984, Madariaga and Bernard 1985].

The displacement components for the far field P and S waves in spherical coordinates due to a point – source shear dislocation of seismic moment M_0 located in an infinite space, can be written as

$$U_P = \frac{1}{4p\rho r\alpha^3} R^P \frac{M_0}{t_r}$$

$$U_{SV} = \frac{1}{4p\rho r\beta^3} R^{SV} \frac{M_0}{t_r}$$

$$U_{SH} = \frac{1}{4p\rho r\beta^3} R^{SH} \frac{M_0}{t_r}$$

where ρ is the crust density, r the distance from the source, t_r the rise time, α and β are the P and S-wave speed, R^P, R^{SV} and R^{SH} are Aki and Richards' radiation pattern coefficients [Aki and Richards 1980]. This source is geometrically defined by three angles, two identifying the fault plane (strike ϕ_f and dip δ) and one for the rake (λ) on the fault. A 2 layer velocity model simplified from Zollo et al. [2002] was utilized (Table 2), also accounting for the volcanic rocks/limestone discontinuity constrained by gravity and deep well data for geothermal exploration.

For the October 9, 1999, earthquake we assume that the wave field amplitude at a point is caused by a small source, controlled by the radiation pattern R and the geometrical spreading (1/r). Only the 15 sites that were within 10 km from the epicentre were considered in order to reduce the effects of complex ray paths and anomalous attenuation. They are distributed around the source, with the maximum azimuthal gap of 70° between Torre del Greco and Torre Annunziata. These sites are numbered in Figure 4, while list and related *felt index* are resumed in Table 3.

The best fit for three source parameters (ϕ_f, δ, λ) is reached by minimizing the standard deviation of the residual between the theoretical (max absolute R/r values) and observed *felt index* values. Due to the small distance range, from 5 to 10 km, very similar results are obtained by linear or loglinear relation. The solution obtained utilizing the felt-index data for a pure shear source (Table 4) indicates a sub-vertical fault with ipocentral depth of 5 km, consistent with the results obtained above by Blake's and Chandra's relations. The theoretical displacement field is shown in Figure 10, where the near source macroseismic field of Figure 4 and the sites numbered from 1 to 15 are also reported for comparison. The sites with FI > 80 (empty squares in Figure 10) are mainly located in the westward lobate shape of the first isoseismal (cfr. Figure 4). Also, those with FI > 90 (filled squares in Figure 10) characteristically fall along the strike of the source fault.

A number of authors [Zollo et al. 2002, Del Pezzo et al. 2004, De Natale et al. 2004] determined the fault plane solution of the October 9, 1999, earthquake under the double-couple hypothesis. In spite of some differences, they obtained fault planes with a NW-SE striking, the P axis orientation being roughly NS.

3.2. Ground motion simulation

On February 5, A.D. 62, a strong earthquake hit Campania, causing considerable damage to Pompeii and Herculaneum and relatively minor damage to Naples and Nuceria [Tacitus, Ann. XV.22.1; Seneca, NQ VI. 1.1-3], with maximum intensity of IX MCS degree and a magnitude M = 5.1±.3. In light of recent archaeological and epigraphic evidences, this earthquake and subsequent low-moderate energy seismic swarms have been considered as precursors of the A.D. 79 eruption [Marturano and Rinaldis 1998, Luongo et al. 2003, Marturano 2006] confuting farther away apenninic sources of previous interpretation [e.g. Sigurdsson et al. 1985]. Here we will compare the intensity data of this earthquake with the synthetic macroseismic field taking into account the seismotectonic interpretation proposed by Cubellis et al. [2007]. For this purpose, the source fault is subdivided into smaller parts summing the single contributions to obtain effects at observation points.

The idea of modelling large earthquakes with a summation of small ones started with Hartzell [1978], who summed empirical records of foreshocks and aftershocks, with appropriate time delay, to approximate the mainshock record. Afterwards a number of semi-empirical and theoretical approaches have been pro-

Layer	h_0	h_1	b_i	Vp_0
1	0	2	1.0	2.0
2	2	10	0.2	5.5

Table 2. Velocity model.

site	Lon (°)	Lat (°)	R (km)	A (%)	Locality
1	14.48	40.85	5.5	67	Ottaviano
2	14.37	40.84	5.7	92	S. Sebastiano
3	14.47	40.77	5.7	95	Boscotrecase
4	14.50	40.81	6.0	84	Terzigno
5	14.37	40.79	6.2	84	Torre del Greco
6	14.44	40.87	6.2	71	Somma Vesuviana
7	14.50	40.83	6.7	70	S. Giuseppe Vesuviano
8	14.35	40.81	6.7	88	Ercolano
9	14.34	40.82	7.3	84	Portici
10	14.35	40.86	7.5	94	Cercola
11	14.46	40.75	7.9	60	Torre Annunziata
12	14.32	40.84	8.6	86	Napoli (Ponticelli)
13	14.32	40.82	9.4	56	Napoli (Barra)
14	14.52	40.86	9.6	48	S. Gennaro Vesuviano
15	14.54	40.80	9.7	59	Poggiomarino

Table 3. October 9, 1999, earthquake: sites within 10 km from epicentre, A(%) is the *felt index* related to Question 1 (*Did you feel the earthquake?*).

ϕ_f (°)	δ (°)	λ (°)	st.dev.	R^2	h (km)
131	90	101	0.01	0.67	5

Table 4. October 9, 1999, earthquake. Source parameters. Location (Lat.: 40.8095°; Lon.: 14.4192°) by Zollo et al. [2002] is imposed.

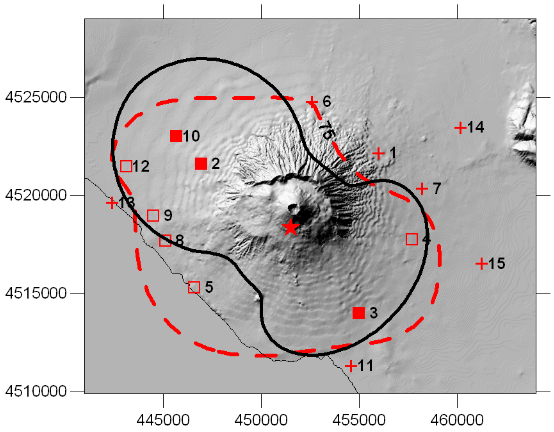

Figure 10. Earthquake of October 9, 1999: theoretical displacement field (continuous line) according to solution in Table 4 computed for near source data (relative units). The symbols numbered from 1 to 15 are localities as in Table 3 and Figure 4 utilized to determine the fault plane solution. Squares represent highest observed value (filled: A > 90; empty: A > 80; plus: A < 80). *Felt index* isoline A = 75 (dashed line). The star is the epicentre. Coordinates (meters) in UTM reference.

posed to represent the source processes, as the use of observed near-field records, theoretical source time function, stochastic ω^2 source spectrum [e.g. Somerville et al. 1991, Zeng et al. 1994, Beresnev and Atkinson 1997]. Another method models propagation effects empirically by using observed dependence of ground motion amplitude and duration on distance [Midorikawa 1993]. In this approach, the source of the earthquake is modelled as a rectangular rupture, and the simulation technique is based on the EGF technique of Irikura [1986]. This method employs an acceleration envelope as Green's function. The shape of the envelope function is estimated using empirical relations applicable in the source region, and the source is consistent with the ω^2 source model in the high frequency range. The source of an earthquake is treated as a finite fault generating a target earthquake of magnitude M. This fault is further divided into subfaults or small elements and each element releases the acceleration envelope waveform as the rupture front approaches the center of the element representing earthquakes of magnitude M'. The acceleration envelope waveform is determined from empirical relation and the summation of envelopes from each element gives the resultant envelope. According to Midorikawa [1993], Joshi and Midorikawa [2005], the shape of the envelope function of the acceleration waveform used (e(t)) is based on the function given by Kameda and Sugito [1978]:

$$e(t) = \{(a(g)\,t)/Td\}\ \exp(1 - t/Td).$$

In this expression a(g) is the peak ground acceleration and Td is the duration parameter.

3.2.1. *The A.D. 62 earthquake*

In order to apply this technique to the Vesuvian area, the macroseismic field of the $M_D = 3.6$ October 9, 1999, earthquake was utilized as a test assuming a homogeneous model of the earth (Vp = 4 km/s; Vp/Vs = 1.8; Vr = 0.8 Vs; where Vr is the rupture velocity) and using the relations Intensity–epicentral distance (2) and Magnitude–epicentral Intensity (3), as well as the peak ground acceleration (PGA) *versus* Intensity relation [Gomez Capera et al. 2007]

$$\text{Log PGA} = 0.28\ I\ (MCS) - 1.84.$$

By utilizing these three relations the following resultant expression is obtained:

$$\log a(g) = 0.56\ (M - \log h) - 1.40\ \log(1+r^2/h^2)^{.5} + 0.51,$$

in which M is the Magnitude, r and h the epicentral distance and depth of the source respectively. The relations are assumed without errors by considering the speculative aim of the test. Besides, the Magnitude evaluation and the use of relations relating seismic parameter with the magnitude are utilized in the assumption $M_D = M_w = M$.

In Figure 11 the synthetic and experimental isoseisms are reproduced. Note that at the epicentre the Intensity $I_0 \approx 6$ MCS and the *felt index* A ≈ 100 are accounted by PGA values of 0.07 g. It is to note that to a rise of one degree of Intensity, the PGA and the FI are 100% and 50% greater respectively.

For the A.D. 62 earthquake we assume that the small event is definited by an earthquake, M' = 4.5, $M_0' = 7.1\ 10^{22}$ dyn cm according $\log M_0 = 1.5\ M + 16.1$ [Lay and Wallace 1995]. The seismic moment ratio be-

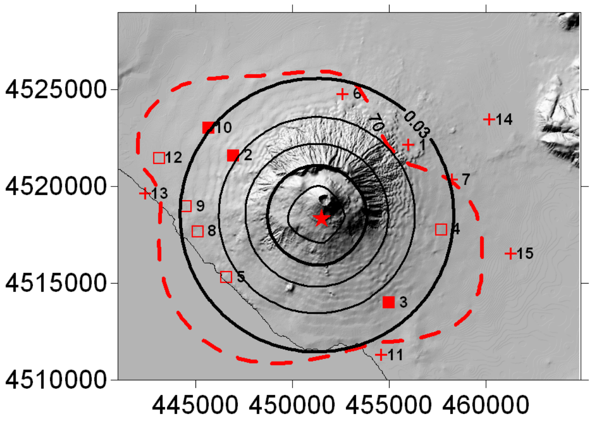

Figure 11. Earthquake of October 9, 1999: distribution of calculated peak ground accelerations (continuous lines). The top of the causative fault (0.6 × 0.6 km) is at 3 km b.s.l. *Felt index* isoline A = 75 (dashed line). The epicentral Intensity $I_0 = 6$ MCS, *felt index* A = 100, is accounted by peak ground acceleration value of 0.07 g. Coordinates (meters) in UTM reference.

tween target and event is defined according to Kanamori and Anderson [1975]:

$$N = (M_0/M_0')^{1/3}$$

where N*N are the elements within the rupture plane, M_0 and M_0' the seismic moment of large and small events respectively.

For N = 3 (fault plane composed by 9 subfaults) the moment and the magnitude of the target event result $M_0 = 1.9\ 10^{24}$ dyn cm and M = 5.4 respectively, in according with magnitude estimated for the A.D. 62 event (M = 5.1±0.3) by Cubellis and Marturano [2002]. The finite faults of the events are estimated in according with the Wells and Copersmith [1984] relation and their strike is coincident with the tectonic lines recognized on the southern side of the volcano (Figure 12).

Cubellis et al. [2007] recognized an upper level of seismic energy linked to seismogenetic structures at the boundary of the volcanic complex with respect to the level of energy of shocks, which comes before eruptions. These authors estimated also the prevailing directions in the faulting planes as NE-SW in the eastern sector of the volcanic complex, and roughly WNW-ESE in the southern part of the volcano along the coast. The last option is here considered favourable to represent the strike of the A.D. 62 source, which, according to Marturano and Rinaldis [1995], should be located near Pompeii, where the highest damage occurred. This is also in according with the Coulomb stress change due to expanding source operating before of the A.D. 79 eruption [Marturano 2008].

The distribution of PGA is shown in Figure 12. The nucleation point is in the central-bottom sub-fault element; the top of the fault (~1 km b.s.l.) is assumed coincident with the top of the Mesozoic carbonate basement [Brocchini et al. 2001]. The epicentral Intensity I_0 = IX estimated at Pompeii is accounted with a PGA value of 0.50 g, in the range of the max simulated values obtained by Galluzzo et al. [2008]. The south-east side of the volcano and the near Peninsula of Sorrento result hit by PGA values ≥ 0.15 g, well reproduced by effects I ≈ VIII MCS, as recorded by historical account at Herculaneum, epigraphical and archaeological evidence of injuries at Oplontis, Stabiae, Surrento Peninsula and at villas in the Sarno Plain [e.g., De Spagnolis Conticello 1995, Pisapia 1995, Guidoboni 1989, Luongo et al. 2003].

Finally, the simulated values show good agreement with macroseismic survey of both the M = 3.6 earthquake that occurred in 1999, and the A.D. 62 (M = 5.4) earthquake that struck the ancient town of Pompeii 17 yr before the A.D. 79 eruption of Mt. Vesuvius. The same model has been previously utilized to obtain source parameters of the January 15, 1466, earthquake by reproducing the observed macroseismic field of the November 23, 1980, two earthquakes that struck the same seismogenetic area of the southern Apennine [Marturano 2007]. The results obtained enable this method as a useful tool in evaluating source parameters and ground motion of large earthquakes in volcanic and tectonic areas of southern Italy as well.

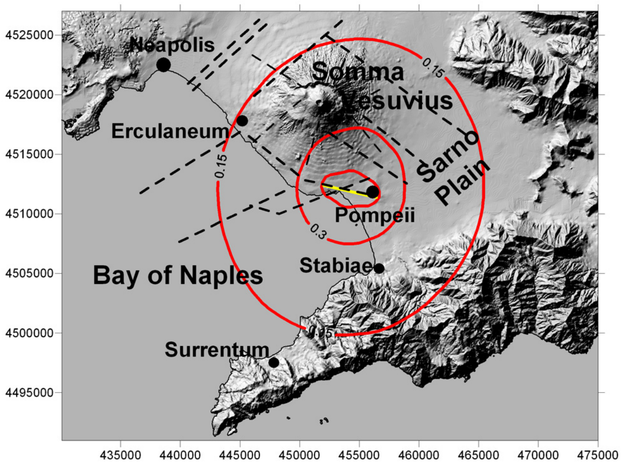

Figure 12. Earthquake of A.D. 62: distribution of calculated peak ground acceleration. The top (continuous line) of the subvertical causative fault (5 × 5 km) is at ~1 km b.s.l., and coincides with the top of the calcareous basamennt. The Intensities I = IX at Pompeii and I = VIII at Herculaneum, assigned by hystorical reconstructions, are accounted by peaks of acceleration a = 0.5 g and a ≈ .15 g respectively. Dashed lines represent faults and fractures of the shallow basement from geophysical surveys [from Cubellis et al. 2007]. Coordinates (meters) in UTM reference.

4. Conclusions

An integrated analysis of both historical and current seismicity as well as the geological structure of Vesuvius and the surrounding areas, evidence that the seismogenetic sources are located below the crater and at the boundaries of the volcanic complex. On analyzing the whole data set of the 1999 earthquake we observe that the maximum intensity occurs on the volcanic edifice from which it decreases radially. Marked attenuation areas were found East and NE of the volcano, and in the Campi Flegrei. In order to provide an estimation of expected effects it is necessary to consider that Vesuvian earthquakes show as much as one to two epicentral intensity degrees greater than equivalent magnitude earthquakes occurring in tectonic areas like the near seismogenetic Apennines Chain.

From the analysis described above we can summarize the following features of the seismic hazard and precursors of eruptions at Mt. Vesuvius:

1. The A.D. 79 eruption was preceded by a long sequence of earthquakes, probably accompanied by ground deformation, which started with a M = 5.1±.3 earthquake on February 5, 62;

2. The seismic crisis preceding the 1631 subplinian eruption, on the contrary, is characterized by a temporal seismic sequence with magnitude similar to the 1999 earthquake;

3. The earthquakes from 1631 to 1944 do not exceed the value of M = 4.5;

4. The sources of the maximum expected earthquake (alike A.D. 62), obtained by summation method (M = 5.4), as well as the 1999 (M = 3.6) earthquake develop prevalently in the NW-SE direction which resembles the strike of faults at the basement of southern slope of Mt. Vesuvius.

In sum, the application of the novel computational method of *felt index* to recent earthquakes of low energy at Mt. Vesuvius furnishes constrain on location, source characteristic and magnitude of moderate energy earthquakes, obtaining noteworthy scenarios about the energy level of seismicity occurring before eruptions that determine the seismic risk of the area.

Acknowledgements. We are grateful to P. Capuano, G. De Natale and G. Macedonio for helpful specialist discussions. Comments and suggestions from two anonymous reviewers greatly helped to improve the manuscript. We thank the Editors for the kind cooperation.

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Appendix

Questionario Macrosismico	Earthquake Questionnaire
Nome della scuola:	School Name:
Indirizzo:	Address:
1. Hai avvertito il terremoto?	1. Did you feel the earthquake?
2. Ti trovavi a casa?	2. Were you indoors?
Se sì, indica indirizzo:	What address?
piano:	What floor?
3. Eri sveglio?	3. Were you wide-awake?
4. Se stavi dormendo, ti sei svegliato?	4. If sleeping, were you awakened?
5. Ti trovavi per strada?	5. If outdoor, what locality?
Se sì, indica via / piazza:	place / street:
all'altezza del numero civico:	close to civic number:
6. Eri in una macchina ferma?	6. Were you in a motionless car?
7. Eri in una macchina in movimento?	7. Were you in a moving car?
Se stavi in casa e hai avvertito il terremoto:	If indoors and you felt the earthquake, please give details:
8. E' stato difficile mantenere l'equilibrio?	8. Did you loose balance?
9. Hai avuto paura?	9. Were you frightened?
10. Sei scappato via?	10. Did you run outdoor?
11. Hai sentito scricchiolare porte e finestre?	11. Did any door or windows rattle?
12. Hai sentito vibrare pentole e tegami nei mobili?	12. Did you feel creak pots and pans on furniture?
13. Hai sentito tintinnare bicchieri?	13. Did you feel clink glasses?
14. Hai visto oggetti sospesi oscillare?	14. Did any hanging objects swing?
15. Si sono spostati i quadri sui muri?	15. Did any painting move on wall?
16. Si sono spostati o rovesciati oggetti piccoli e leggeri?	16. Did any little or light object fall or upset?
17. Si sono aperte o chiuse porte e imposte?	17. Were windowpanes and gateways open or closed?
18. Sono caduti libri dagli scaffali?	18. Did any books fall from shelves?

Table A1. October 9, 1999, earthquake. Macroseismic questionnaire.

Locality	School	Int.
Afragola	G. A. Rocco	5
Afragola	A. Mozzillo	4
Afragola	G. Ciaramella	4
Agerola	E. De Nicola	3
Arzano	G. B.Vico	4
Bacoli	A. Gramsci	2
Bacoli	(Fusaro-Cuma)	2
Boscotrecase	Card. G. Prisco	6
Bracigliano (SA)	Angrisani	3
Capri	I. Nievo	2
Cardito	G. Galilei	3
Casalnuovo	E. De Nicola	4
Casandrino	E. Torricelli	3
Casoria	L. da Casoria	4
Castellammare di Stabia	G. Bonito	3
Castellammare di Stabia	L. Denza	3
Castello di Cisterna	A. de Gasperi	4
Cava dei Tirreni (SA)	G. Carducci and S. Lucia	2
Cercola	L. Giordano	5
Cercola	A. Custra	6
Cicciano	G. Pascoli	2
Crispano	S. Quasimodo	4
Ercolano	E. Iaccarino	5
Giugliano	Cante	nv
Marano	V. Alfieri	3
Marcianise (CE)	San G. Bosco	3
Mariglianella	G. Carducci	4
Marigliano	Pacinotti	4
Meta	39° Distretto	4
Monte di Procida		2
Mugnano di Napoli	Cirino	3
Mugnano di Napoli	F. Illuminato	3
Napoli	Ann. V. Emanuele II	4
Napoli	G. Marotta	4
Napoli	P. Borsellino	4
Napoli	F. Baracca	3
Napoli	R. Bracco	4
Napoli	S. Italico	4
Napoli	A. Belvedere	3
Napoli	G. B. Marino	5
Napoli	G. Salvemini	4
Napoli	C. Cavour	4
Napoli	S. Di Giacomo	4
Napoli	S. Maria di Costantinopoli	4
Napoli	D'Ovidio e Nicolardi	3
Napoli	M. Schipa	4
Napoli	G. Capuozzo	nv
Napoli	S. D'Acquisto	nv
Napoli (Bagnoli)	C. Console	3
Napoli (Barra)	F. Solimene	4
Napoli (Pianura)	F. Russo	3
Napoli (Secondigliano)	Tito Lucrezio Caro	4
Nocera Inferiore	A. Genovesi	2
Nocera Superiore	G. Pascoli	3
Nola (CE)	G. Bruno	2
Ottaviano	G. D'Annunzio	4
Ottaviano	Amedeo D'Aosta	5
Pagani (SA)	Sant'A.M. de' Liguori	2
Parete (CE)	M. Basile	2
Piano di Sorrento	G. Amalfi	3
Poggiomarino	E. De Filippo	4
Pomigliano D'Arco	Omero and Catullo	4
Portici	M. Melloni	5
Portici	Don Milani	5
Positano (SA)	A. Scarlatti	2
Pozzuoli	G. Diano	3
Pozzuoli (M. Rusciello)	A. Diaz	2
Procida	A. Capraro	2
Quarto	P. Gobetti	3
Sant'Antonio	Abate E. Forzati	3
San Giuseppe Vesuviano	Don G. Ceschelli	5
San Sebastiano	G. Salvemini	6
San Gennaro Vesuviano	A. Cozzolino	4
San Marzano sul Sarno (SA)	A. Frank	4
San Nicola la Strada (CE)	G. Mazzini	3
Sant'Agnello	Gemelli	4
Santa Maria la Carità	E. Borrelli	3
Sarno	Amendola	nv
Scafati (SA)	Anardi	4
Siano (SA)	Mons. S. Corvino	4
Somma Vesuviana	San G. Bosco	5
Somma Vesuviana	Summa Villa	4
Sorrento	T. Tasso	3
Terzigno	G. Giusti	5
Torre Annunziata	VI Scuola M. S.	4
Torre Annunziata	A. Manzoni	4
Torre Annunziata	V. Alfieri	nv
Torre del Greco	Don R. Scauda	5
Torre del Greco	Istituto Statale d'Arte	5
Torre del Greco	D. Morelli	5
Tramonti (SA)	G. Pascoli	2
Volla	M. Serao	nv

Table A2. October 9, 1999, earthquake. MCS Intensities.