

A MICROTREMOR SURVEY IN THE AREA SHOCKED BY THE ML 5.2 SALO' EARTHQUAKE (NORTH ITALY): AN EMPIRICAL APPROACH TO DETERMINE THE EFFECTS OF GROUND MOTIONS

Massa M.⁽¹⁾, Lovati S.⁽¹⁾, Di Giacomo D.⁽²⁾, Marzorati S.⁽¹⁾, D'Alema E.⁽¹⁾ and Augliera P.⁽¹⁾

⁽¹⁾ Istituto Nazionale di Geofisica e Vulcanologia, Sezione Milano-Pavia, via Bassini 15, 20133 Milano, Italy.

⁽²⁾ GeoForschungsZentrum, Section 2.1 Earthquake Risk and Early Warning, 14473 Potsdam, Germany.

Corresponding author: massa@mi.ingv.it

Abstract

In this work the results of a quick microtremor survey performed in the municipalities situated in the epicentre area of the MI 5.2 2004 Salò earthquake (North Italy) are presented. The aim of this study is to understand if the large amount of damage caused by the event (about 215 millions of euros only in the areas near to the epicenter) is correlated more to the local surface geology conditions or to the vulnerability of ancient Italian historical centers.

A preliminary seismic zonation was carried out in 5 villages including about 30 measurements of microtremors analysed by the Nakamura technique (hereinafter HVNR). The points of measurement were carefully selected considering sites located both near damaged buildings and over different local geology conditions (alluvium deposits, fluvial-glacial deposits, debris fans and rock). In order to strengthen the HVNR results and to evaluate the reliability of the Nakamura analysis, a comparison with spectral ratios calculated on earthquakes (hereinafter HVSR) recorded at the strong motion station of Vobarno was made. In general, the outcomes of the survey highlight a possible correlation between local geology conditions and ground motion amplification for different frequency bands. In order to check if this evidence is linked with the damage, a series of macroseismic intensities values were collected for different zones of the investigated area, and a non parametric correlation approach was used to establish a possible correlation between damage and ground motion amplification for selected frequency bands. The results show, from a statistical point of view, that in the area surrounding the epicenter of the 24 November 2004 mainshock, the damage pattern is not strongly dependent upon the local surface geology but more correlated to the low quality of the civil structures present in the area, including old buildings of the last century.

Key words: Salò earthquake, local surface geology, HV spectral ratios, non parametric correlation technique.

Introduction

On 24 November 2004 at 22:59 UTC, the MI 5.2 (Mw 5.0) Salò earthquake shocked the Northern Italy regions. It is the strongest event for that area for several decades. On the basis of the official data provided by the Lombardia Region authorities, this earthquake strongly affected 66 municipalities close to the epicentral area, damaging about 3700 buildings (involving about 2500 people) and 300 churches, for an approximate damage evaluation of 215 million euros. The Salò earthquake was located at 45.685 N, 10.521 E by Centro Nazionale Terremoti (INGV-CNT, <http://www.ingv.it>); the focal depth was determined to be 5.1 km by Augliera et al. (2006). Following the mainshock, 159 aftershocks, ranging in local magnitude between 0.3 and 2.8, have involved an area located about 5 km South with respect to the Salò earthquake epicentre. The aftershocks were precisely located due to the presence of a dense velocimetric network installed in the study area from the 25th November 2004 to the end of December 2004. In figure 1 (left) the location of the MI 5.2 Salò earthquake and the distribution of the aftershocks are shown together with the background seismicity that occurred in the study area from January 2003 to December 2007; on the right the scenario for the 24 November 2004 mainshock, calculated considering macroseismic intensity, is reported. It is worth noting that in the past the area under study was shocked by other energetic events such as the Mw 5.6 30 October 1901 Salò earthquake (I_s=VIII degree of the Mercalli, Cancani, Sieberg macroseismic intensity scale, hereinafter MCS; Gruppo di lavoro CPTI, 2004). The results reported in the seismic hazard map of Italy (Gruppo di lavoro, 2004) show that the study area falls within a region where the predicted horizontal acceleration with a 10% probability in 50 years ranges from 0.150 g to 0.175 g, indicating that the possible occurrence of damaging earthquakes for the populated and industrialized study area is not negligible.

For this study we focused the microtremor survey on some municipalities located in the epicentral area (fig. 1, left) that suffered a high damage pattern: Barghe, Sabbio Chiese, Vobarno and Salò, for which this paper represents one of the first efforts to investigate the presence of site effects. The Nakamura technique has been adopted for the analysis of the microtremor measurements (HVNR) (e.g. Nakamura, 1989; 2000; Parolai et al., 2001). Indeed, over the past years, single station microtremor surveys have been extensively used to evaluate the site response and its association with damages observed after an earthquake (i.e. Mucciarelli and Monachesi, 1998, 1999) since they are able to predict the fundamental frequency of vibration of sedimentary deposits when no two or three dimensional effects are present. For a detailed discussion on the reliability and the limitation of the microtremor measurements see, for example, Lachet and Bard, 1994; Field and Jacob, 1995; Mucciarelli, 1998; Bard, 1999; Mucciarelli and Gallipoli, 2001; Parolai et al., 2004. The HVNR results, carefully checked through comparison with spectral ratios on earthquakes (HVSr) calculated at Vobarno strong motion station (code VOBA in figure 1, left), were used to compute statistical analysis

in order to determine both the influence of local geology and building vulnerability on the damage pattern of the study area.

Geological setting

The study area ranges in latitude from 45°36' N to 45°41' N and in longitude from 10°24' E to 10°31' E (fig. 1). From the geological point of view it can be divided into two portions: the Sabbia valley, between the town of Barghe and the town of Vobarno and the southern most part of the Alto Garda Bresciano, that includes the town of Salò.

The deposits that fill the investigated portion of the Sabbia valley are represented by (Regione Lombardia, 2002):

- present-day and recent alluvium, characterized by a variable granulometry spanning from clay to gravel;
- fluvial-glacial deposits of variable thickness (up to 100 m), characterized by cobbles with an imbricate structure;
- Pleistocenic alluvial terraces, whose origin has many different interpretations depending on the different evaluation of the extension of the glacier that filled the Sabbia valley.

Massive dolomite and massive to bedded and cherty limestone, belonging to Triassic and Giurassic formations, characterize the flanks of the valley: from Barghe to Vobarno outcrop the Angolo and Esino Limestone (middle-lower Anisian-Ladinian), the Carnian Porphyritic in the area of Barghe, the Dolomia Principale (upper Carnian-middle Norian), the Zu Limestone (upper Norian-Rhaetic), the Corna (upper Rhaetic-Sinemurian) and the Domaro Limestone (Pliensbachian) (Boni and Cassinis, 1972). The outcrops of rocks are often covered by debris, eluvium-colluvium deposits and are characterized by landslides (underwater landslides) that evidence the quartering of the Giurassic carbonate slate (CNR-IRRS and Regione Lombardia-Servizio Geologico, 1996).

In the area of Salò a wide recent alluvium develops NW-SE. Beside the alluvial sediments fluvial-glacial and morainic deposits, both belonging to the Wurm period, outcrop (CNR-IRRS and Regione Lombardia-Servizio Geologico, 1996).

The geology of the surveyed area has been simplified to four classes as shown both in table 1 and in figure from 2 to 5: alluvium deposits (A), fluvial-glacial deposits (G), debris fans (C) and rock (R).

Data acquisition

The field campaign was conducted using a sensor Lennartz LE3D-5sec (flat response in velocity between 0.2 and 40 Hz) equipped with the 24 bit data logger Reftek 130/01 (<http://www.reftek.com>). The measurements were conducted at 23 different sites (table 1) selected in order to combine both the interest in measuring at sites where damage information were available (QUEST, 2005) and the

need for characterizing sites with different types of lithological units. The points from 11 to 14 are related to the Clibbio village (fig. 1). For this site the large amount of damage was caused by landslides that occurred after the mainshock and for this reason we have not considered this site here. For each point of measurement 30 minutes of ambient noise were recorded at the sampling rate of 100 Hz. The data processing to obtain the HVNR at each site was performed in the following way: the data was filtered between 0.2 and 25 Hz by a band-pass 4 poles Butterworth filter after the mean and a linear trend were removed; then each component of the recorded signal was windowed in a time series of 60 sec length (cosine taper 5%) and for each time window an FFT was calculated and smoothed using the Konno and Ohmachi (1998) window ($b=20$). For each time window the spectral ratio between the root-mean square average spectrum of the horizontal components over the spectrum of the vertical component was calculated and, finally, the average HVSR and the standard deviation was computed.

To verify the reliability of noise measurement results, the HVNR were compared with the calculated HVSR considering the events (table 2) recorded at strong motion station installed in the city of Vobarno (VOBA) in the framework of the DPC-INGV project "Strong Motion Stations in Northern Italy" (<http://accel.mi.ingv.it>). The Vobarno station (black square in fig. 4), equipped with a force balance accelerometer Kinematics Episensor ES-T (<http://www.kinematics.com>) coupled with a data logger Reftek 130/01 (sampling rate 100 Hz), sits on antique alluvial terrace. In order to obtain the HVSR response we followed this procedure: first, the detrend and the 4 poles Butterworth band-pass filter between 0.5 and 25 Hz were applied to the earthquake data; then an FFT of each component, smoothed using the Konno and Ohmachi (1998) window ($b=20$), was calculated on time windows of 10 sec of S-waves starting 1 sec before the onset of the chosen S-waves, and the H/V ratios and the standard deviation were calculated.

Results of microtremor survey

In figures 2 to 5 we report the positions of the points of measurement over the 1:10.000 geological maps (Regione Lombardia, 2002) and the results of HVNR for the cities of Barghe, Sabbio Chiese, Vobarno and Salò, respectively. For each analyzed village, in figures are reported the meaningful HVNR: the selection was made by visual inspection. Over each map (see figures 2 to 5) the MCS scale intensity values taken from QUEST (2005) are also shown. In table 1 all the information regarding the microtremor survey are shown. Taking into account that the official MCS intensity by QUEST are assigned to each village evaluating an average of the damage, for our analysis the macroseismic intensities were verified and in some cases modified (see table 1) considering the status of the buildings located close to the noise measurements.

In order to make some general considerations about the HVNR results, the points of measurement were separated into four geological classes (alluvium deposits, fluvial-glacial deposits, debris fans and rock). For these classes figure 6 shows the box-and-whisker plots considering HVNR amplifications for seven frequency classes ranging from 0.2 Hz (the lower capability of the available instruments) to 25 Hz: the line represents the median, the box ranges from the 25th to the 75th percentile and the whiskers range from the 10th to the 90th percentile. In general the scattering of the distribution is greater for the alluvium deposits and debris fans and this reflects the high variation of thickness and behaviour of these deposits. With regard to the fluvial glacial deposits and rock the scattering is less evident and it reflects a more homogeneous behaviour. It is possible to note as, even considering the non negligible dispersion of the values, higher amplifications preside in sites located over alluvial deposits (between 2 and 10 Hz with amplification up to 5.5), whereas the absence of amplification phenomena is detected for points over rock. Regarding to measurements over both debris fans and fluvial-glacial deposits it is possible to note the same peaks of amplification up to 5 in the frequency range 2-5 Hz.

Taking into account that the more damaged buildings of the area are represented by ancient masonry buildings with two or three floors, with a fundamental period of oscillation of 0.15-0.2 s (Faccioli and Paolucci, 2005), we have focused our attention on the points of measurement that present amplification in the frequency ranges 2-5 Hz and 5-10 Hz: Franceschina et al. (2008) found a fundamental frequency of about 6 Hz for a two-story building located in Vobarno on fluvial-glacial deposits.

Considering 7, it is possible to note as the superimposition of the fundamental frequency of soils and the fundamental frequency of buildings occurs in the range 5-10 Hz in particular for point GN06 and GN20, both located on alluvial deposits in the city of Barghe and Vobarno, respectively, and occurs in the range 2-5 Hz for point GN04 (Barghe), GN13 (Sabbio Chiese), GN16, GN17 and GN21 (Vobarno) located, respectively, over debris fans and fluvial-glacial deposits. A particular case is represented by GN01 (Barghe), a noise measure over rock that shows a non negligible amplification (up to 4.3) in the range 2-5 Hz and 5-10 Hz.

For each analysed municipality it is possible to highlight the following remarks:

Barghe:

Among the investigated municipalities, the town of Barghe is the smallest and the least damaged ($I_s=V/VI$ MCS). The urban area is mainly developed near the Chiese river where different types of deposits are present. On the whole, the results of the analysis show a non negligible presence of amplification effects, except for site GN05 laying over fluvial-glacial deposit where the noise HVSR

response does not show important peaks. The measurement GN03 (debris fans) was done beside damaged buildings and shows the presence of a moderate amplification between 4 and 6 Hz.

Sabbio Chiese:

The town of Sabbio Chiese suffered an MCS intensity spanning from VI to VII at the locality of Pavone (an example is shown in figure 9, top panel). The urban area lies mainly over alluvial and fluvial-glacial deposits. The measurements GN07 (recent alluvium deposit) and GN09 (fluvial-glacial deposit at the locality of Pavone) were done close to damaged buildings. GN07 shows only a small peak at about 9 Hz, differently GN09 has a sharp amplification peak at about 5 Hz. Measurements GN00 and GN10 have been done on outcrops of massive dolomite and, as expected, their HVNR responses are nearly flat.

Vobarno:

Vobarno is one of the municipalities more damaged by the Salò earthquake. The MCS intensity spans from VI to VII/VIII at the locality of Pompegnino (an example is shown in figure 9, middle panel). The town is mainly developed over fluvial-glacial deposits and over antique alluvial terrace. Here each measurement point was done near damaged buildings. The area presents important amplification effects for all the points of measurements. It is possible to observe that the results of the measurements carried out over the fluvial-glacial deposit (GN16 and GN17 along two sides of the severely damaged church of Pompegnino, GN18 and GN19) show the presence of a stable amplification peak between about 2 and 3 Hz. Also the measurements GN20 and VOBA (the latter at the same location of the strong motion station) done over alluvium deposits show the presence of a sharp amplification peak: at 6.8 Hz for site GN20 and at lower frequency, namely at 5.5 Hz, for site VOBA. Such a frequency misfit of the amplification peaks for sites GN20 and VOBA may be explained by the difference of thickness of the alluvium deposit at GN20 with respect to VOBA, since the former is placed closer to the Chiese river so that the antique alluvial terrace thickness may be smaller. In figure 8 it is possible to note how the results obtained from HVNR performed at GN20, and both HVNR and HVSr performed at VOBA station, are quite similar.

Salò:

Salò is the most populated city of the study area and here the MCS intensity was established as VII (an example is shown in figure 9, bottom panel). The urban area is mostly characterized by the presence of important deposits of recent alluvium and by fluvial-glacial deposits. Contrarily to what was expected, here the results did not show the presence of significant amplification functions: sites GN22 and GN23 (fluvial-glacial deposit) were close to damaged buildings but they only show a moderate amplification between 3 and 5 Hz; GN25 which was done on recent alluvial deposit as well,

is nearly flat. Finally, the measurement on debris fans GN27 shows only a small amplification peak at 2 Hz.

Non parametric correlation approach: method and results

Taking into account the results of the microtremor survey joined with the HVSR computed at VOBA station, it is possible to state that in the area under study local amplification phenomena due to local surface geology can be expected to be associated with fluvial-glacial and alluvial deposits. Regarding other geological units, the HVNR do not lead to a clear conclusion: for example analysing some site over rock (like point GN01) it is possible to note some amplification likely due to altered material and/or to the or presence of shallow fractures.

In order to check the correlation between local surface geology and the damage pattern of the Sabbia Valley a statistical method, based on the non parametric correlation approach, has been used (Mucciarelli and Monachesi, 1998 and 1999; Gallipoli et al., 2004). Considering the available information the method is applicable for the cities of Barghe, Sabbio Chiese and Vobarno, the latter showing the higher intensity values (VII/VIII of MCS scale). We considered 7 frequency intervals, in the range 0.2-20 Hz, and for each of them the maximum of the amplification function was selected (table 3).

Considering the values of table 3, the ratio between amplification factors for more damaged sites divided by values of less damaged sites were calculated for each village: the results are presented in table 4. This approach for the city of Salò has not been performed due to the absence both of clear amplifications (see figure 5) and differences found in the MCS values.

For the city of Barghe we selected the points GN03, GN05 and GN06 located near more damaged buildings (over debris fans, fluvial-glacial deposits, and alluvium deposits, respectively) and the point GN01 located over rock and near less damaged buildings. For the city of Sabbio Chiese we selected the points GN07 and GN09 (alluvium deposits and fluvial-glacial deposits, respectively) near more damaged buildings, and the points GN00 and GN10 (both over rock) near less damaged buildings. For the city of Vobarno, we selected the points GN16, GN17 (fluvial-glacial deposits), GN20 (alluvium deposits) and GN21 (debris fans) near more damaged buildings, and points GN15 (rock) near less damaged buildings. For each of the aforementioned points we need to associate different macroseismic intensity values (see MCS values of table 1). Considering all the towns, for each frequency range, there is a dimensionless parameter (ratio between amplification factor for more damaged site divided for values of less damaged site, calculated in the same town) whose value has to be greater than 1 (table 4); if the value is less than 1 the damage pattern depends on vulnerability of buildings and does not depend on local geological conditions. Using the ratios in table 4 a non parametric correlation was attempted using both Kendall's coefficient τ and Spearman index (table 5).

In both cases the non parametric correlation between the amplification ratio and intensity differences give variable results. Considering that in the surveyed area there were no buildings taller than three stories, and that the majority of the houses in the analyzed villeges were two stories high, in the frequency bands of interest for damage pattern (2-5 Hz and 5-10 Hz) it is possible to note (see table 5) positive correlation coefficients only for the frequency range 2-5 Hz.

After the 12th April 1998, MI 5.6 Slovenia earthquake, Mucciarelli and Monachesi (1999) found, considering the ratio between HVSR function obtained for the ground floor and for the second floor, that the fundamental frequency of a typical isolated house of the village of Bovec (Slovenia) was 6 Hz. In that case this value was very closed to the maximum amplification frequency observed in the free field and, as a consequence, damage was strongly influenced by double resonance-effects.

In a different case, after the 30th October 2002, MI 5.4 San Giuliano earthquake, Gallipoli et al. (2004) found in San Giuliano di Puglia (Italy) high values of positive correlation between MCS intensity and HVSR also for lower frequencies: in this case the authors highlighted that even if the main building type in the area is two-story, load-bearing stone masonry, the connection among buildings in long rows could make them more sensitive to frequencies lower than the resonance mode of single, isolated house.

In our case, the town-planning of the analyzed villages is characterized by an intermediate condition, where few and short rows of one or two stories, load-bering masonry, are merged with isolated two or three stories houses. Taking into account both the age (the beginning of the last century, see figure 9) of the great number of the damaged masonry buildings and the results coming from the statistical tests (table 5), it is possible to state that for the Sabbia Valley the damage pattern is in general mainly due to the high degree of vulnerability of the ancient buildings (fig. 9). This conclusion is however implicitly included also in table 4, that shows a poor number of amplification ratios greater than the unity. A particular case is the narrow area in correspondence of the river bed of Vobarno: considering the non negligible values of amplification peaks at frequancies around 6 Hz, detected for GN20 and VOBA (see figure 4 and 8), in the case of two-story masonry buildings located on alluvium deposits (GN20, VOBA) it is not possible to exclude some double-resonance effects.

Conclusions

The 24 November 2004, MI 5.2 Salò earthquake represents the main event that shocked Central North Italy since 1901. In this paper the results of a microtremor survey involving some cities of the Sabbia Valley (Barghe, Sabbio Chiese and Vobarno) and Salò are presented. The paper takes its stand on a microtremor survey performed in sites characterized by different local geology conditions and close to buildings with different degrees of damage, for a total of 23 noise measurement points. In order to strengthen the reliability of HVNR technique, HVSR were calculated at a strong motion station

installed in the village of Vobarno. The results provided much information on the ground motion amplification of the investigated municipalities. The results of the survey show, in general, the highest amplification for measurements performed on alluvium deposits, and a moderate amplification for both fluvial-glacial deposits and debris fans; in rare cases also for rock, likely due to alteration and/or fractures, some amplification was detected (see GN01, Barghe). In order to understand if the interaction between the ground motion and the surface geology played an important role on the damage pattern of the Sabbia Valley a non parametric correlation approach has been used. The results presented in table 5 lead to the conclusion that, considering the characteristics of the damaged buildings observed in the area under study (one or two stories), there is no evidence for a clear correlation between surface geology and damage. Such a correlation could arise for frequencies 2-5 Hz (in particular between 2-3 Hz, see figures from 2 to 5), that is a range of interest for younger buildings of three stories, that do not present particular damage. Considering these remarks it is possible to state that for the cities of the Sabbia Valley and for the city of Salò the vulnerability of the Italian ancient historical centres plays still at present the fundamental rule.

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Captions

Fig. 1 - Left panel: Map showing the location of the MI 5.2 Salò earthquake (grey star) along with its focal mechanism (<http://mednet.rm.ingv.it>), the events of the sequence following the Salò earthquake (black circles), the seismicity (grey circles) of the Garda lake area from January 2003, the location of the Mw 5.6 event of the 30 October 1901 (grey diamond), the location of the MI 3.8 20 October 2006 (grey hexagon), the location of the strong motion stations VOBA and BAG8 (grey triangles), and of the investigated towns (dark grey squares). The grey area highlights the investigated area.

Right panel: Scenario calculated for the 24 November 2004 MI 5.2 Salò earthquake, considering the MCS intensity (<http://esse3.mi.ingv.it/>)

Fig. 2 - Top panel: Geological map of the city of Barghe and noise measurement points (black triangles). The values of the macroseismic intensity are also indicated (circles). Bottom panel: average HVNR (black solid line) \pm 1 standard deviation (grey lines) of the noise measurements.

Fig. 3 - The same as for figure 2 but for the city of Sabbio Chiese.

Fig. 4 - The same as for figure 2 but for the city of Vobarno; the black square indicate the strong motion station VOBA.

Fig. 5 - The same as for figure 2 but for the city of Salò.

Fig. 6 - Box-and-whisker plot grouping the HVNR results for the considered geology classes. In the Y axis the values of amplification factor are indicated.

Fig 7 - Resume of the amplification factors related to all measurement points considering the 3 frequency classes 1-2 Hz, 2-5 Hz, and 5-10 Hz.

Fig. 8 - Comparison among HVSR and HVNR calculated at VOBA strong motion station and HVNR for GN20 point.

Fig. 9 - Pictures showing the typology of buildings that suffered relevant damages: top panel for Sabbio Chiese, middle panel for Vobarno, and bottom panel for Salò.

Table 1 - Description of the noise measurement points: all noise measurements have been made nearby damaged buildings. For all noise measurement points the interpreted (the real values of QUEST are indicated in figures from 2 to 5) value of MCS intensity is reported (in bold).

Table 2 - Parameters of the events used to calculate HVSR at VOBA strong motion station.

Table 3 - Amplification factors of all noise measurement points grouped in 7 frequency ranges.

Table 4 - Ratio between amplification factors for more damaged site divided for values of less damaged sites, calculated for the city of Barghe (GN01, GN03, GN05, GN06), Sabbio Chiese (GN07, GN09, GN00, GN10) and Vobarno (GN15, GN16, GN20, GN21, GN15): in bold are indicated the amplification ratios greater than unity. All noise measurement points have been grouped in 7 frequency ranges.

Table 5 - Non parametric correlation (Kendall's coefficient τ and Spearman index) between amplification ratio and intensity differences. For both the best results are obtained for frequencies 1-5 Hz (in bold).

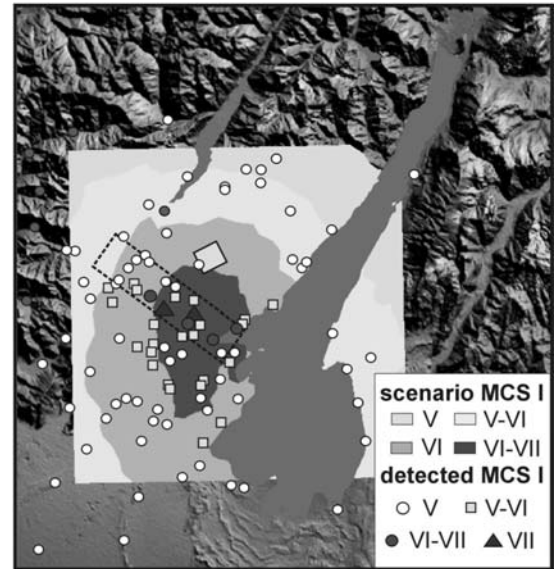
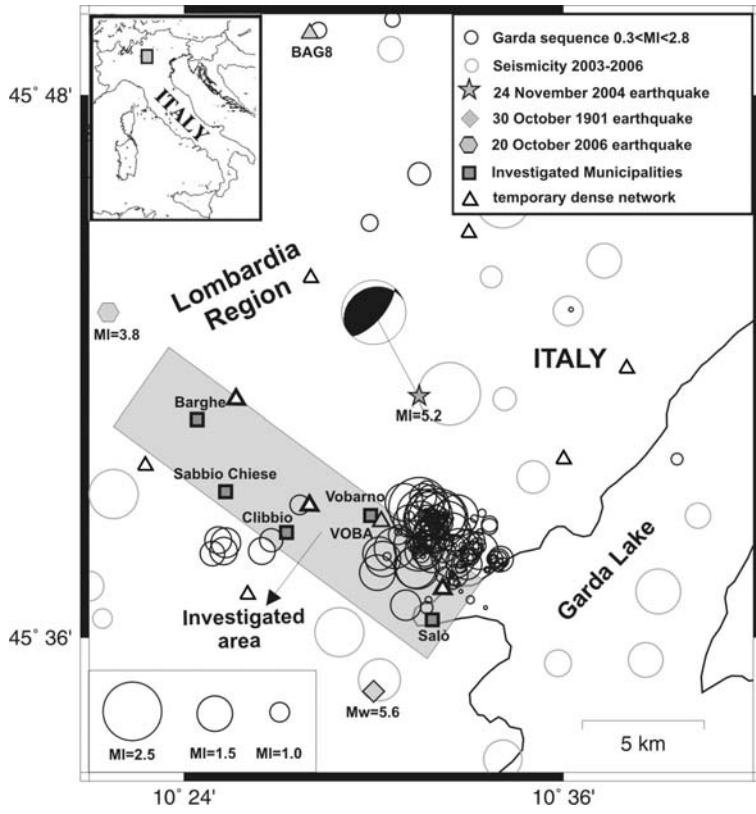


Fig. 1

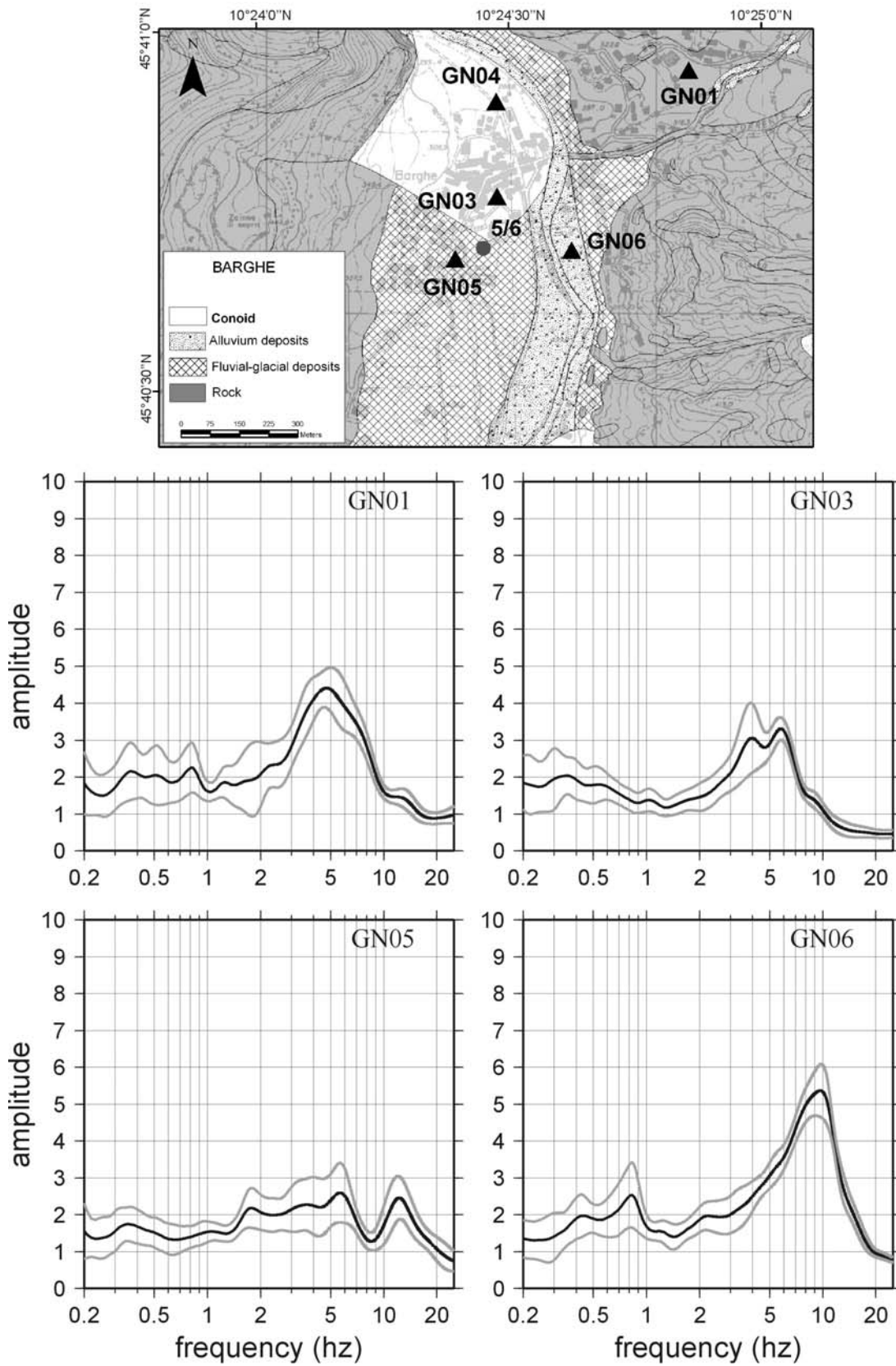


Fig. 2

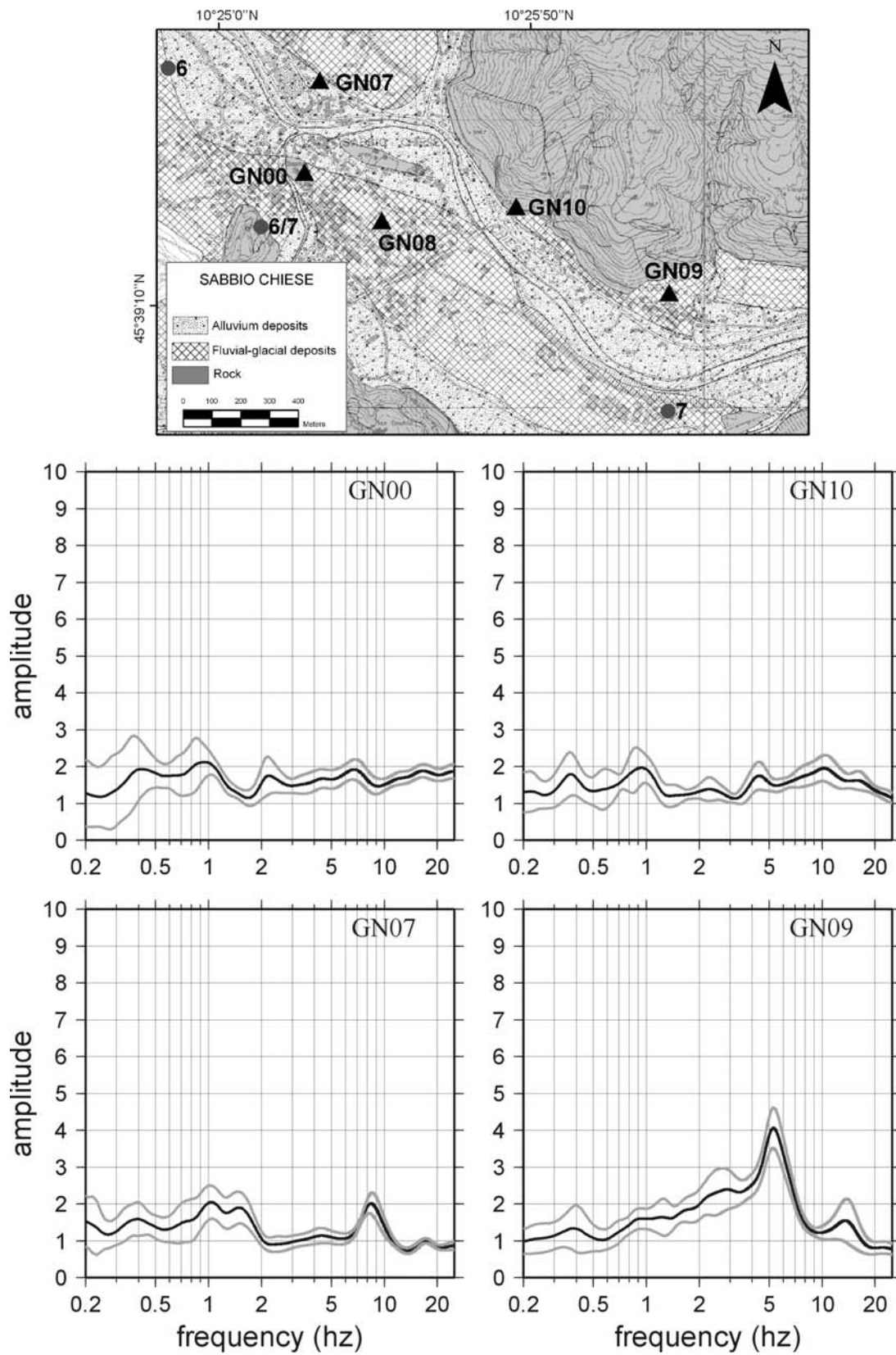


Fig. 3

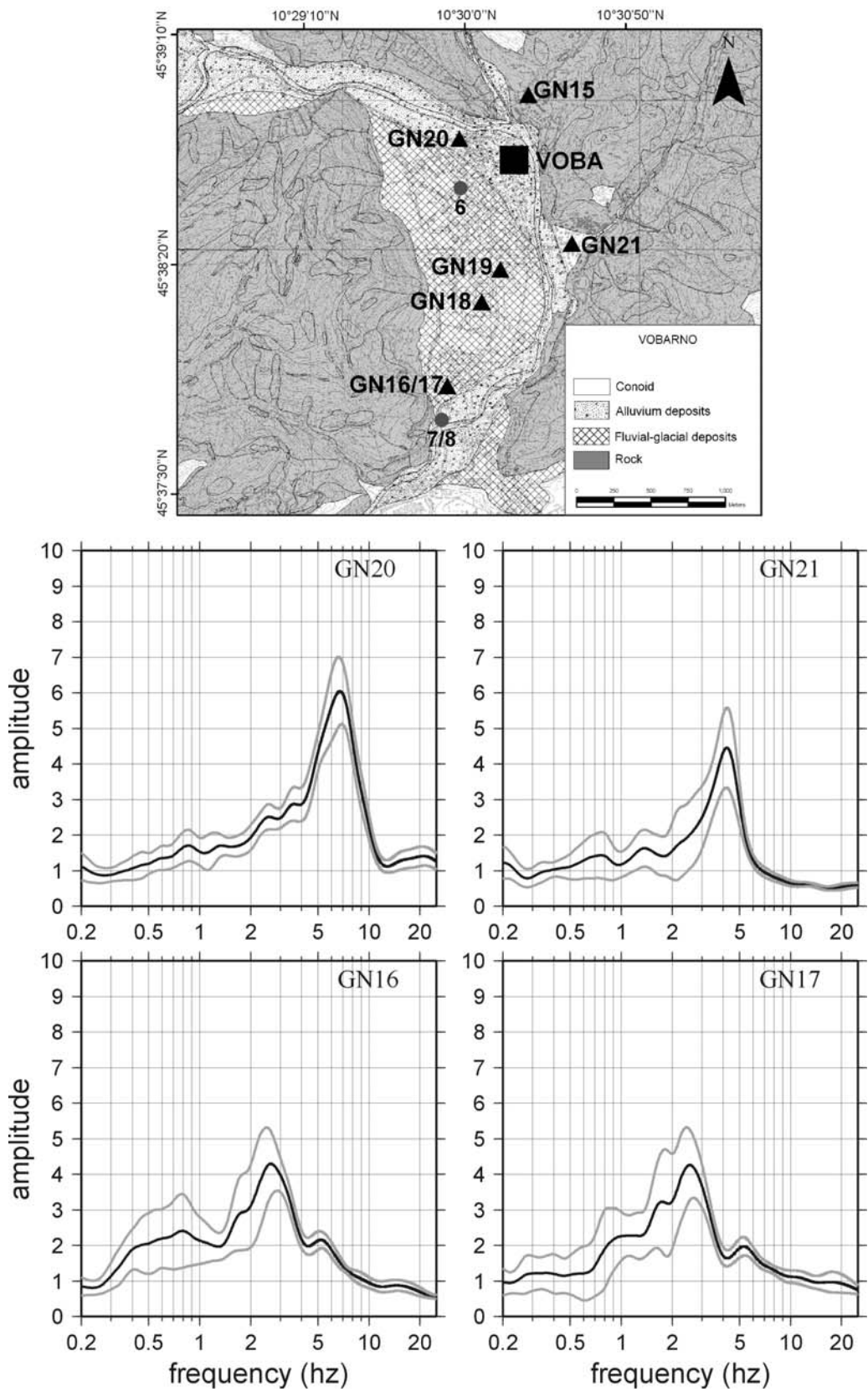


Fig. 4

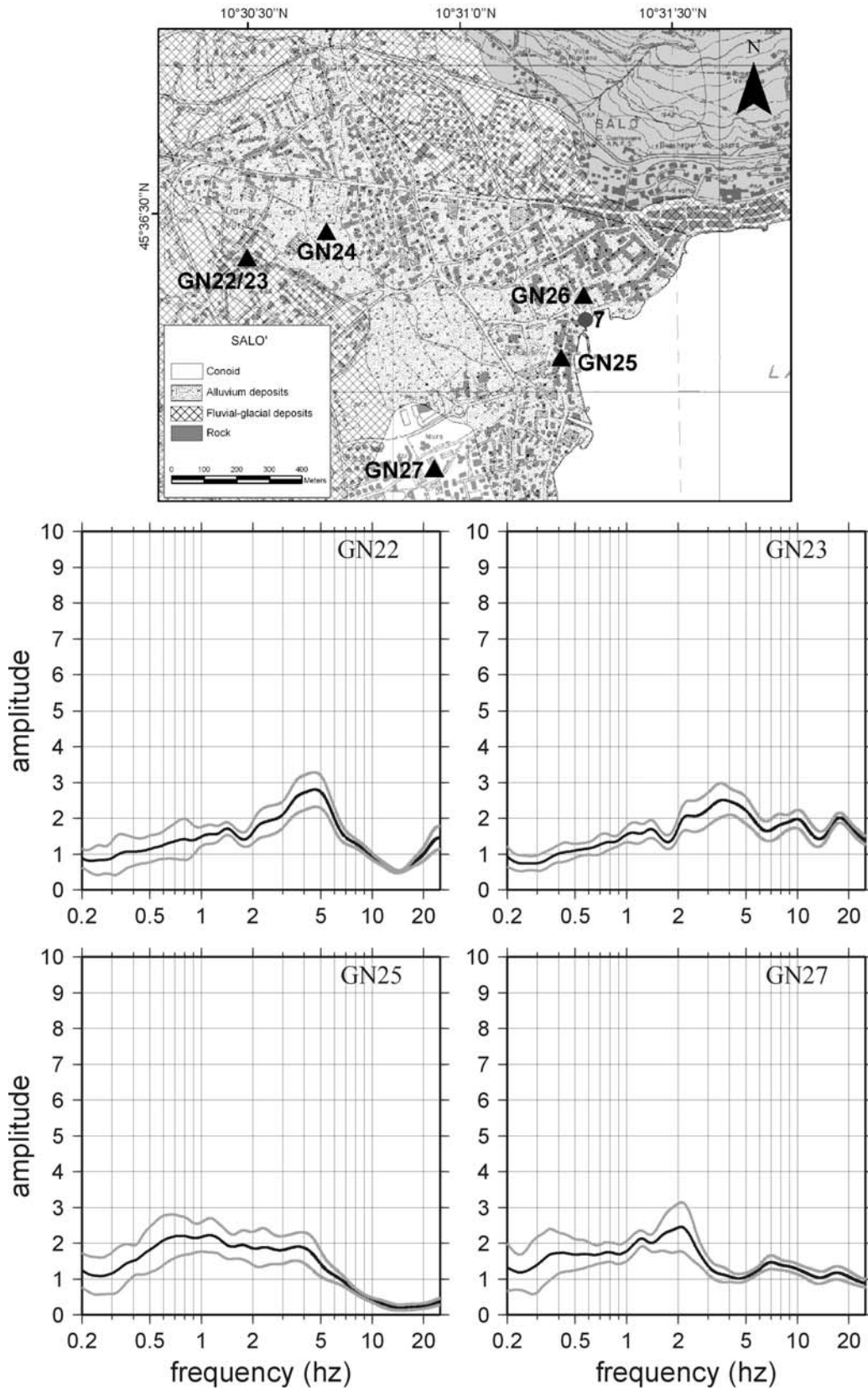


Fig. 5

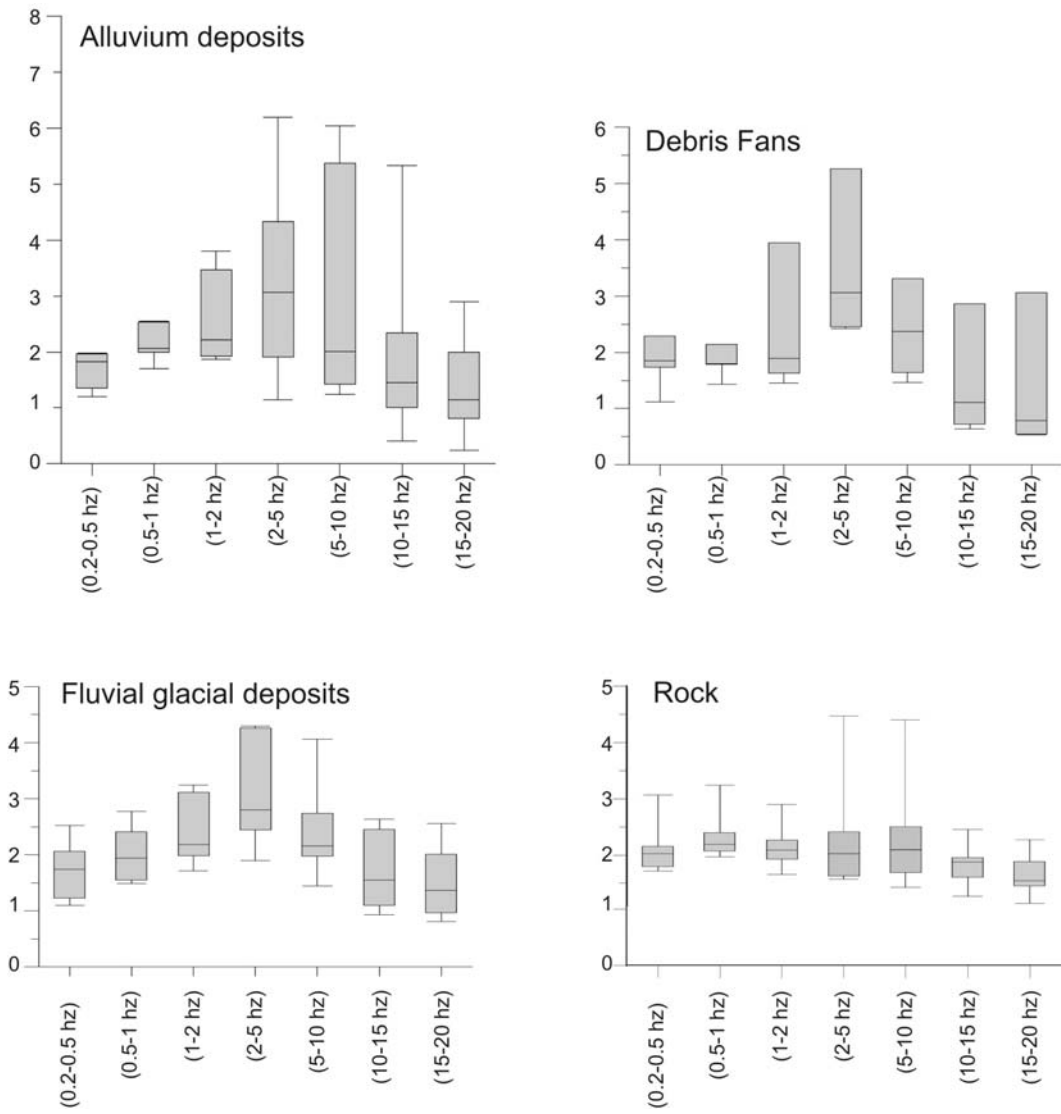


Fig. 6

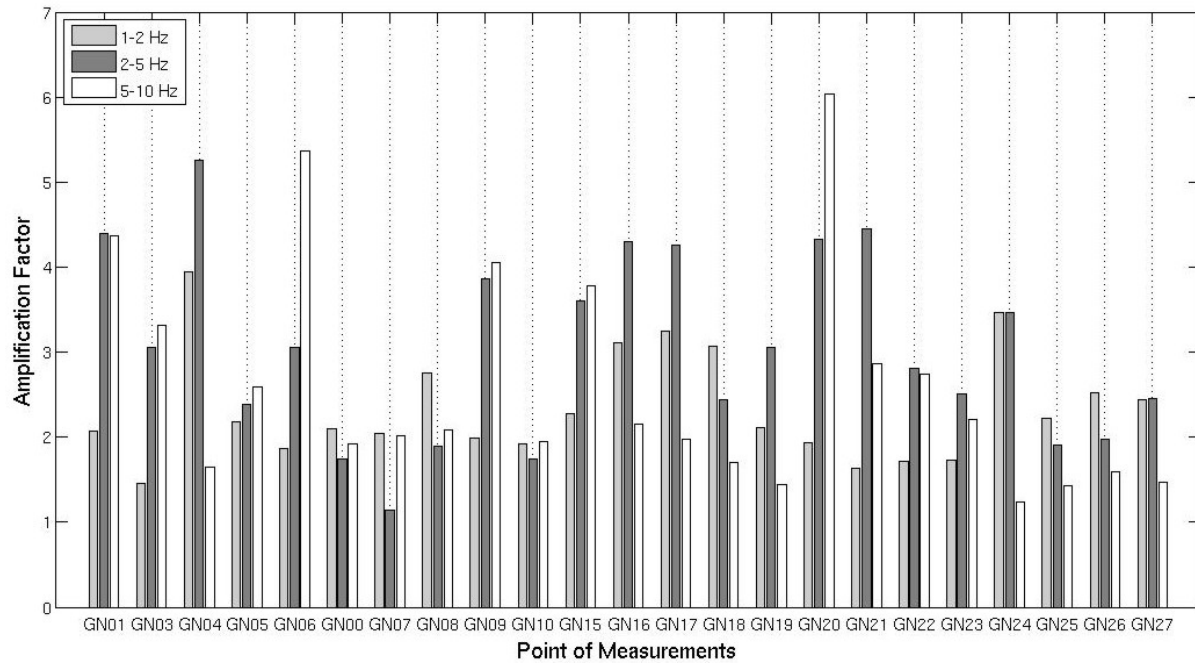


Fig. 7

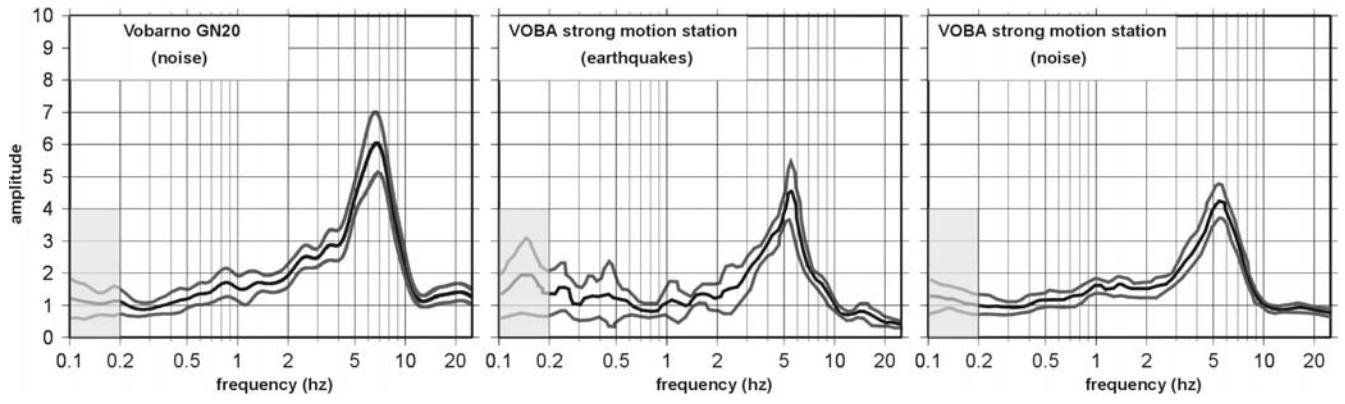


Fig. 8

Sabbio Chiese - I max 7



Vobarno - I max 7/8



Salò - I max 7



Fig. 9

#	City I (MCS)	Lithology	HVNR response
GN01	Barghe V	Rock	Moderate amplification at 4.6 Hz
GN03	Barghe VI	debris fans	Moderate amplification 4-6 Hz
GN04	Barghe VI	debris fans	High amplification at 2.5 Hz
GN05	Barghe VI	Fluvial-glacial deposit	Small amplifications at 5.5 and 11Hz
GN06	Barghe VI	Alluvium deposit	High amplification at 9.5 Hz
GN00	Sabbio Chiese VI	Rock	Nearly flat
GN07	Sabbio Chiese VI	Alluvium deposit	Small amplification at 8.4 Hz
GN08	Sabbio Chiese VII	Fluvial-glacial deposit	Nearly flat
GN09	Sabbio Chiese VII	Fluvial-glacial deposit	High amplification at 5.2 Hz
GN10	Sabbio Chiese VI	Rock	Nearly flat
GN15	Vobarno V-VI	Rock	Moderate amplification 3.8-5.6 Hz
GN16	Vobarno VII-VIII	Fluvial-glacial deposit	Moderate amplification at 2.6 Hz
GN17	Vobarno VII-VIII	Fluvial-glacial deposit	Moderate amplification at 2.6 Hz
GN18	Vobarno VI-VII	Fluvial-glacial deposit	Moderate amplification at 1.7
GN19	Vobarno VI-VII	Fluvial-glacial deposit	Moderate amplification at 2.6 Hz
GN20	Vobarno VI	Alluvium deposit	High amplification at 6.8 Hz
VOBA	Vobarno	Alluvium deposit	High amplification at 5.5 Hz
GN21	Vobarno VI	debris fans	High amplification at 4.1 Hz
GN22	Salò VII	Fluvial-glacial deposit	Moderate amplification between 4-5 Hz
GN23	Salò VII	Fluvial-glacial deposit	Small amplification between 3-5 Hz
GN24	Salò VII	Alluvium deposit	Moderate amplification at 2 Hz
GN25	Salò VII	Alluvium deposit	Nearly flat
GN26	Salò VII	Alluvium deposit	No amplification
GN27	Salò VII	debris fans	Small amplification at 2.1 Hz

Table 1

Event #	Date yy/mm/dd	UTC Time (hh:mm:ss)	Lat. (°)	Long. (°)	Depth (km)	MI	Hypo. distance (km)	Azimet (°)
1	06/07/20	22:47:56	45.670	11.840	15.0	2.9	107.97	266.79
2	06/07/22	18:08:18	45.640	10.180	11.2	3.0	28.24	88.31
3	06/09/08	07:57:48	45.814	10.575	11.4	2.3	22.87	195.1
4	06/09/17	10:25:07	45.552	10.443	5.5	1.4	12.48	24.17
5	06/10/20	00:11:58	45.720	10.360	5.0	3.8	15.20	126.36
6	06/10/20	01:52:02	45.680	10.360	7.1	1.2	14.14	109.16
7	06/12/28	14:10:27	46.130	12.270	7.1	3.6	151.44	246.73

Table 2

City	0.2-0.5 Hz	0.5-1 Hz	1-2 Hz	2-5 Hz	5-10 Hz	10-15 Hz	15-20 Hz	#	Geo
Barghe	2.156	2.255	2.077	4.402	4.365	1.604	1.145	GN01	R
Barghe	2.041	1.800	1.457	3.059	3.312	1.109	0.531	GN03	C
Barghe	2.292	2.140	3.948	5.256	1.641	0.720	0.781	GN04	C
Barghe	1.744	1.535	2.183	2.391	2.595	2.457	1.772	GN05	G
Barghe	1.971	2.533	1.866	3.061	5.367	5.336	1.987	GN06	A
Sabbio C.	1.930	2.121	2.103	1.750	1.918	1.815	1.884	GN00	R
Sabbio C.	1.588	2.029	2.048	1.140	2.013	1.391	1.000	GN07	A
Sabbio C.	1.969	2.776	2.761	1.897	2.082	2.640	2.559	GN08	G
Sabbio C.	1.335	1.600	1.987	3.867	4.060	1.547	1.371	GN09	G
Sabbio C.	1.792	1.967	1.925	1.747	1.947	1.953	1.623	GN10	R
Vobarno	2.119	2.398	2.270	3.596	3.785	1.269	1.457	GN15	R
Vobarno	2.058	2.408	3.111	4.293	2.157	0.949	0.873	GN16	G
Vobarno	1.225	2.257	3.242	4.262	1.973	1.119	0.967	GN17	G
Vobarno	2.522	2.317	3.071	2.442	1.706	1.828	1.820	GN18	G
Vobarno	1.783	1.939	2.118	3.062	1.444	1.100	0.810	GN19	G
Vobarno	1.201	1.707	1.931	4.332	6.040	2.220	1.397	GN20	A
Vobarno	1.116	1.434	1.630	4.456	2.859	0.644	0.541	GN21	C
Salò	1.145	1.489	1.711	2.804	2.739	0.932	1.004	GN22	G
Salò	1.097	1.550	1.727	2.510	2.211	1.977	2.014	GN23	G
Salò	1.353	1.991	3.465	3.460	1.238	1.454	1.141	GN24	A
Salò	1.824	2.206	2.222	1.904	1.424	0.410	0.244	GN25	A
Salò	1.925	2.549	2.526	1.971	1.599	1.000	0.816	GN26	A
Salò	1.731	1.782	2.437	2.455	1.468	1.276	1.174	GN27	C

Table 3

City	Delta I	0.2-0.5 Hz	0.5-1 Hz	1-2 Hz	2-5 Hz	5-10 Hz	10-15 Hz	15-20 Hz	#	#		
Barghe	1.0	0.914	1.123	0.898	0.695	1.230	3.327	1.735	GN06	A	GN01	R
Barghe	1.0	0.809	0.681	1.051	0.543	0.595	1.532	1.548	GN05	G	GN01	R
Barghe	1.0	0.947	0.798	0.701	0.695	0.759	0.691	0.464	GN03	C	GN01	R
Sabbio C.	0.0	0.823	0.957	0.974	0.651	1.050	0.766	0.531	GN07	A	GN00	R
Sabbio C.	1.0	0.692	0.754	0.945	2.210	2.117	0.852	0.728	GN09	G	GN00	R
Sabbio C.	0.0	0.886	1.032	1.064	0.653	1.034	0.712	0.616	GN07	A	GN10	R
Sabbio C.	1.0	0.745	0.813	1.032	2.214	2.085	0.792	0.845	GN09	G	GN10	R
Vobarno	2.0	0.971	1.004	1.370	1.194	0.570	0.748	0.599	GN16	G	GN15	R
Vobarno	2.0	0.578	0.941	1.428	1.185	0.521	0.882	0.664	GN17	G	GN15	R
Vobarno	0.5	0.567	0.712	0.851	1.205	1.596	1.749	0.959	GN20	A	GN15	R
Vobarno	0.5	0.527	0.598	0.718	1.239	0.755	0.507	0.371	GN21	C	GN15	R

Table 4

Frequency	Kendall	Spearman
0.2-0.5 Hz	0.166	0.211
0.5-1 Hz	0.125	0.086
1-2 Hz	0.291	0.379
2-5 Hz	0.210	0.236
5-10 Hz	-0.291	-0.389
10-15 Hz	0.166	0.245
15-20 Hz	0.125	0.211

Table 5