The magnitude of damaging volcanic earthquakes of Mt. Etna: are the commonly used scales adequate?

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ABSTRACT

On October 2002 a seismic swarm occurred on the eastern flank of Mt. Etna. One of the strongest events caused severe damage, up to EMS intensity of VIII that contrasts with its local magnitude of 4.4. The occurrence of significant damage at such small magnitude is repeatedly observed in the Mt. Etna area and is traditionally attributed to the shallow source of volcanic earthquakes. Strong-motion accelerograms and broad-band seismograms recorded during the swarm demonstrate that there is a more cogent cause for the severe damage, i.e. an anomalously strong low-frequency ($0.1 < f < 1$ Hz) radiation deviating from the conventional Brune (1970) spectral scaling. Therefore, these earthquakes cause unexpectedly large ground displacements and long ($\approx$20 sec) durations of shaking. The integration of digital accelerograms recorded on October 2002 yields a maximum peak ground displacement as large as 1.8 cm at a distances of 18 km, out of the largest damage zone. Based on the sharp local attenuation of ground motion amplitudes observed during the Mt. Etna earthquakes, we infer that displacements near the epicentres can have attained 10 cm. So large displacements are consistent with the maximum observed damage. Moreover, the frequency cutoff below 1.25 Hz in the Wood-Anderson response attenuates the peak-to-peak amplitudes used to assess local magnitudes. This instrumental deamplification at low frequency yields underestimated values of local magnitude that are not representative of the real ground shaking. Since a prompt, correct magnitude (and potential damage) assessment is crucial for efficient Civil Protection

actions, a procedure is proposed which, in near-real-time, can be successful in identifying potentially damaging earthquakes of Mt. Etna through the computation of response spectra. The procedure provides a magnitude value that is derived on a statistical basis from the Housner (1952) spectral intensity computed in the low-frequency band. This parameter is a suitable near-real-time indicator of large earthquake-induced building shaking and could also be applied for a preliminary determination of the epicentral macroseismic intensity of volcanic events of Mt. Etna through consolidated relationships established for tectonic earthquakes in Italy.

INTRODUCTION

Between 26 and 29 October 2002, the Mt. Etna area was intensely struck by several earthquakes well felt by the population in a large area of eastern Sicily, from Messina to Siracusa (Figure 1). These shocks were part of a seismic swarm that counted some hundred events in the first 4 days of activity and lasted up to the early 2003. Earthquakes interested two separate areas of Mt. Etna (see Figure 1), as described by Barberi et al. (2004) and Patanè et al. (2006). A first group of epicenters is located in the E-NE part of the volcano, reaching a maximum local magnitude of 4.6 on October 27 at 02:50 UT. The second group, occurring since October 28, is located in the SE flank close to the town of Zafferana Etnea and culminated with the M_L 4.4 earthquake of October 29 at 10:02 UT (Figure 1). The strongest events along with their magnitudes are listed in Table 1. The seismic swarm was concomitant with the opening of a system of fractures in the eastern part of the volcano and the reactivation of the eruptive fracture system originated by the 2001 eruption.

The most damaging event was the M_L 4.4 earthquake of October 29, which occurred in a densely urbanized territory and attained intensity VIII on the European Macroseismic Scale (EMS). In spite of its small local magnitude, the shock caused significant damage to many buildings including reinforced concrete ones (see Figure 2 a), in an area that extends for about 4 km in a NNW-SSE direction and is centered around the villages of S. Venerina and Guardia (Azzaro and Mostaccio, 2002; Azzaro, 2002). A long system of surface fractures originated along the damaged area. Other similar and even stronger events of the October 2002 swarm in the northern zone (see Table 1) did not cause diffuse damage since they occurred in a not densely urbanized area; however, the level of destruction was high for the few sparse buildings close to the epicenters (see Figure 2, b).

The occurrence of severe damage during small magnitude events is not new in the Mt. Etna area where previous earthquakes (in the years 1865, 1911, 1914, and 1952) attained epicentral intensities as large as IX-X EMS in spite of macroseismic magnitudes < 5 (Azzaro, 2002). On 1879, a damaging earthquake caused a macroseismic field and surface effects very similar to those of the October 29, 2002, M_L 4.4 event.

The goal of this paper is to investigate the discrepancy between the small magnitude and the high level of damage by analyzing as many as possible recordings of the October 2002 swarm. These volcanic earthquakes were the first ones to be recorded locally by broadband instruments. Their data offer the opportunity of analyzing the spectral content of the volcanic events of Mt. Etna down to frequencies of about 0.1 Hz that were never investigated so far. In this study we document to what extent the volcanic earthquakes of October 2002 deviate from the conventional source scaling of tectonic earthquakes, attaining much larger amplitudes in the low-frequency band. Thus, we demonstrate that shallow source or permanent deformations can be possible concomitant causes for the large damage but there are more cogent factors intrinsically connected to the special spectral structure of the volcanic events of Mt. Etna.

DATA

The data used in this study are strong-motion accelerograms recorded at Catania (CATA) and Bronte (BRNT) as well as broad-band seismograms recorded at 5 temporary stations (SVN1 to SVN5) deployed in the Santa Venerina territory (Figure 1). The strong motion stations CATA and BRNT belong to the Italian Accelerometric Network (D.P.C, 2005). These stations are equipped with Kinemetrics model Etna digitizers and Episensor accelerometers. The full scale is set to 1g, data were recorded in trigger mode with an activation threshold of 3 gals on any of the three components. The sampling rate was 200 samples per sec.

The broadband seismological stations, equipped with three component Guralp CMG-40T seismometers and Ref-Tek 72A digitizers, were installed in the Santa Venerina area since December 3, 2002. They operated up to January 25, 2003 in a continuous recording mode with a sampling rate of 125 samples per sec, and recorded late events of the swarm up to a maximum local magnitude of 3.7.

Magnitudes of the swarm events are computed from recordings at local and regional distances. Moment magnitudes (M_W) are available only for 3 of the strongest events and can be found in the MedNet catalog of Regional Centroid Moment Tensor (RCMT) determinations (Pondrelli et al., 2004). For the same events, the MedNet catalog also provides local magnitudes M_L obtained through Wood-Anderson numerical synthesis of broad-band seismograms of the MedNet stations, applying the conventional distance correction (Richter, 1958). For the events of October 2002 not included in the MedNet catalog of local magnitudes, we have generated synthetic Wood-Anderson seismograms using the strong motion accelerograms of CATA and BRNT. These M_L values tend to overestimate those of the MedNet catalog, when both are available. The same procedure was also adopted for events occurred after December 3, 2002 using the local records of stations SVN1 to SVN5.

The list of earthquakes in the used dataset and their magnitude estimates are shown in Table 1.

GROUND MOTION ANALYSIS

Strong motions

The pattern of activation of the two strong motion stations reflects the temporal and spatial evolution of the swarm. The accelerometer of BRNT, which is closer to the epicenters in the E-NE part of Mt. Etna, was triggered by three of the events of October 27 occurred in that area. The M_L 4.6 event of October 27 at 02:50 UT is the only one that triggered both BRNT and CATA. The accelerometer of CATA, which is closer to the SE flank of Mt. Etna, was also triggered by two of the events of October 29 occurred in the Santa Venerina area (Table 1).

The ground motion waveforms of these earthquakes (specimens are shown in Figure 3) indicate a long ($\approx$20 sec) duration along with a predominance of low frequencies in the ground motion. Horizontal peak ground acceleration (PGA) and velocity (PGV) deviate from the statistical expectations of the Sabetta and Pugliese (1987) regression (SP87 hereonafter) fitting the Italian strong-motion data (see Table 2). This comparison is made only to give a first idea about the anomaly of the recorded events, in full awareness that it is not strictly appropriate for two reasons. First, the attenuation relationships were assessed by SP87 using earthquakes in Italy with magnitude > 4.6 and should not be used for smaller magnitudes; second, the authors did not include earthquakes of volcanic areas in their analysis and therefore their attenuation law is not intended for them. Nevertheless, we believe that this comparison is useful to stress how large the inadequacy is, for volcanic events, of the commonly adopted ground motion scaling laws. This is especially important for the hazard assessment in the Mt. Etna area.

Observed and expected PGAs and PGVs of Table 2 indicate that recorded PGAs are always smaller than predictions whereas recorded PGVs are always larger, and the discrepancy tends to increase when the earthquake size increases. This means that the low-frequency amplitudes of volcanic events are larger than those of tectonic events at the same magnitude and distance whereas the opposite occurs for the high-frequency band, implying a source scaling completely different between tectonic and volcanic events.

To confirm this inference, Figure 4 (a to e) compares the amplitude Fourier spectra of the accelerograms to the Brune (1970) spectra expected for the moment magnitude and source-to-receiver distance of the events. Theoretical spectra of Figure 4 are modeled through the attenuation law inferred from eastern Sicily tectonic earthquakes by Scognamiglio et al. (2005). The evident deviation from the conventional scaling of tectonic earthquakes is therefore the origin of the anomalously small accelerations and large velocities of volcanic events. Acceleration spectra of

CATA show a significant depletion in the high-frequency amplitude and a large spectral bump in the frequency band 0.1 – 1 Hz. Also station BRNT has the same tendency, although the exaggeration of low-frequency amplitudes has a smaller extent. The difference in the spectral bump between BRNT and CATA for the same event (Figure 4, a and c) could erroneously lead to the conclusion that CATA is affected by a site effect. However, this interpretation has to be ruled out since the same station shows no amplification at low frequency in the spectra of the local tectonic events (a specimen is shown in Figure 4 f).

The anomalously large low-frequency content of volcanic events can play an important role on the high damage level for $M_L > 4$. For the strongest events of October 2002, the integration of the digital accelerograms yields ground displacements ranging from 0.4 to 1.8 cm at distances between 13 and 27 km (Figure 5). Considering that attenuation in the Mt. Etna area is usually very sharp within the first ten kilometers from the epicenter (see Figure 5 for a well documented case), we infer that horizontal ground displacement could have attained amplitudes as large as 5 to 10 cm in the epicentral area. A sharp amplitude decay within the first 20 km is also expected, for earthquakes of Mt. Etna, on the basis of the strong attenuation of macroseismic intensities (Barbano et al., 2002; Azzaro et al., 2006). Values of more than 5 cm in the epicentral area are consistent with the experienced maximum damage. Therefore, shallow source is probably a second-order factor but large ground displacements close to the epicenters can be the first-order cause for the severity of damage during volcanic earthquakes, at least for those of the October 2002 swarm.

Moreover, for these earthquakes, the predominant amplitude in the long-period (LP) component makes the local magnitude estimation misleading: the low-frequency cutoff at 1.25 Hz in the Wood Anderson response causes a strong underestimation of the maximum peak-to-peak amplitude. Therefore, M_L is not the most suitable magnitude scale to be used for volcanic earthquakes, especially when the predominant spectral content moves to frequencies $f < 1.25$ Hz. Also moment magnitude derived from the CMT inversion is not appropriate since the spectral bump is significant for periods $1 < T < 10$ sec but seems not to affect the longer periods ($T > 30$ sec) where the inversion is made. A third magnitude estimate can be derived from the seismogram duration (D'Amico and Maiolino, 2005). However, duration-magnitude *(i)* could depend on the instrumental bandwidth (a difference is expected using short-period or broad-band seismograms), and *(ii)* is based on a calibration using another magnitude scale (M_L) that in this case is proved not to work properly. The latter limitation suggests a careful use of duration-magnitude for volcanic earthquakes of Mt. Etna.

Weak motions

Stations in the Santa Venerina area (Figure 1) confirm that smaller size events of the swarm are characterized by the same spectral behavior of the largest events. Figure 6 shows two example seismograms recorded by the same station (SVN4) at short (R < 10 km) epicentral distance. Of the two earthquakes, one is characterized by a high-frequency spectral content, where P- and S-waves are clearly visible: it could be classified as a VT-A type, according to the conventional definition of earthquakes in volcanic areas (Wassermann, 2002). The other one shows an intermediate behavior between VT-B and hybrid type where body waves are weakly emergent and a LP component predominates in amplitude.

Although the two earthquakes of Figure 6 attained approximately the same peak ground velocity and are at a similar epicentral distance, their Fourier amplitude spectra show a very different shape. The VT-A event is well fit by a Brune spectrum with a stress drop of 40 bars, attenuated according to the scaling law by Scognamiglio et al. (2005). The hybrid event shows amplitudes at 1 Hz that are a factor of 30 larger than those of the VT-A earthquake. This corresponds to a difference by a factor of about 12 in terms of observed peak ground displacements. In contrast, high frequencies are drastically depleted. Peak ground accelerations of the of the VT-A event exceed those of the VT-B event by a factor between 4 and 5. Low amplitudes at high frequencies could be a source property of volcanic earthquakes but could also be due to a shallower propagation, Q-tomography indicating the presence of a 2-km thick, highly attenuating topmost layer in the southeastern flank of Mt. Etna

(De Gori et al., 2005). Unfortunately, the P-onset of volcanic events is weakly emergent and consequently the hypocentral determination is not so precise to solve easily the source/propagation ambiguity. However, Figure 7 confirms that also the smallest volcanic earthquakes have the predominant spectral content in the low-frequency band (f < 2 Hz) deviating significantly from the source scaling of VT-A events. It has to be also noted that, for $M_L < 4$, the spectral content does not move toward frequencies much lower than 1 Hz, and therefore the underestimation of the maximum peak-to-peak amplitude on synthesized Wood-Anderson seismograms is not as significant as it is for the $M_L > 4$ events.

CAN DAMAGING VOLCANIC EARTHQUAKES BE RECOGNIZED IN NEAR-REAL-TIME?

A consolidated magnitude scale like the Richter one is difficult to be replaced: seismic moment inversion is rarely successful for $M_W < 5$, and there is no reliable calibration for a regression using the seismogram durations of volcanic earthquakes. For these reasons, we still believe that the use of the Richter magnitude has to be continued for the Mt. Etna earthquakes. However, the above discussed limitations and the increasing number of broadband stations in the Mt. Etna area suggest that *i)* the M_L determination has to be improved for local earthquakes, and *ii)* new criteria, not based on M_L, have to be found to recognize damaging earthquakes in near-real-time.

Target *i)* will be achieved by calculating a new distance correction using broadband seismograms of local earthquakes. Even though the Richter (1958) correction seems to be satisfactory for Italian earthquakes at a zero order approximation (Bonamassa and Rovelli, 1986), the fast attenuation in the Mt. Etna area (Figure 5) requires a specific correction, with a particular attention to the problem of the wide range of possible source depth (Patanè et al., 2006). As shown by Hutton and Boore (1987), hypocenter depth variations are crucial for the distance correction at short distance. In the last years, the number of broad-band seismograms recorded in Mt. Etna area is continuously increasing and data will be soon enough to permit a distance correction more accurate than previous attempts substantially based on few short-period seismograms (D'Amico and Maiolino, 2005).

However, seismologists and Civil Protection operators must be aware that even a correctly determined M_L value will underestimate the size of volcanic earthquakes when the low-frequency content increases below 1 Hz, and additional tools are necessary for events with $M_L > 4$.

To this purpose, this is the question we have to find an answer to: there is a way to get an objective ground motion parameter representative of potential damage few minutes after the occurrence of a volcanic earthquake? If a criterion is found which is based on a quantification of the excitation of structures, a numerical procedure could be implemented to be routinely used with real-time recordings.

Computing response spectra offers this opportunity. Figure 8 shows examples of 5%-damped pseudovelocity response spectra for the strongest of the October 2002 earthquakes. In the same figure, statistical expectations for tectonic earthquakes based on the Sabetta and Pugliese (1996) regression (SP96 hereonafter) are also shown. Again, there is a significant (up to a factor of 3) depletion in the observed high-frequency response spectra compared to the expected curves of SP96. In contrast, at low frequency, response spectra computed from the local recordings are fit by spectral ordinates statistically corresponding to M_L 5.5 to 6 of tectonic earthquakes in Italy. In other words, in sites where the Wood-Anderson amplitude yields magnitudes < 5, the effects of volcanic earthquakes on buildings could be as large as those experienced in tectonic regions of Italy during much stronger (up to M_L 6) earthquakes.

Figure 8 indicates that the frequency band 0.3 to 1.5 Hz gives the largest contribution to the pseudovelocity response spectra of volcanic events of Mt.Etna. For a given earthquake and a given epicentral distance *R*, it is simple to determine the magnitude that, in the SP96 regression, would attain the same spectral ordinates in that frequency band. This is accomplished by constructing a theoretical curve of the Housner (1952) spectral intensity

$$H(M, R) = \int_{0.3}^{1.5} PSV_{M,R}(f)\, df \qquad (1)$$

where $PSV_{M,R}(f)$ is the statistical expectation of 5%-damped pseudovelocity response spectra

$$log\, PSV_{M,R}(f) = a(f) + b(f)\ M - log\sqrt{R^2 + h^2(f)}$$

and *a(f)*, *b(f)*, and *h(f)* are the regression coefficients computed by SP96. In Figure 9, examples of the theoretical curve *H(M*, *R*) are intersected by the value of the Housner spectral intensity (horizontal straightline) computed from the accelerograms of the volcanic earthquakes of the October 2002 swarm. As expected on the basis of the fit shown in Figure 8, the values of the Housner spectral intensity computed from records of volcanic earthquakes (diamonds) are significantly larger than the statistical expectation of tectonic earthquakes at the same magnitude and distance. The diamond abscissa corresponds to the local magnitude synthesized from the same accelerograms used to compute the Housner spectral intensity. In each panel of Figure 9, the intersection of the horizontal straightline with the theoretical Housner curve indicates the magnitude of the earthquake that, in the SP96 regression, excites elastic structures at the same level of intensity. The larger the difference between observed and expected Housner spectral intensity, the higher the probability of damage during the earthquake. In the case of the two major events of October 27 and 29, the computed Housner intensity corresponds to a magnitude of 5.1 (BRNT) and 5.3 (CATA), respectively, exceeding significantly all the available magnitude estimates of Table 1. It is worthy of note that the magnitude value inferred from the Housner curves of Figure 9 is strictly consistent with the one expected on the basis of conventional macroseismic intensity-magnitude relationships of Italian earthquakes, as demonstrated in the following.

The computation of the Housner spectral intensity can be implemented in near-real-time. Compared with other ground-motion parameters that might be obtained from real-time records (cumulative energy, Fourier amplitude spectra, etc.), the advantage of pseudovelocity response spectra is that they are more directly related to the building excitation and that their dependence on magnitude and distance has been investigated very accurately on a statistical basis (SP96).

Thanks to the increasing number of broadband records now available in real-time, the procedure could provide, within few minutes after an earthquake, the magnitude value that, according to SP96, corresponds to Housner spectral intensity attained at the recording sites. Averaging these values would yield a magnitude estimate statistically consistent with the excitation suffered by elastic structures. In this approach, also a preliminary indication of the epicentral macroseismic intensity (I_o), that is urgently required by the Civil Protection authorities, could be more realistic than using regressions versus magnitude. Figure 10 shows the magnitude−maximum intensity curve computed for Italian earthquakes (Di Filippo and Marcelli, 1950). This is the relationship conventionally used in Italy for a statistical determination of the maximum intensity as soon as an earthquake occurs. For the October 29, 2002 earthquake, using the magnitude abscissa inferred from the Housner intensity we obtain an average of 5.1: this would have predicted a maximum intensity of VII-VIII which is much closer to the experienced one whereas the official M_L value (4.4) did correspond to intensity VI-VII. Of course, other intensity-magnitude correlations exist that have been specifically computed for shallow volcanic earthquakes (e.g. Barbano et al., 2002; Azzaro et al., 2006). They would have yielded a high intensity as well. However, *a priori* it is not obvious what regression is the best one to be used just after an earthquake. Moreover, volcanic-earthquake relations make use of duration-magnitude and this does increase uncertainties, duration-magnitude suffering the lack of an appropriate calibration. In contrast, the proposed method to assess I_o is based on a quantification of elastic structure vibrations excited by the recorded ground motions. Therefore, the result is valid independently of the nature of the causative earthquake.

CONCLUSIONS

Volcanic earthquakes of the October 2002 swarm were the first ones to be recorded locally by broadband instruments. Both strong-motion accelerograms and weak-motion seismograms enhance a marked LP component in the horizontal motions. Compared with tectonic earthquakes at the same local magnitude and distance, volcanic earthquakes show both a depletion in amplitude at high frequencies and a large spectral bump in the frequency band 0.1 – 1 Hz. These two features imply that *(i)* conventional source scaling of tectonic earthquakes does not fit ground motions of volcanic earthquakes, *(ii)* commonly used magnitude scales are not adequate for volcanic earthquakes being not calibrated for their large spectral content at low frequency, and *(iii)* ground displacements of volcanic earthquakes at magnitudes of the order of 4 attain amplitudes typical of tectonic earthquakes at magnitudes as large as 5 to 6. We believe that the latter can be the main cause of the occurrence of high damage level during volcanic earthquakes. Moreover, the large low-frequency content below 1 Hz is attenuated by the Wood-Anderson transfer function that produces underestimation of local magnitudes.

Based on statistical regressions of pseudovelocity response spectra as a function of magnitude (Sabetta and Pugliese, 1996), a procedure is proposed which computes the spectral ordinates from real-time records and provides magnitude values more usable to assess the potential level of damage in near-real-time.

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TABLE CAPTIONS

Table 1 – List of the events used in the present study. Station codes B and C refer to BRNT and CATA, respectively; the numbers indicate stations SVN1 to SVN5. Local magnitudes of this work are synthesized from the available local recordings.

Table 2 – Comparison between observed and predicted PGAs and PGVs. Local magnitude are from the MedNet catalog, when available, or synthesized from strong motion accelerograms (asterisk).

Date	Time	Lat.	Lon.	M_L Mednet	M_W Mednet	M_L This work	Recording Stations
2002/10/27	01:28:17.59	37.808	15.051			4.3	B
2002/10/27	01:58:11.23	37.740	14.964			4.6	B
2002/10/27	02:50:25.01	37.768	15.021	4.6	4.9	4.7	B/C
2002/10/29	10:02:20.23	37.687	15.100	4.4	4.7	4.8	C
2002/10/29	16:39:46.78	37.666	15.138	4.1	4.2	4.4	C
2002/12/03	13:50:27.00	37.795	15.089			2.7	1
2002/12/03	21:07:59.00	37.648	15.122			3.2	1/2/3/4
2002/12/04	05:17:25.00	37.649	15.139			3.0	1/2/3/4
2002/12/04	13:16:33.00	37.718	15.123			3.4	1/2/3/4/5
2002/12/05	22:59:57.00	37.794	15.060			3.0	1/2/3/4/5
2002/12/24	01:12:59.00	37.807	15.056			3.7	4/5
2002/12/24	13:32:09.00	37.805	15.047			2.4	5
2002/12/27	10:37:17.00	37.809	15.091			3.1	5
2002/12/28	08:24:22.00	37.829	15.041			2.5	5
2003/01/19	00:34:59.00	37.718	15.107			2.7	4
2003/01/25	03:29:20.00	37.636	15.065			2.2	2/3/4

Table 1

Date	Time	M_L	Distance	PGA SP	PGA Obs.	PGV SP	PGV Obs.
2002/10/27	01:28	4.3*	19	28	4	0.9	0.7
2002/10/27	01:58	4.6*	13	50	14	1.9	2.3
2002/10/27	02:50	4.6	17	38	9	1.4	2.4
2002/10/27	02:50	4.6	27	25	4	0.9	1.6
2002/10/29	10:02	4.4	18	32	15	1.1	4.5
2002/10/29	16:39	4.1	16	28	6	0.9	0.9

Table 2

FIGURE CAPTIONS

Figure 1 - Map of the study area. The zone of the largest damage, including the village of Santa Venerina, is elongated NW-SE (left hand panel). In the right hand panel, open circles are the strongest events of the swarm, recorded at the accelerometric stations CATA and BRNT; diamonds are later, minor events recorded by temporary stations SVN1 to SVN5.

Figure 2 - Example of severely damaged buildings in the epicentral area of (a) the M_L 4.6 earthquake of October 27, 2002, and (b) the M_L 4.4 earthquake of October 29, 2002.

Figure 3 - Specimens of ground accelerations and velocities of events of the October 2002 swarm. Observed accelerations are smaller and velocities are larger than values expected on the basis of the Sabetta and Pugliese (1987) regressions.

Figure 4 - Amplitude spectra of the two horizontal components of ground acceleration: (a to e) volcanic events of the October 2002 swarm, (f) tectonic event of December 30, 2004 in the Hyblean Foreland. The smooth curves are theoretical Brune spectra attenuated to the recording sites according to Scognamiglio et al. (2005).

Figure 5 - Time histories of ground displacement (EW components) of the strongest events of the October 2002 swarm, at distances of 13 to 27 km. Peak ground displacement (PGD) at CATA was as large as 1.8 cm, but likely attained significantly larger values in the damaged zone. The panel in the right hand side shows an example of the usually observed sharp amplitude decay in the epicentral area: PGD decreased by more than a factor of 10 in the first 20 km during a colocated M_L 3.5 tectonic earthquake of October 31, 2005 that was well recorded by INGV stations in Sicily (courtesy by Alessandro Amato and Alessandro Bonaccorso). The black diamond is PGD of CATA.

Figure 6 - Weak motions of the 2002 swarm recorded in the village of Santa Venerina: note the opposite behavior of low- and high-frequencies between VT-A and VT-B events.

Figure 7 - Spectra of smaller magnitude earthquakes of the 2002 swarm (a, events of the NE sector; b, events of the S-SE sector).

Figure 8 - Pseudovelocity response spectra of the strongest events of October 2002 compared to predictions of the Sabetta and Pugliese (1996) regression.

Figure 9 - Curves of the Housner spectral intensity computed through Equation (1). Housner intensity from the local accelerograms is represented by black diamonds. Intersection between horizontal and vertical straight lines gives the magnitude of a tectonic event with the same Housner intensity in the 0.3-1.5 Hz frequency band.

Figure 10 - Maximum intensity-magnitude relationships of volcanic and tectonic earthquakes in Italy. The prediction of the epicentral macroseismic intensity of volcanic earthquakes is improved by using the magnitude values derived from the statistical relationship between pseudovelocity response spectra and moment magnitude of tectonic earthquakes (Sabetta and Pugliese, 1996).

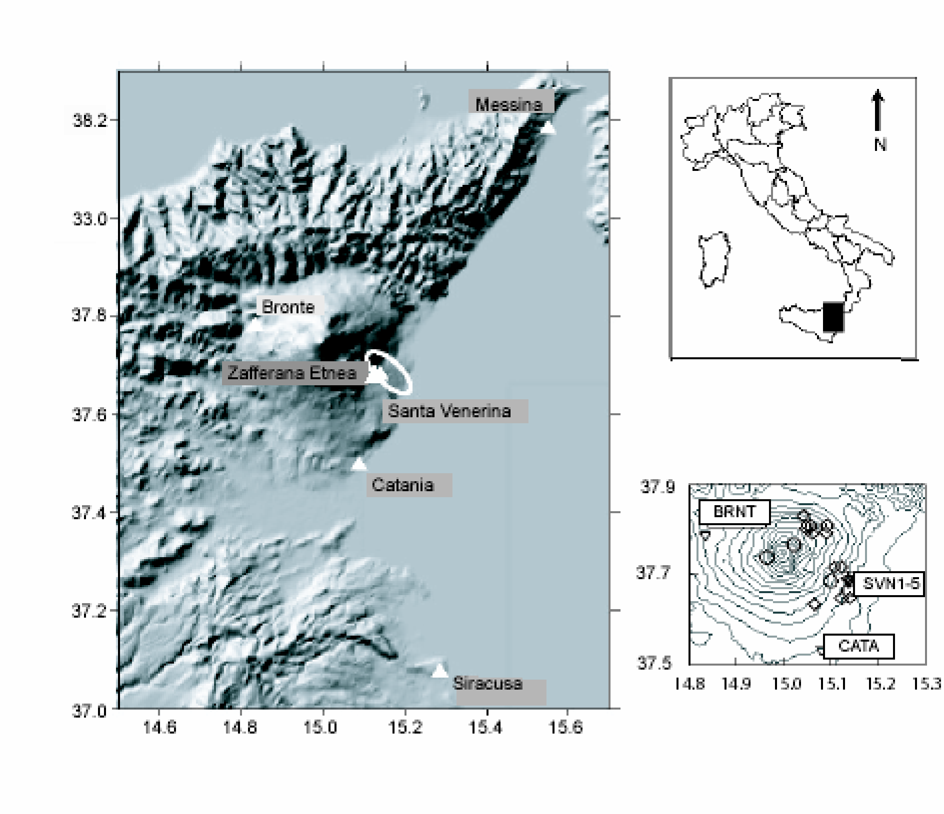

Messina
Bronte
Zafferana Etnea
Santa Venerina
Catania
Siracusa
38.2
33.0
37.8
37.6
37.4
37.2
37.0
14.6
14.8
15.0
15.2
15.4
15.6
N
37.9
37.7
37.5
BRNT
SVN1-5
CATA
14.8
14.9
15.0
15.1
15.2
15.3

Figure 1)

b)

a)

Figure 2)

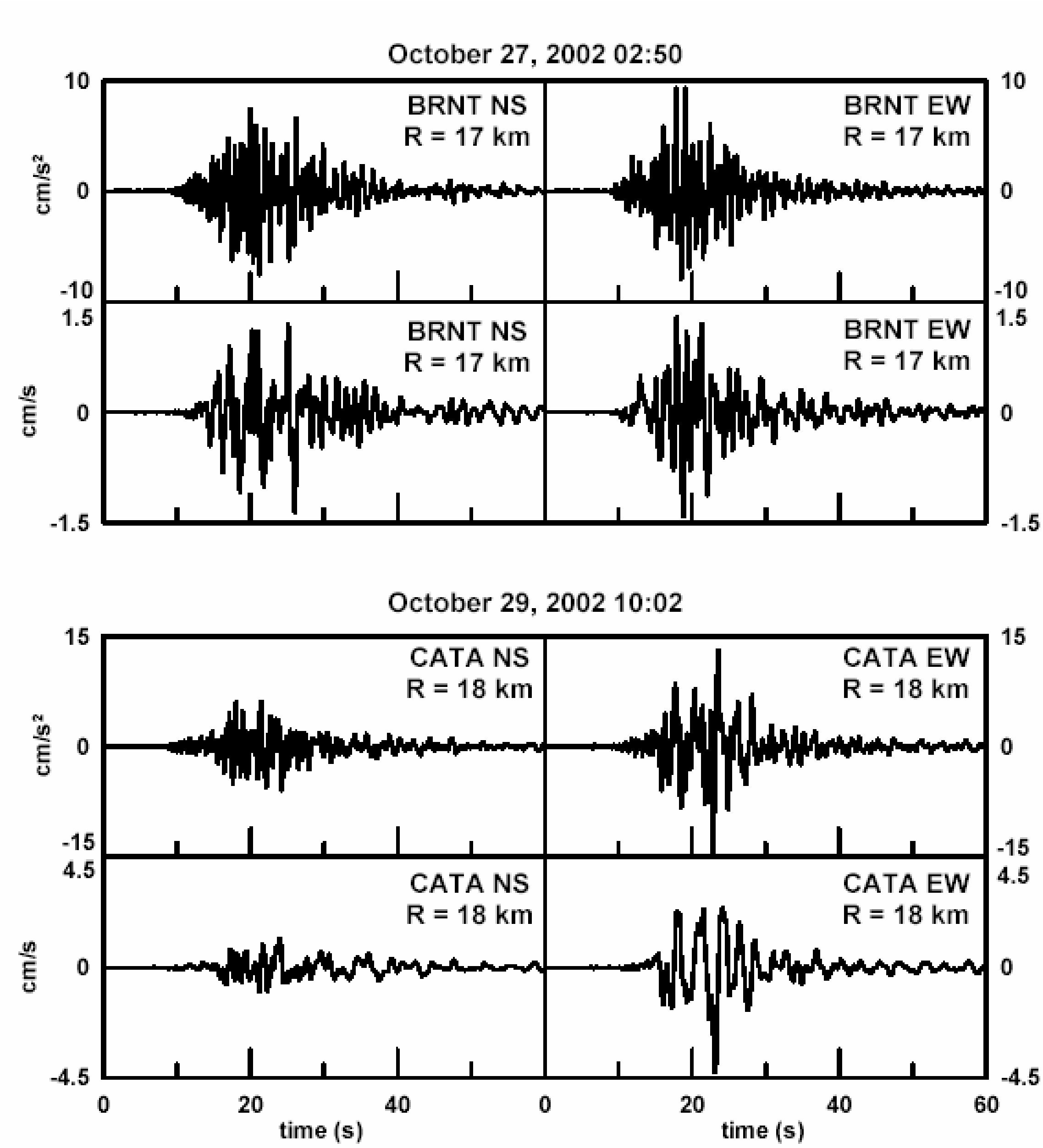

October 27, 2002 02:50
BRNT NS
R = 17 km
BRNT EW
R = 17 km
cm/s²
cm/s
10
0
-10
1.5
-1.5
October 29, 2002 10:02
CATA NS
R = 18 km
CATA EW
R = 18 km
15
-15
4.5
-4.5
0
20
40
60
time (s)

Figure 3)

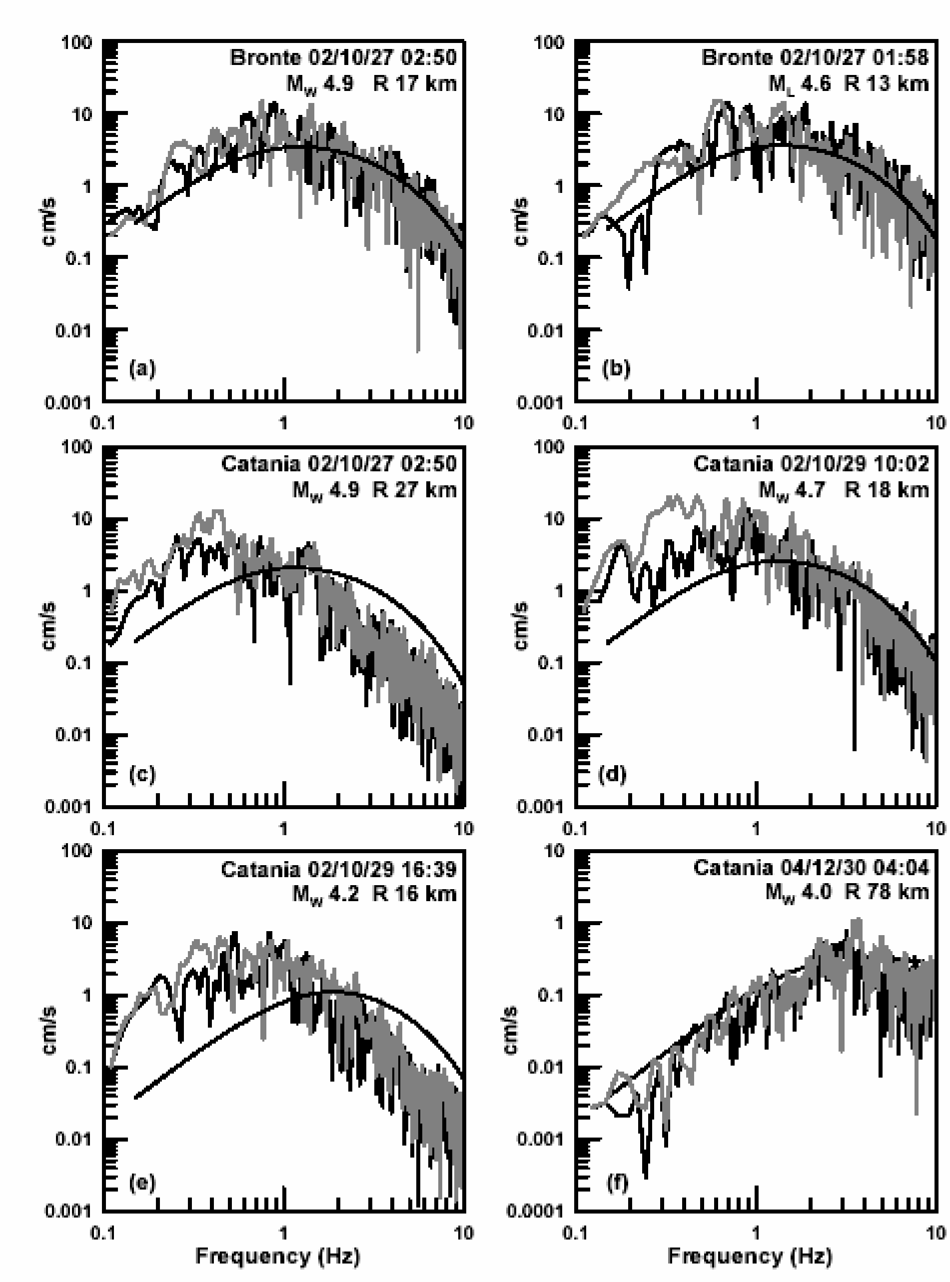
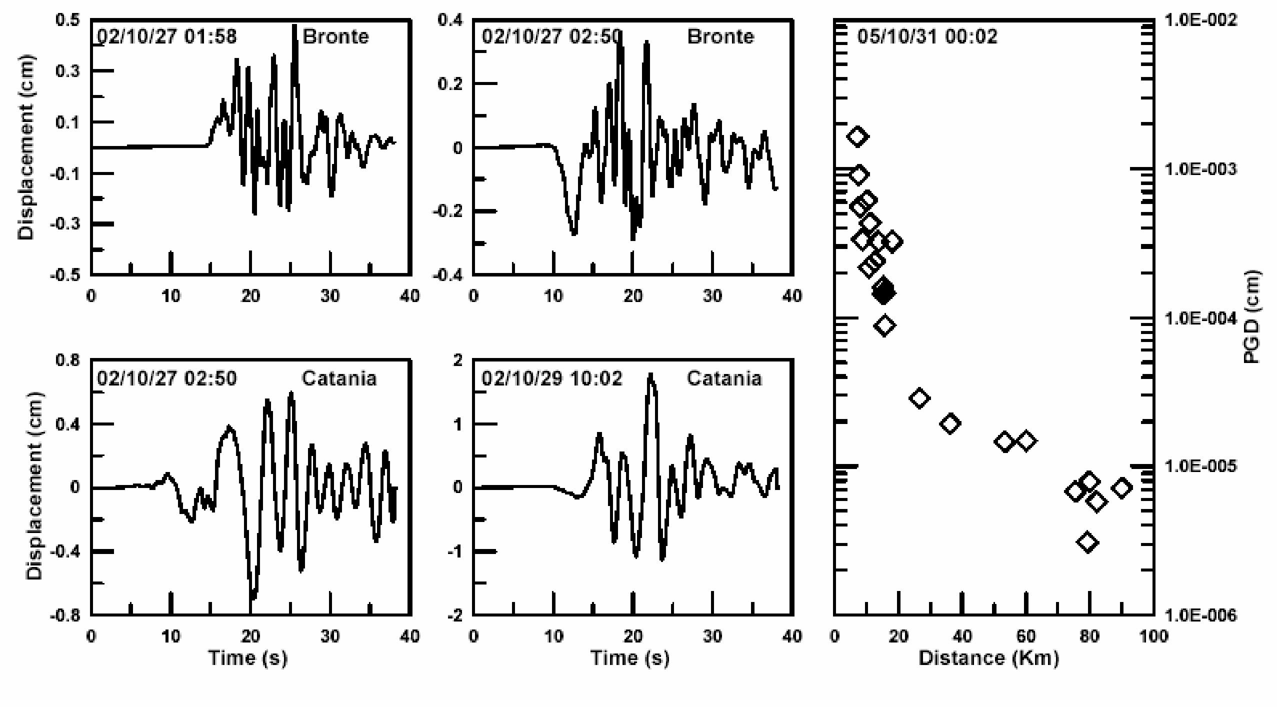

Bronte 02/10/27 02:50
Mw 4.9 R 17 km
(a)
Bronte 02/10/27 01:58
ML 4.6 R 13 km
(b)
Catania 02/10/27 02:50
Mw 4.9 R 27 km
(c)
Catania 02/10/29 10:02
Mw 4.7 R 18 km
(d)
Catania 02/10/29 16:39
Mw 4.2 R 16 km
(e)
Catania 04/12/30 04:04
Mw 4.0 R 78 km
(f)
cm/s
Frequency (Hz)
100
10
1
0.1
0.01
0.001
0.0001

Figure 4)



02/10/27 01:58
Bronte
02/10/27 02:50
Bronte
05/10/31 00:02
02/10/27 02:50
Catania
02/10/29 10:02
Catania
Displacement (cm)
Displacement (cm)
Time (s)
Time (s)
Distance (Km)
PGD (cm)

Figure 5)

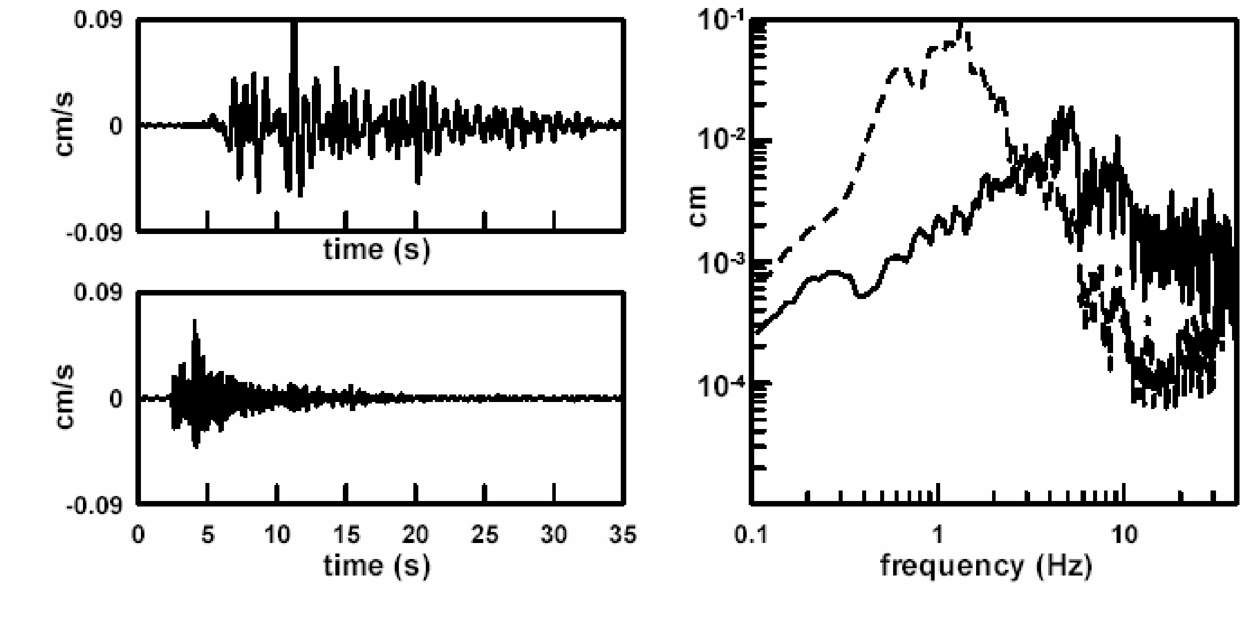

0.09
cm/s
0
-0.09
time (s)
0.09
cm/s
0
-0.09
0
5
10
15
20
25
30
35
time (s)
10^{-1}
10^{-2}
cm
10^{-3}
10^{-4}
0.1
1
10
frequency (Hz)

Figure 6)

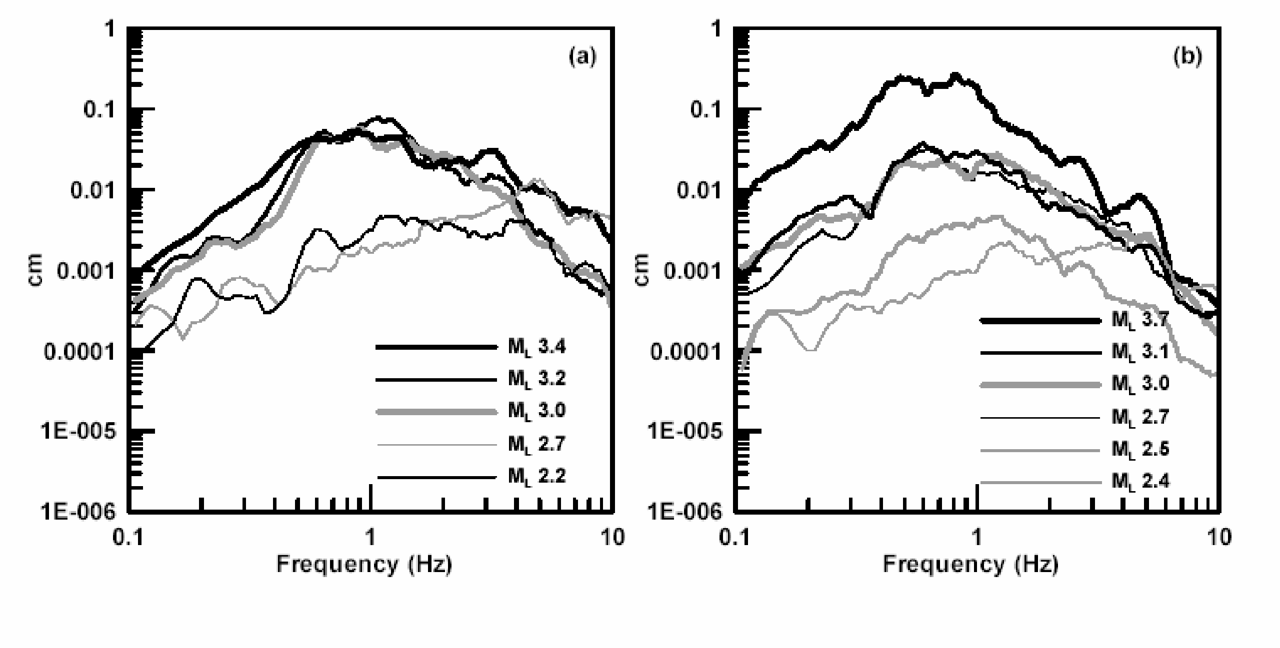
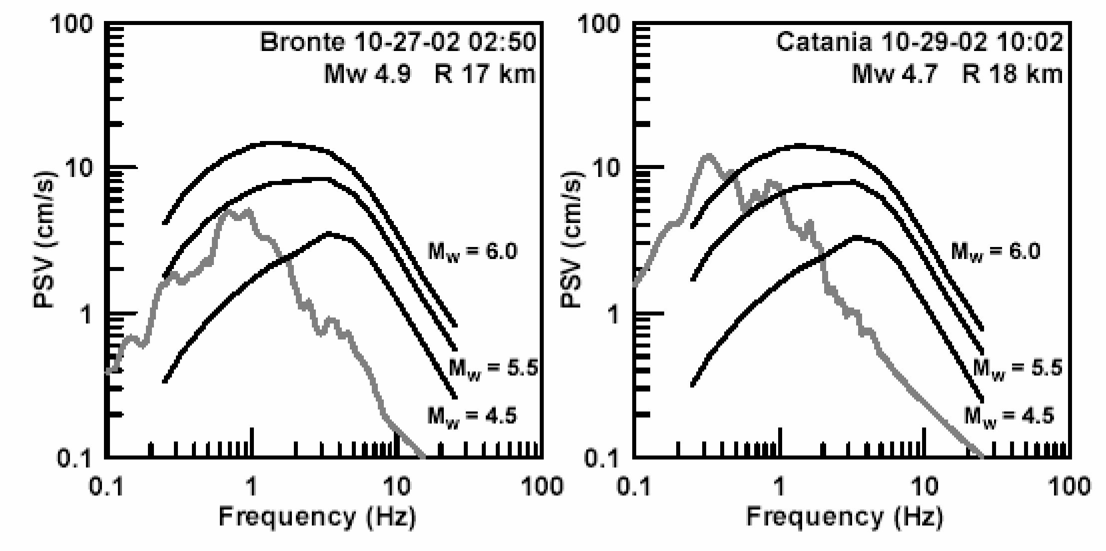

(a)
(b)
cm
Frequency (Hz)
M_L 3.4
M_L 3.2
M_L 3.0
M_L 2.7
M_L 2.2
M_L 3.7
M_L 3.1
M_L 3.0
M_L 2.7
M_L 2.5
M_L 2.4

Figure 7)



Bronte 10-27-02 02:50
Mw 4.9 R 17 km
PSV (cm/s)
Frequency (Hz)
M_W = 6.0
M_W = 5.5
M_W = 4.5
Catania 10-29-02 10:02
Mw 4.7 R 18 km
PSV (cm/s)
Frequency (Hz)
M_W = 6.0
M_W = 5.5
M_W = 4.5

Figure 8)

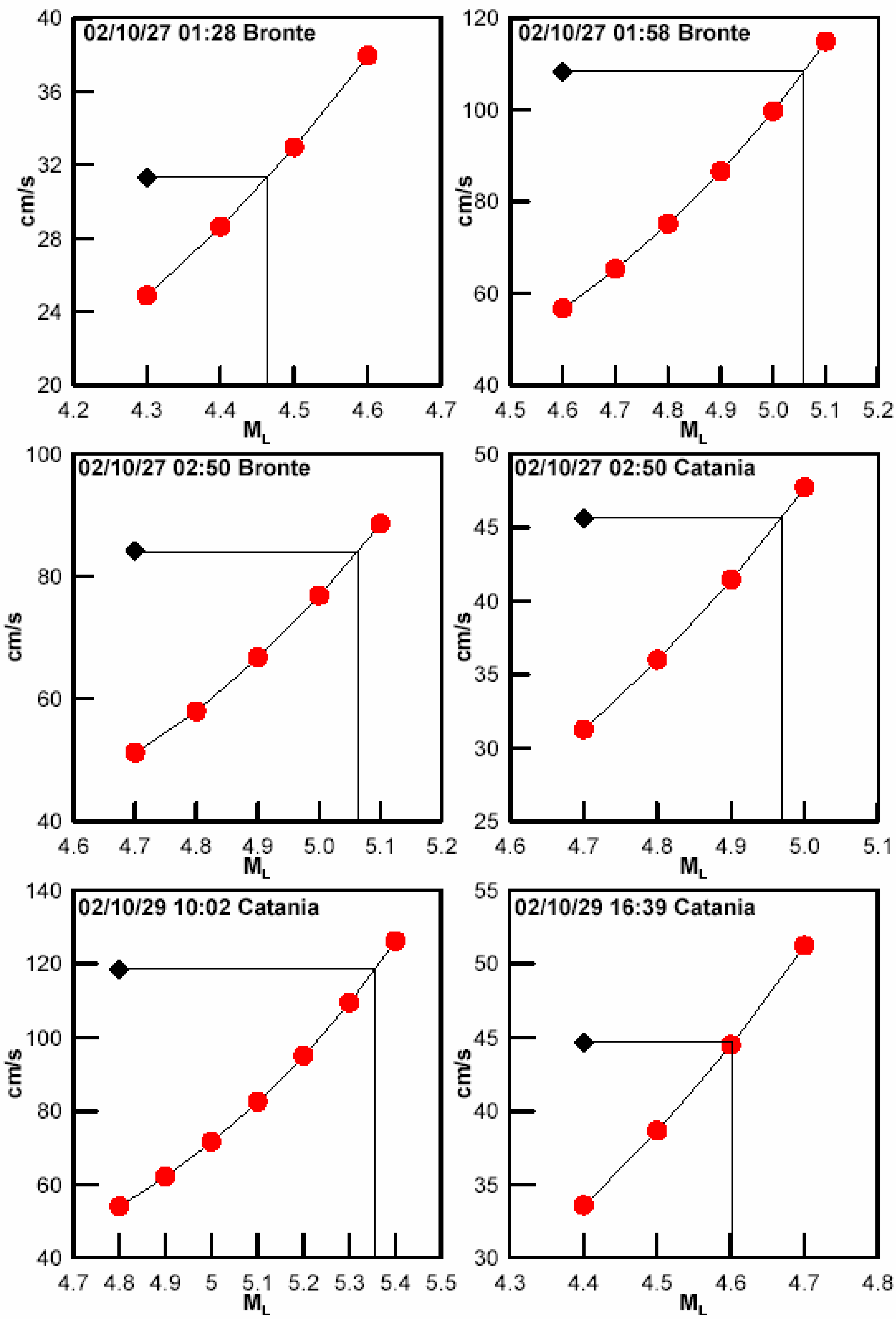
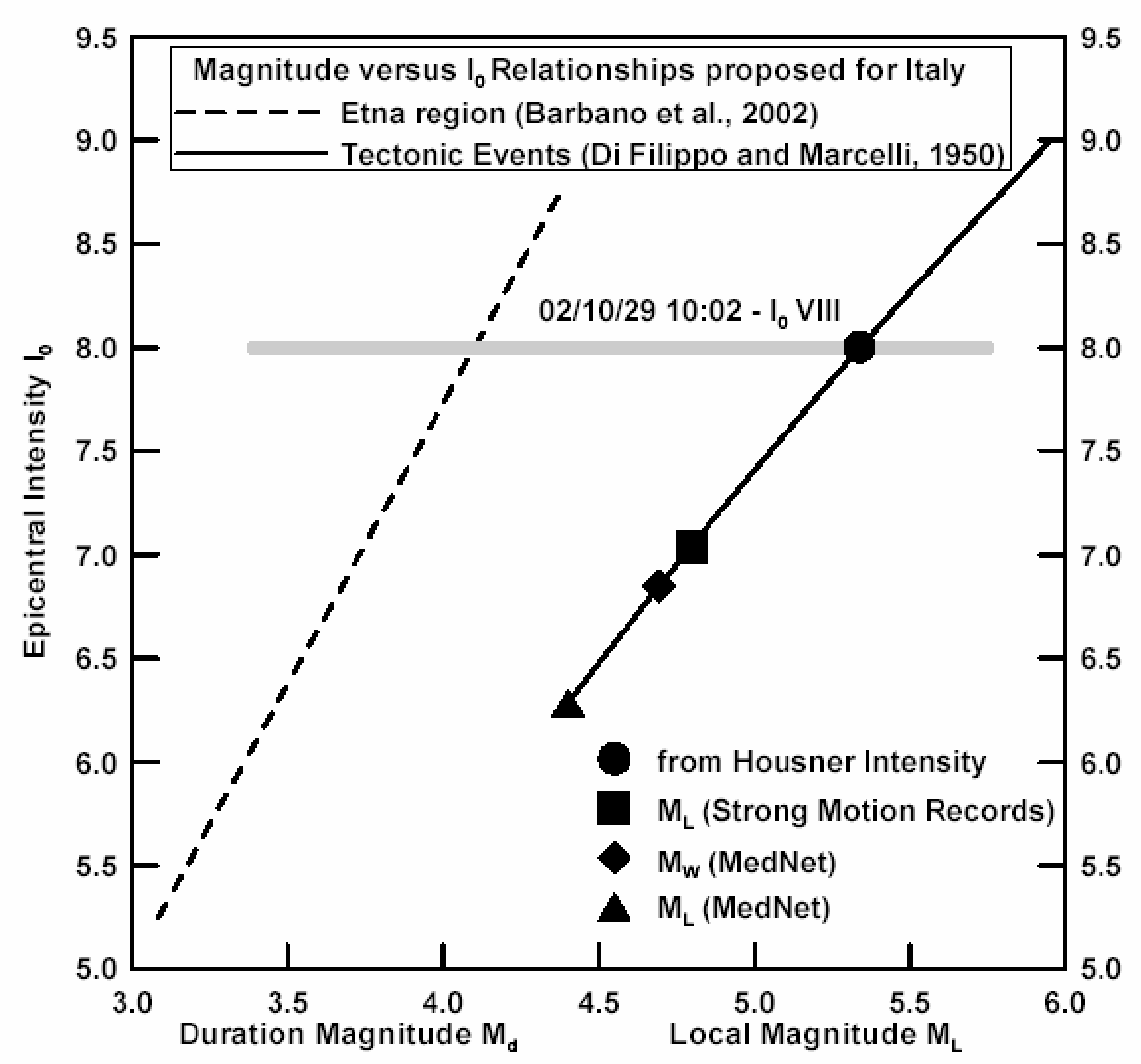

02/10/27 01:28 Bronte
02/10/27 01:58 Bronte
02/10/27 02:50 Bronte
02/10/27 02:50 Catania
02/10/29 10:02 Catania
02/10/29 16:39 Catania
cm/s
M_L

Figure 9)



Magnitude versus I_0 Relationships proposed for Italy
Etna region (Barbano et al., 2002)
Tectonic Events (Di Filippo and Marcelli, 1950)
02/10/29 10:02 - I_0 VIII
from Housner Intensity
M_L (Strong Motion Records)
M_W (MedNet)
M_L (MedNet)
Epicentral Intensity I_0
Duration Magnitude M_d
Local Magnitude M_L
9.5
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
3.0
3.5
4.0
4.5
5.0
5.5
6.0

Figure 10)