THE ATERNO VALLEY STRONG-MOTION ARRAY:

SEISMIC CHARACTERIZATION AND DETERMINATION OF SUBSOIL MODEL

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ABSTRACT

The paper focuses on the strong motion array deployed in the upper Aterno River Valley, in the immediate outskirts north-west of the town of L'Aquila, which is part of the Italian Strong Motion Network operated by the Department of Civil Protection. The array is composed of six accelerometric stations located along a cross section of the valley. The importance of this array relies on the fact that a large amount of high-quality records were obtained during the 2009 L'Aquila seismic sequence, from both the mainshock and several aftershocks. These data are especially important to investigate site effects in sediment-filled valleys during moderate earthquakes in epicentral area because well-documented observational studies are very limited in the literature. However, the main drawback for the study of site effects in the Aterno valley is the lack of a detailed knowledge of the geometry of the valley, soil layering and dynamic properties of materials. The main motivation for this study stems from the need to provide high-quality strong motion data coupled with a reliable subsoil model of the valley.

Based on the above, in the framework of S4 project, a major effort was undertaken to get a trustworthy cross section of the valley by an *ad hoc* investigation, comprising geological and geotechnical surveys as well as an extensive geophysical campaign, characterized by both active and passive measurements. These results were complemented by additional geological and geotechnical data available in the literature.

By merging all the information acquired, a 2D subsoil model of the transversal section of the upper Aterno valley has been produced. The valley is characterised by an asymmetric shape with a shallower rock basement at the western edge of the valley that deepens at the valley centre. Moreover, based on the results of geophysical tests, representative V_s values were assigned to the different lithologic units forming the alluvial deposits filling the valley. Shear wave velocity is a fundamental parameter for ground response studies and it is also effective in classifying the accelerometric station from a seismic point of view.

The 2D model can be therefore considered a benchmark model for future studies of site effects. It will offer the possibility to examine site effects with a complex underlying geology and to validate the results of numerical simulations of site response analyses with the numerous observations from earthquake recordings, both for weak and strong ground motion conditions.

Keywords: L'Aquila earthquake, Aterno Valley, strong-motion array, seismic characterization, microtremors, subsoil model.

1. Introduction

It is nowadays well established that local geological and geotechnical conditions can significantly affect the resulting ground motion at a given site. The surface topography and the subsurface geometry, the horizontal and vertical stratigraphic variations as well as the physical and mechanical soil properties and their variation with depth may determine amplification, even large, of ground motion and may control the uneven distribution of damages over relatively short distances.

Local effects may be studied using both observations and numerical modeling. For the simple one-dimensional (1D) case there is a wealth of earthquake recordings, from both weak and strong motion, that are satisfactorily reproduced by custom numerical simulations. Moreover, many investigators have reported the successful application of the horizontal-to-vertical spectral ratio from noise measurements (HVNSR) in estimating the 1D fundamental resonance frequency, whenever the surface layer exhibits a sharp impedance contrast with the underlying stiffer formation. For two-dimensional (2D) geometries, such a sedimentary valley, numerical simulations have long highlighted the appearance of different physical phenomena with respect to the 1D case, such as generation of surface waves and possible 2D resonance (e.g., Bard and Bouchon, 1980). On the other hand, observational studies are relatively scarce and generally limited to weak motion data. Well known examples are, among others, the Ashigara valley in Japan (Kudo and Sawada, 1998), the Turkey Flat valley in California, United States (Cramer and Real, 1992, Real et al., 2006; Kwok et al., 2009) and the Euroseistest experiment in Greece (e.g. Raptakis et al., 2000; Chavez-Garcia et al., 2000). For these cases, the availability of high-quality earthquake recordings, coupled with detailed knowledge of subsurface geometry and dynamic material properties, has been fundamental to understand the physics of site effects in the valleys under examination, so that many observations have been correctly modeled. Therefore, if we are able to compare satisfactorily empirical site effects with the results of numerical modeling, this will allow to gain confidence in the prediction of site effects for complex 2D geometries and to enhance our capability of accounting for them during future earthquakes.

In this paper we present the activities carried out to improve our understanding on the geological structure and dynamic soil properties in the upper Aterno River Valley, close to the urban centre of L’Aquila. In this area a strong motion array is installed, which can be considered of very valuable seismologic and engineering interest for the study of site effects in sediment-filled valleys. During the April 6, 2009 L’Aquila earthquake (M_w 6.3), a huge amount of high-quality earthquake data was recorded by the array which makes this earthquake the best-recorded in Italy in a near-fault area (Lanzo et al., 2010; Pacor et al., 2009). Recordings from these stations may therefore provide a unique opportunity to evaluate, among others, the impact of soil conditions on ground shaking in the epicentral area during moderate earthquakes (Lanzo and Pagliaroli, 2011). The major shortcoming of the accelerometric dataset available is a lack of a detailed description of the geologic structure of the Aterno valley and of dynamic properties of sedimentary deposits.

Based on the above considerations, the aim of this paper is twofold: a) the subsoil characterization of the strong motion accelerometric stations to properly use the significant set of strong motion records for seismological and engineering applications; b) the determination of the geologic structure of the valley, especially with regard to the identification of the bedrock deep morphology, and the characterization of the mechanical properties of the filling material. To achieve these goals attention was focused on: i) the acquisition of accurate information on the geological, geotechnical and geophysical data in the instrumented area; ii) the execution of geotechnical borehole surveys; iii) the execution of active in-hole seismic tests as well as passive microtremors measurements. The synthesis of this information proved to be essential for the definition of the shape of the valley, the basic soil formations and the depth of bedrock and therefore for the construction of a reliable 2D model which will serve as benchmark for conducting accurate site response studies.

2. Geologic setting of the L'Aquila Basin

The study area is located in the north-western part of L'Aquila intramontane plain (Western l'Aquila Basin - WAB) which was struck by the recent April 6 earthquake. WAB is a typical Quaternary basin of the central Apennines, extended in a WNW-ESE direction, between the structural units of the Gran Sasso and Ocre Mountains, along the Aterno River Valley, which are included in the Apennine thrust and fold belt placed here during upper Miocene-lower Pliocene age (Doglioni, 1991) (Fig. 1). Afterwards, from the upper Pliocene through the Quaternary, the area experienced extensional tectonics, with dominantly S-dipping and NW-SE or W-E trending normal faults, which conditioned the evolution of intramontane basins and their fill deposits (Galadini and Messina, 2004) such as WAB. Quaternary activity of the master fault along Mt. Pettino produced a half graben or maybe an asymmetrical graben of triangular shape (Galadini and Galli, 2000; Moro et al., 2002), filled with continental deposits (Blumetti et al., 1996; Blumetti et al., 2002; Working Group MS-AQ, 2010). The Mt. Pettino fault has an extensional kinematics, is about 14 km long, W-E-trending and S-dipping, with a high dip immersion angle at the surface (Working Group MS-AQ, 2010).

Continental deposits sedimented inside WAB are dominantly lacustrine, fluvial and slope environments which are characterised by complex architecture reflecting not only the different tectonic movements, but also climate changes which occurred throughout the Quaternary (Cavinato et al., 1994; Demangeot J., 1965). The most ancient units of the basin-fill deposits are unexposed and only known from boreholes (Ge.Mi.Na., 1963; Amoroso et al., 2010).

WAB is characterised by a middle Pleistocene- upper Pliocene (?) sedimentary sequence consisting of three main units (Ge.Mi.Na., 1963; Amoroso et al., 2010; Working Group MS-AQ, 2010): i) clayey-sandy-gravelly unit (unexposed and resting on the pre-Quaternary bedrock); ii) gravelly-sandy-clayey intermediate unit (unexposed); and iii) outcropping clayey-sandy-lignitiferous upper unit. Recent deep boreholes drilled in L'Aquila downtown hill, located east of WAB, evidenced a 250 m-thick homogeneous sequence formed by clayey silts and sands laid upon carbonate bedrock (Amoroso et al., 2010); this layer is responsible for the low frequency amplification found in the area (De Luca et al., 2005).

Middle Pleistocene variably-cemented calcareous breccias and dense calcareous gravels (the so called L'Aquila Breccias) outcrop in several areas of WAB and form L'Aquila downtown hill. They are superimposed to the clayey-sandy-lignitiferous upper unit of WAB and the clayey-sandy unit of L'Aquila downtown hill. L'Aquila Breccias are composed by clasts, whose size may reach even some m^3, came northwards from the Gran Sasso chain. They were deposited into the lacustrine paleoenvironment via debris-flow or rock-avalanche processes, which are likely to have occurred under the effect of extreme morpho-climatic events (Blumetti et al., 1996; Blumetti et al. 2002).

The Quaternary sequence (Fig. 2) continues with terraced fluvial deposits from the Aterno paleo-River (Vetoio Stream unit) which are laterally in contact with alluvial-debris fan deposits (Mt. Pettino unit) corresponding geomorphologically to the pediment surface of Mt. Pettino. Those sedimentary units are characterised by tephra horizons suggesting a middle-upper Pleistocene age (Galli et al., 2010). Finally, the youngest and topographically lowest deposit of WAB corresponds to the alluvial unit of Holocene age, which represent the current stage of sedimentation in the Aterno River plain. The alluvial deposit consists of alternations of more or less coarse gravels, sands and silty clays of fluvial and alluvial-fan environments organised in lenticular bodies.

In brief, the WAB Quaternary outcropping formations are supposed to belong to at least two main sedimentary cycles: in the lower-middle Pleistocene, the cycle of the clayey-sandy-lignitiferous unit and, in the upper-middle Pleistocene, the cycle of the Vetoio river terraced alluvia and of the pediment debris, which is in part laterally in contact with Vetoio alluvia. The first sequence is mostly found in the southern and central part of WAB. The second sequence, unconformably overlying the first one, has its depocentre against the Mt. Pettino fault, pointing to a close tectono-sedimentary relationship between the activity of the fault and those deposits. This last consideration is reinforced by the N-dipping toward the Mt. Pettino fault of the middle Pleistocene breccia-base surface (Tallini et al., 2002; Working Group MS-AQ, 2010).

Moreover the Upper Aterno River Valley geologic section investigated in detail in this study features a pre-Quaternary bedrock and surrounding reliefs of Meso-cenozoic cherty limestone with calcareous-detrital intercalations of slope to basin lithofacies: “Corniola Formation” forming the Pettino Mt. fault footwall whose shear zone is strongly dolomitised and the “Maiolica Formation” and “Calcarenites and calcareous breccia with fucoids Formation” representing the Pettino Mt. fault hanging-wall (Vezzani and Ghisetti, 1998). The carbonate bedrock is variably displaced by normal faults, with both Apennines and anti-Apennines directions, and by a N-dipping back-thrust, whereby the detrital “Maiolica Formation” geometrically overlaps the arenaceous terrigenous unit of Messinian age outcropping a little outside the investigated area.

3. The strong motion array in the upper Aterno River valley

The strong motion array deployed in the upper Aterno Valley, in the immediate outskirts north-west of the town of L’Aquila, is part of the Italian Strong Motion Network (*Rete Accelerometrica Nazionale*, RAN) operated by the Department of Civil Protection (*Dipartimento della Protezione Civile*, DPC). The array was installed in 1994 by the former National Seismic Service (*Servizio Sismico Nazionale*, SSN), currently incorporated in the DPC, to investigate the effects of local soil conditions along a cross section of the valley (Bongiovanni et al., 1995).

In its original configuration the array was composed of 7 free-field strong motion stations: four were located on soil deposits, two on limestone bedrock at the NE (Mt. Pettino) and SW (*Colle Grilli*) edges of the network while an additional rock station was installed close to the village of *Cansatessa* at the edge of a limestone outcrop (Fig. 2). The total length of the network was of about 2 km, the maximum difference in elevation between stations was of about 350 m. In the original configuration, one station was also equipped with two down-hole instruments, one at mid-height in the soil deposit and another just below the rock interface.

The early deployment of the Aterno array was based on Kinemetrics SSA16 and SSR1 digital data loggers equipped with Kinemetrics strong motion sensors FBA23. The dynamic range of data loggers was of 16 bits and the sensors full scale range was of 1 g. During its first setup the first moderate magnitude local event recorded was the 1994/06/02 M_L 3.9 earthquake that triggered the four instruments located on soil sites. The 1997 Umbria-Marche seismic sequence triggered only few records with the first two mainshocks. The third mainshock of the sequence, the 1997/10/14 Mw 5.4 event, was able to trigger four of the network stations included the reference site of Pettino Mt (http://itaca.mi.ingv.it/ItacaNet/).

After its first deployment the array was modified both in terms of station’s number and equipment. Regrettably, the station equipped with the surface and two down-hole sensors was dismounted for logistic problems. The remaining stations were equipped with new generation strong motion instruments based on Kinemetrics Etna (18 bits) or Everest (24 bits) data loggers and FBA23 sensors. In the new deployment all the stations were synchronized by absolute GPS timing and data were centralized on demand by GSM-GPRS data link.

The actual configuration of the upper Aterno Valley array is shown in Fig. 3 while a plain view showing the location of instrument recording sites is illustrated in Fig. 4. Also shown in the figure is a cross-section line (A-A') passing through the accelerometric stations and aligned in the SW-NE direction. The AQG recording site is located at the hilltop of *Colle Grilli*, an highly weathered outcrop of the base rock formation. AQA is located in proximity of the right bank of the Aterno river, at the southern edge of the alluvial valley, while AQV lies at the valley's centre. Of the remaining stations, AQM is set on outcropping rock, AQF is located on slope debris deposits while AQP is located on top of Mt. Pettino on calcareous rock. The stations AQG, AQA and AQV generally recorded both the mainshock and numerous aftershocks and therefore they have been deserved special attention in programming the in situ investigation within S4 project.

4. Geological, geotechnical and geophysical data

A major effort was dedicated to provide a detailed and complete description of the geometry of the deposits overlying the bedrock formation as well as of the soil-bedrock interface and also to supply accurate information on dynamic material properties. To this aim, data were collected from previous investigations and available geotechnical reports from consultant studies, public agencies and others. Moreover, *ad hoc* geotechnical and geophysical investigations have been undertaken in the framework of the S4 project. Overall, the following data were analysed: a) 60 stratigraphies of continuous-coring boreholes, of which 10 intercepted the carbonate bedrock; b) active seismic investigations (down-hole, cross-hole and seismic dilatometer); c) passive seismic investigations (about 70 noise recordings collected at single three-component stations).

The results of these investigations are presented and discussed in the following three sections.

4.1 Borehole data and identification of lithologic units

In 1993, before the seismic network was deployed, an extensive program of site characterization has been undertaken on behalf of *Servizio Sismico Nazionale* (Bongiovanni et al., 1995). Specifically, seven boreholes (S1, S2, S3, S4, S5, S6 and S7) were drilled and samples were retrieved for geotechnical laboratory investigation (Fig. 4). The majority of these boreholes are located at the north-eastern edge of the valley: S1, S3 and S7 reached the carbonate bedrock at depths of 23.5, 52.0 and 23.9 m from ground level, respectively, whereas boreholes S2 and S5 were relatively shallow since they have been drilled to depths of 14 and 20 m, respectively. The bedrock proved to be fractured and locally highly fractured. Borehole S6, instead, approximately placed at the centre of the valley, was drilled to 50 m depth without intercepting the bedrock. The location of S4 was uncertain and therefore it has not been considered for the reconstruction of a litostratigraphic section.

This information was enriched by data resulting from numerous drillings performed by individual studies carried out in the instrumented area. SF1, SF2 and SF3 boreholes (Fig. 4), executed in 1988, reached the carbonate bedrock at depths of 15, 5 and 10 m, respectively; their lithologies included clayey-sandy and sandy-silty alluvia. Borehole S2.3 was drilled as part of the project “Seismic microzoning of L’Aquila plain”, developed after the April 6 earthquake (Working Group MS-AQ, 2010). The borehole encountered gravelly deposits in direct contact with the extremely fractured carbonate bedrock, which was intercepted at 8 m depth. Evidence of bedrock’s depth at the middle of the valley was obtained by the deepest available borehole SM (55 m), in proximity of the AQV station, which shows the top of the bedrock at a depth of 46 m.

In the framework of the S4 Project, other surveys were carried out in 2010 between the accelerometric stations AQA and AQV, where information was very limited. In the additional boreholes SL1 and SL2 the bedrock was intercepted at depths of 25 and 12 m, respectively. The carbonate bedrock appeared to be fractured and with evidence of microkarst. A further borehole SG was drilled adjacent to the station AQG to a depth of 40 m, which showed for the whole length the presence of pervasively fractured calcareous breccia, locally tectonized.

Borehole data identify a geological setting with frequent lithological changes and intercalations of levels of lenticular gravel in a sandy matrix with levels of silty clay, sandy and gravelly silts (Fig. 5). Lithotypes encountered in the boreholes, from the youngest to the oldest, are as follows:

A. *silty clay with gravel* - dark brown colour; constant average thickness of about 4 m; homogeneously distributed throughout the investigated area, excepted for SG borehole;
B. *sandy gravel and gravelly sand* - polygenic clasts, weakly rounded and heterometric with a maximum diameter of 5 cm, sandy matrix decreasing downwards and fine, monometric, calcareous sand in an silty matrix, with diffuse, decimetre-scale, calcareous pebbles and clasts averagely rounded and flattened (average size: about 0.5-1 cm); this lithotype has a lenticular geometry with maximum thickness of about 30 m in the middle of the valley (SM borehole), decreasing its thickness in the eastern sector of the valley to disappear completely;

C. *silty/sandy clay with gravel and sandy silt* - silty sand and silty clay with gravel and scattered pebbles, dark brown colour, locally oxidised and sandy silt with clayey levels, with sand and pebbles (max diameter: 5 cm); lenticular geometry and maximum thickness of about 12 m, occurring only in the eastern sector, on the left bank of the Aterno river; in the western sector, its thickness tends to diminish; in boreholes SM, SL1, SL2 and S2.3 no evidence of this lithotype was found;

D. *alternation of silty sand, silty clay and clay with gravel* - continuous alternation of metre-scale levels of silty sand of light brown colour, sandy silt with poorly dense gravel and silty clay with rosy sand and gravel; lenticular geometry, occurring only in the eastern sector, with maximum thickness up to 28 m (S3 borehole) in the middle of the valley;

F. *carbonate bedrock* - calcareous rocks, locally weathered and highly fractured nearer the surficial portion (SG and S2.3 boreholes)

4.2 Geotechnical and geophysical data

Considering the description of the lithologic units from the free surface to the bedrock given above, their predominant composition mainly constituted by coarse-grained materials which render very difficult to retrieve undisturbed samples for laboratory tests, and the large variation from site to site as well as with depth, a comprehensive characterization of the Aterno valley soils is not an easy task. As already mentioned the only source of geotechnical information from laboratory tests, albeit limited, is represented by the data acquired during the 1993 campaign (Bongiovanni et al., 1995). Conventional laboratory testing for classification purposes was carried out on selected samples of coarse-grained soils obtained from the boreholes and on undisturbed samples of fine-grained soils. This testing included grain size analyses, unit weight, moisture content and Atterberg limits determination. Table 1 presents a summary of the results. Note that in the boreholes executed in 2010 within the S4 Project only sandy gravels, with local presence of cobbles and/or boulders, were encountered above the limestone bedrock and this has made difficult to retrieve undisturbed samples as well as the execution of standard in situ tests.

Groundwater table was encountered in the 1993 campaign during drilling excavation at about 5 m below ground surface level in borehole S3 and S5 while it was found at approximately 15 m depth in borehole S1.

Geophysical tests in the study area have been carried out in the framework of the S4 Project, in part specifically addressed to acquire information for the seismic classification of the accelerometric stations. Between December 2009 and March 2010, down-hole tests were therefore conducted at AQG and in the borehole SL2 and S2.3, located in proximity of AQA (Fig. 4). A seismic dilatometer test (SDMT) was also carried out in SL1 borehole. In non penetrable soil or rock SDMT probe is inserted in the borehole filled with sand as reported in Totani et al. (2009). The only shear wave velocity information already available for the instrumented area is close to AQV station where a cross-hole test was carried out in SM borehole. The results of these tests are presented in terms of stratigraphic and velocity profiles in Fig. 6.

The V_s profile at AQG (Fig. 6a), characterized by highly fractured limestone in the top 26 m, indicates velocities of about 500 m/s in the top 5 m, with an increase to about 750 m/s at a depth between 5 and 20 m; from 25 to 38 m V_s is on average equal to 900 m/s. Similar values for the shear wave velocity of the calcareous bedrock can be recognized for the other seismic tests for which Vs vary between about 900 m/s (borehole S2.3) and 1300 m/s (boreholes SL2, SL1, SM). The more surficial lithotype A (silty clay with gravel) shows a shear wave velocity comprised between approximately 200 and 300 m/s. Lithotype B (sandy gravel and gravelly sand) exhibits a shear wave velocity profile increasing with depth from about 400 m/s to about 800 m/s. This is particularly evident from down-hole tests SL2 (Fig. 6c) and SL1 (Fig. 6d) whereas data from cross-hole test show a slight increase only in the first few meters of the lithotype and an approximately constant value of about 600 m/s at greater depths (Fig. 6e). For lithotype D (alternation of silty sand, silty clay and clay with gravel) data are available only from cross-hole test and indicate a fairly constant Vs value of about 600 m/s (Fig. 6e).

Compression wave velocity V_P profiles are also available limitedly to AQG and AQA stations and SL2 borehole, where down-hole tests have been carried out. For AQG (Fig. 6a) the P-wave velocity is about 2000 m/s in the uppermost 7 m, then decreases to 1200 m/s from 7 to 18 m; at greater depths, V_P gradually increases reaching the maximum value of 2500 m/s at a depth of 38 m. The other two down-hole tests indicate V_P values for the bedrock of about 3000-3500 m/s (Figs. 6b and c). V_P values for lithotype A are in the range 500-700 m/s whereas for lithotype B V_P increases with depth from about 1000 to 2000 m/s (Figs. 6b and c).

4.3 *Results from ambient vibration measurements*

In order to extend on a wider area the information inferred by geological and geophysical data we collected a large set of ambient vibration measurements already available or specifically performed in the study area. The resonance frequency f_o (SESAME, 2004) of soil deposits was investigated using the spectral ratio between the horizontal and the vertical component of the recorded ground motion as proposed by Nakamura (1989). Microtremor data analysis (HVNSR) was performed starting by signals collected by two different sets of sensors and data loggers. We used data recorded by high sensitivity three components velocity transducers Lennartz LE3D-5s connected to high dynamic range digital recorders RefTek 130 and Micromed Tromino ® three component velocity sensors and digital data logger. The first instrumental configuration allows to record with a good resolution seismic noise in a very quiet environment due to the high sensitivity of the sensors (400 v/m/s), in a frequency band that extends towards low frequencies. The second instrument is more suitable for environment with highest values of seismic noise and resonance frequencies above 1.0-1.5 Hz. Due to the characteristics of the investigated area, with intense human activities and sediment thickness compatible with resonance frequencies above 2 Hz, the results obtained by the two different instrumental schemes are quite comparable and reliable.

The microtremors data were collected during a short time window (40-60 minutes). Signals were cut into short duration (30 seconds) windows and processed through a detrigger algorithm (SESAME, 2004), to remove those affected by strong transient disturbs. Fourier spectra were evaluated and smoothed using the method proposed by Konno-Omachi (1998). Finally the average spectral ratio, along with the standard deviation, was evaluated for the geometrical mean of horizontal components. The characteristic peak in the H/V relation was assumed to be the predominant frequency of the site. The map of the HVNSR measuring points is reported in Fig. 4.

The high density of measuring points allowed to define with a good detail the lateral variation of resonance frequency f_0 and to detect zones with homogeneous behaviour. The investigated area can be divided into three subzones: the outcropping rock (limestone) measurements in the *Colle Grilli* and *Cansatessa* areas, the Mt. Pettino area, in the eastern part of Fig. 4, and the Aterno River valley in the central and north-western section. The HVNSR results obtained on the outcropping limestone, shown in Fig. 7, are quite different between *Colle Grilli* and *Cansatessa*. In the first case (Fig. 7a) a clear large peak, centered at about 8 Hz with amplitude of about 4, is found; in the second case (Fig. 7b), HVNSR is quite flat with average amplitude centered on 1. These results suggest the peak in the *Colle Grilli* response curve may be related to the presence of a highly fractured outcropping limestone, as indicated by the borehole SG specifically carried out in proximity of the AQG station while the *Cansatessa* site shows characteristics of a good reference bedrock. This last feature was already detected during microzoning studies, since the site of *Cansatessa* was selected as reference site for earthquakes data analysis in the ”Macroarea 2 (Working Group MS-AQ, 2010).

For the Mt. Pettino area (Fig. 8a) all the HVNSR measurements (Figs. 8b and c) show a clear peak at about 2 Hz with amplitude ranging between 4 and 8 (Benedettini et al., 2011). This peak is quite stable and represents one of the most significant effect found in ”Macroarea 2” during microzoning studies (Working Group MS-AQ, 2010). Its origin can be related to the impedance contrast between the Mt. Pettino scree deposits overimposed to the limestone bedrock. The depth of scree deposits can be inferred between 40 and 50 meters on the basis of V_S values obtained by downhole data.

The Aterno River valley is the area that shows some more complex features that cannot be easily explained in terms of simple 1D structure. One of the main characteristics of HVNSR data for the area is the presence of a double amplification peak in many of the measuring points located close to AQV accelerometric station, as shown in Fig. 9a. The HVNSR rotate computing, displaying the H/V as a function of azimuth, is also shown in Fig. 9b where it is clear the absence of any directional effect in the noise field. The results of microtremor analysis can be related to the presence of two significant impedance contrasts in the sediments filling the Aterno valley. A first shallow contrast, due to the presence of a thin silty-clay layer resting on stiffer gravelly soil, is responsible for the high frequency (>10Hz) HVNSR peak, while the deeper contrast between Quaternary alluvial deposits and the underlying limestone bedrock at depth of few tens of meters produces the first peak centered at 3Hz. The double-peak feature is not always clear in the valley probably due to the 2D geometry of the gravel layer whose extent is due to lateral and vertical sedimentation process changes of Aterno River.

A synthesis of HVNSR results is shown in Fig. 10, where a contour map of resonance frequency f_0 is presented along with some of spectral ratio curves obtained along the Aterno valley section. These dominant frequencies f_0 are slightly greater than 10 Hz at the western edge of the valley (measurement points b and c) with exception of point a, close to AQG station, in which f_0 is about 6 Hz. At the valley’s centre (measurement points d and e) a lower value, between 3 and 4 Hz, is observed indicating bedrock at greater depth. Moving towards the Mt. Pettino area at the eastern side of the section (measurement points f and g), fundamental frequencies are again shifted towards higher values (4-5 Hz).

5. Definition of 2D subsoil model

The 2D subsoil model of the upper Aterno valley was reconstructed by merging geological, geotechnical and geophysical data. The inversion of microtremor data, constrained by stratigraphic logs and seismic in-hole tests, allowed to develop the map of carbonate bedrock depth. Specifically, the employed methodology was subdivided into the following steps:

1) comparison of the measured f_0 by HVSR method and those estimated via the formula f_0= Vs/4H using the measured Vs and H (bedrock depth) values from boreholes with in-situ seismic tests;
2) Vs values of the cover all over the area have been constrained with bedrock depth obtained through borehole logs (about 60, but only 10 reached the carbonate bedrock), f_0 from microtremor surveys (about 70) and other geophysical investigations (seismic refraction profiles, MASW and SEV from Bongiovanni et al. (1995) and Working Group MS-AQ (2010)). Figure 11 shows the zones of the soft cover overlying the seismic bedrock characterised by equal Vs values. The Vs value of the different areas correspond to an average value of the cover. The Vs velocities of the alluvial and slope covers range from 300 m/s to 600 m/s. The Vs velocities in the central sector of the valley, extending between the AQA and AQV stations, exceed 400 m/s; this is due to the occurrence of lenticular gravely bodies, which reach their maximum thickness in this sector. Between the stations AQG and AQA and between AQV and AQM, velocities are below 350 m/s, owing to the diminishing thickness and/or disappearance of the gravelly deposits, replaced by dominantly sandy-silty ones. The slope deposits of Mt. Pettino (sector between the stations AQM and AQF) exhibit velocities of 400 to 500 m/s. The limestone outcrops were considered to be the seismic bedrock and associated with a Vs value greater than 800 m/s.
3) the bedrock depth contour line map (Fig. 12) was drawn using the following equation: H= Vs/4f_0 using f_0 values from microtremor data and the Vs values map of Fig. 11.

As illustrated in Fig. 12, along section A-A’, the bedrock outcrops at the valley’s borders and deepens to slightly less than 50 m at the valley centre. The varying geometry of the bedrock is more evident in Fig. 13a which illustrates the geologic cross section built along the seismic array. The valley shows an asymmetrical shape. Moving from AQA to AQV, the valley is first shallow with a gentle slope gradient, then it deepens reaching its maximum depth just below AQV revealing a deep paleo-incision filled with alluvium. Moving further to the east, the bedrock rapidly rises near AQM station. In the area between AQM and AQF, the bedrock deepens, probably as a result of buried tectonic features, and it is filled with slope deposits.

In the valley (Fig. 13b), the alluvial soils overlying the bedrock were grouped according to the lithologic units defined in section 4.1. To each lithotype a Vs value (or range of values) has been assigned. From top to bottom, these are as follows: a) lithologic unit A (silty clay with gravel): it is found throughout the entire valley cross section with an approximately constant thickness (4 m) and it is characterized by average Vs=250 m/s; b) lithologic unit B (sandy gravel and gravelly sand): this layer is about 10 m-thick at the western edge of the valley, it deepens up to a maximum of about 30 m at the valley center and then its thickness decreases until it disappears at the eastern edge; the shear wave velocity is in the range Vs =400-800 m/s showing a stiffness generally increasing with depth; c) lithologic unit C (silty/sandy clay with gravel and sandy silt): this layer of lenticular geometry is present in the uppermost part of the stratigraphic profile only at the eastern edge of the valley; lacking experimental determination, for this layer Vs = 350 m/s was assumed, slightly higher than the average value deduced from the inversion process (Fig. 11) in order to take into account the softer surficial layer; d) lithologic unit D (alternations of silty sand, silty clay and clay with gravel): this layer is found only at the eastern sector of the valley, just above the bedrock formation; its thickness is comprised between 15 and 30 m, and is characterised by Vs=600 m/s. Regarding the carbonate bedrock, a distinction between weathered/fractured and unweathered bedrock can be made assigning V_S=700-800 m/s and 900-1200 m/s, respectively. Table 2 summarises physical properties and Vs range of values of the lithologic units. Lithologic unit E (Mt. Pettino scree deposit), which occurs only outside the valley between AQM and AQF stations, has been not characterised because no data are available.

6. Conclusions

The strong-motion array deployed in the upper Aterno River valley recorded mainshock and several aftershocks of the 2009 L'Aquila earthquake in central Italy. These recordings have provided a strong motion data set of very valuable seismological and engineering interest which can be used, among others, to improve our knowledge on site effects in sediment-filled valley in epicentral area during moderate earthquakes. However, the availability of these high-quality data was not accompanied by a detailed knowledge of buried geometry and dynamic soil properties of the instrumented area.

A major effort was therefore undertaken in the framework of the S4 Project with the purpose of determining the subsoil geometry along the cross section of the Aterno valley passing through the accelerometric stations as well as the dynamic material properties. This was accomplished by a geological and geotechnical survey and an extensive geophysical campaign. Specifically, boring logs and in-hole seismic tests were carried out at different sites along the cross section and results from these tests were complemented with gathered data from previous investigations. By merging this information, five lithologic units were identified from surface to bedrock whose thickness vary laterally and with depth. Moreover, ambient vibrations records were analysed at 70 measurements points using horizontal to vertical spectral ratios technique (HVNSR). These measurements have proved reliable to determine the site dominant frequency f_0 and therefore, constrained by stratigraphic logs and seismic in-hole tests, to reconstruct bedrock morphology along the cross section. The results show that the geological section is characterised by an asymmetric shape with the carbonate bedrock deepening in the central part of the valley.

All the information acquired were synthesized in a 2D subsoil model describing the soil layering, the soil-bedrock interface geometry and the dynamic material properties with reasonable accuracy. This model represent an important step useful to provide a better understanding of the role played by site effects in the seismic response of the valley through a more accurate numerical modeling and a validation with the observations from earthquake recordings.

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List of Tables and Figures

Table 1 – Physical properties from conventional laboratory tests.

Table 2 – Physical and mechanical properties of the lithologic units of the Aterno Valley cross-section.

Fig. 1 – Geologic outline (modified from Vezzani and Ghisetti, 1998 and Working Group MS-AQ, 2010). 1 - continental deposits (Holocene – upper Pliocene?); 2 - terrigenous units (upper Miocene); 3 – Mesozoic platform and miocenic limestones (area of Aterno River); 4 – Cretaceous platform and miocenic limestones (Ocre Mts.) and cherty-calcareous-marly-detrital lithologies; 5 – Liassic and Triassic platform limestone and dolomite (Mt. Ruzza area); 6 - Filetto-Pescomaggiore area; 7 - Mt. Pettino area; 8 - Roio-Tornimparte area; a - normal fault; b - presumed normal fault; c - overthrust or transpressive fault; d - studied area.

Fig. 2 – Geological map (modified from Working Group MS-AQ, 2010). Quaternary units – Ri: filling anthropic material (Holocene); Cl: fine-grained eluvial-colluvial units (Holocene); Dt: debris slope units (Holocene); Al: alluvial units of Aterno R. and Raio S. (Holocene); Cd: alluvial-debris cone units of Mt. Pettino; dense and poor cemented calcareous gravels with tephra horizons and well-cemented micro-karstified calcareous gravels (Cda) (upper-middle Pleistocene); At, terraced alluvial unit of Vetoio S.: gravels, sand and sandy-clayey silt with tephra horizons (upper-middle Pleistocene); Br1, L’Aquila Breccia: dense and poor- to well-cemented calcareous gravels (middle Pleistocene).
Meso-cenozoic carbonate and terrigenous units - MO: marly unit (middle Miocene); SC: mud-supported and micro-detrital limestone (“detrital Scaglia Formation” Auctt.) (Eocene p.p. - Cenomanian p.p.); MA: mud-supported, micro-detrital and oolitic limestone (“detrital Maiolica Formation” Auctt. and “Calcarenite and calcareous breccias with fucoids” Auctt.) (Cenomanian p.p. - upper Titonic); Co, mud-supported and micro-detrital at times dolomitised limestone (“detrital Corniola Formation” Auctt.) (middle Lias).

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Fig. 3 – Actual configuration of the Upper Aterno River valley accelerometric array (stations name in red boxes; white arrows mark the trace of the normal fault along the Mt. Pettino slope; the blue line marks the Aterno River).

Fig. 4 – Map of in situ investigations. 1 - continuous core borehole; 2 - borehole equipped for down-hole test; 3 - borehole equipped for cross-hole test; 4 - borehole equipped for SDMT test; 5 - noise measurement site (Micromed-Tromino sensor); 6 - noise measurement site (Lennartz MarsLite and Lennartz 3D/5s sensors); 7 - RAN accelerometric station; 8 - geologic cross-section.

Fig. 5 – Borehole logs used for the geological model: A - silty clay with gravel; B - gravel with sand and gravelly sand; C - silty/sandy clay with gravel and sandy silt; D - alternations of silty sand, silty clay and clay with gravel; F - carbonate bedrock (red dashed lines represent the weathered/fractured portion).

Fig. 6 – In-hole geophysical tests in the upper Aterno River valley (DH=down-hole; CH=cross-hole; SDMT= seismic dilatometer).

Fig. 7 – H/V curves for a) *Colle Grilli* and b) *Cansatessa* sites.

Fig.8 –Location of HVNSR measurement points (a) and H/V curves (b, c) at Pettino site.

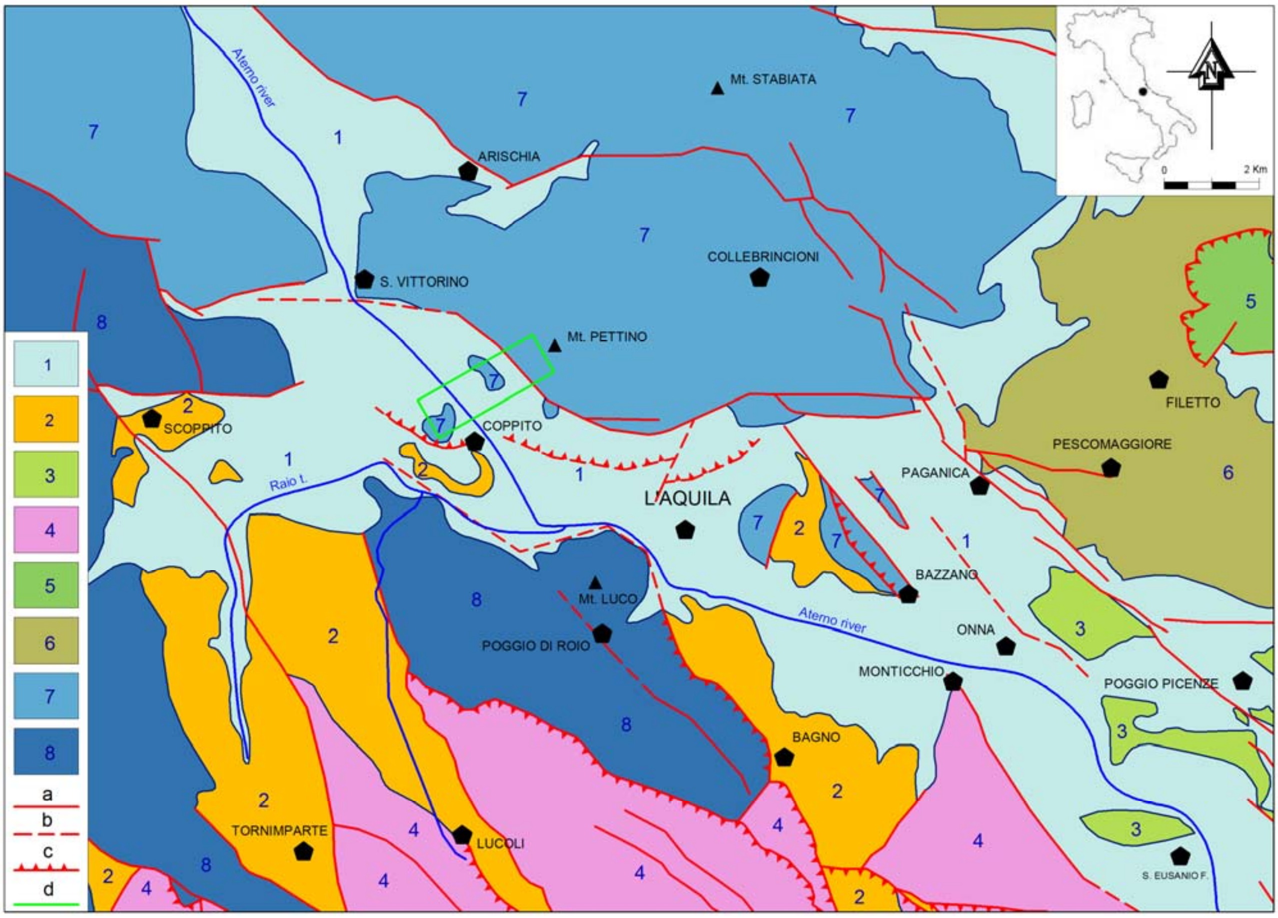
Fig. 9 – H/V curve at AQV site (a) along with directional H/V (b).

Fig. 10 – Contour map of the fundamental frequency peak derived from HVSR analysis of microtremor data (contour line step: 0.5 Hz) and examples of H/V curves in selected points along the transversal A-A’ section.

Fig. 11 - Vs values in the studied area. a- RAN station; b- geologic section.

Fig. 12 – Contour map showing the geometry of soil-bedrock interface (contour line step: 2.5 m).

Fig.13– Geologic section of the Aterno River valley (a) and section of its central sector (b). Ao - anthropic filling material; A - silty clay with gravel; B - gravel with sand and gravelly sand; C - silty/sandy clay with gravel and sandy silt; D - alternations of silty sand, silty clay and clay with gravel; E - Mt. Pettino scree deposit; F - carbonate bedrock (“Maiolica formation” Auctt.); G - arenaceous bedrock; 1 - overthrust; 2 - normal fault, hatched when uncertain; 3 - accelerometric station; 4 - borehole.



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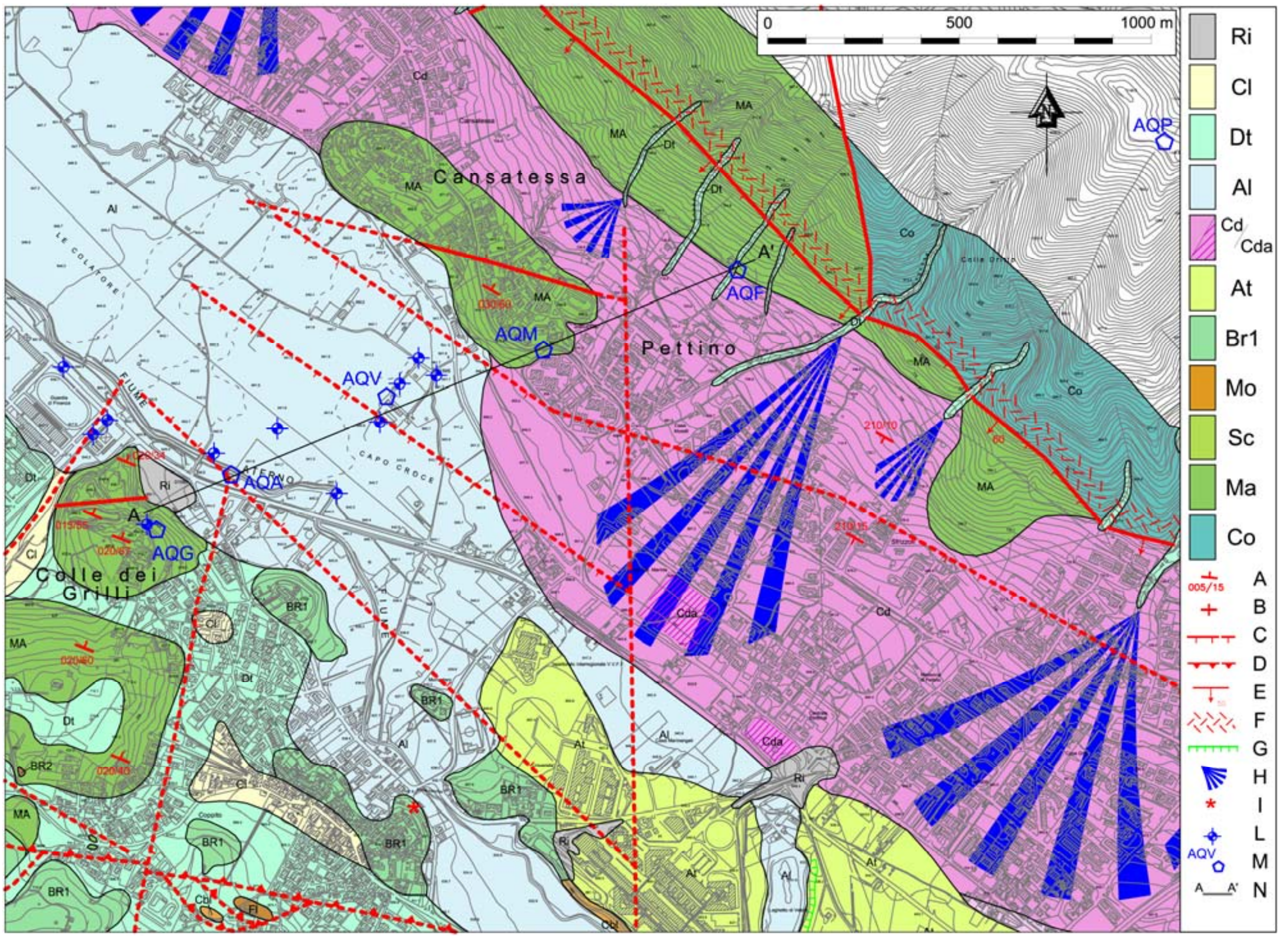

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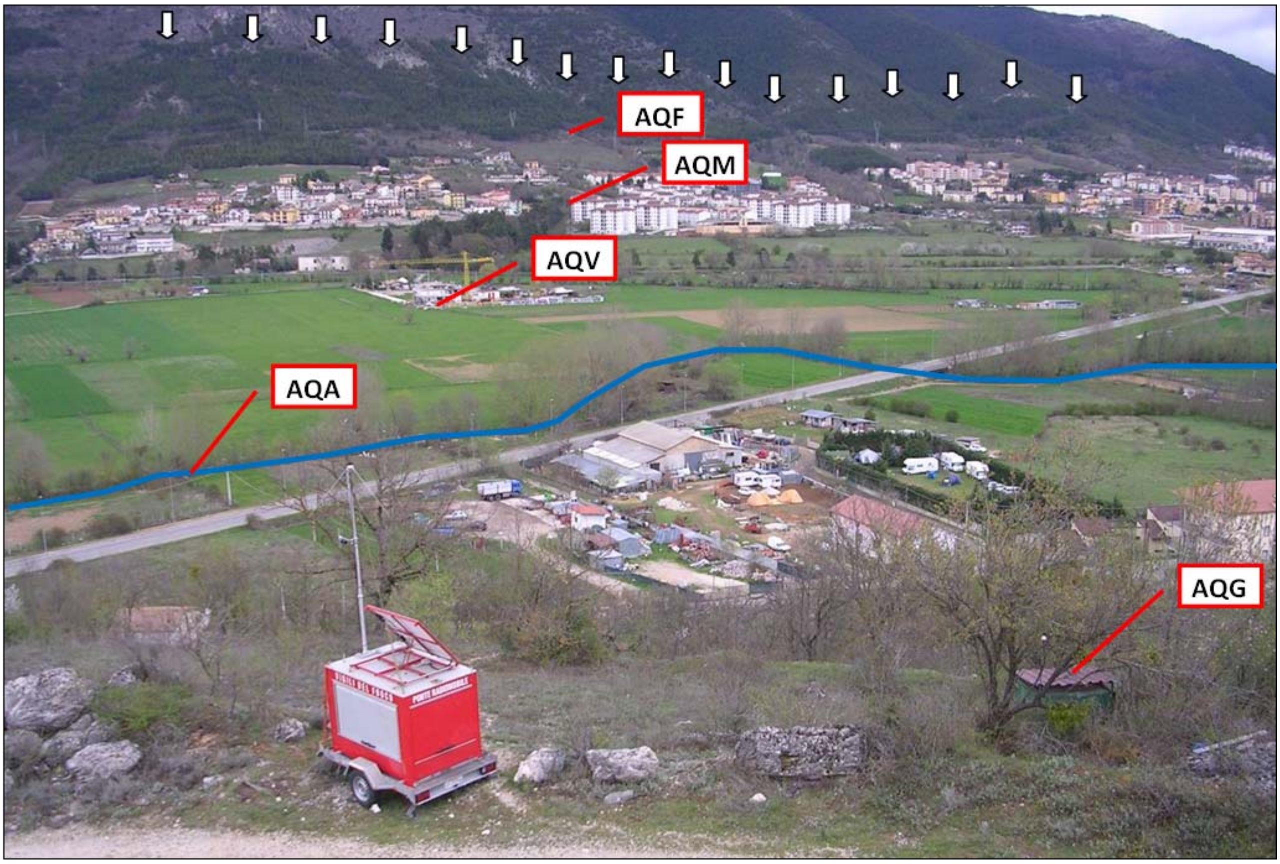

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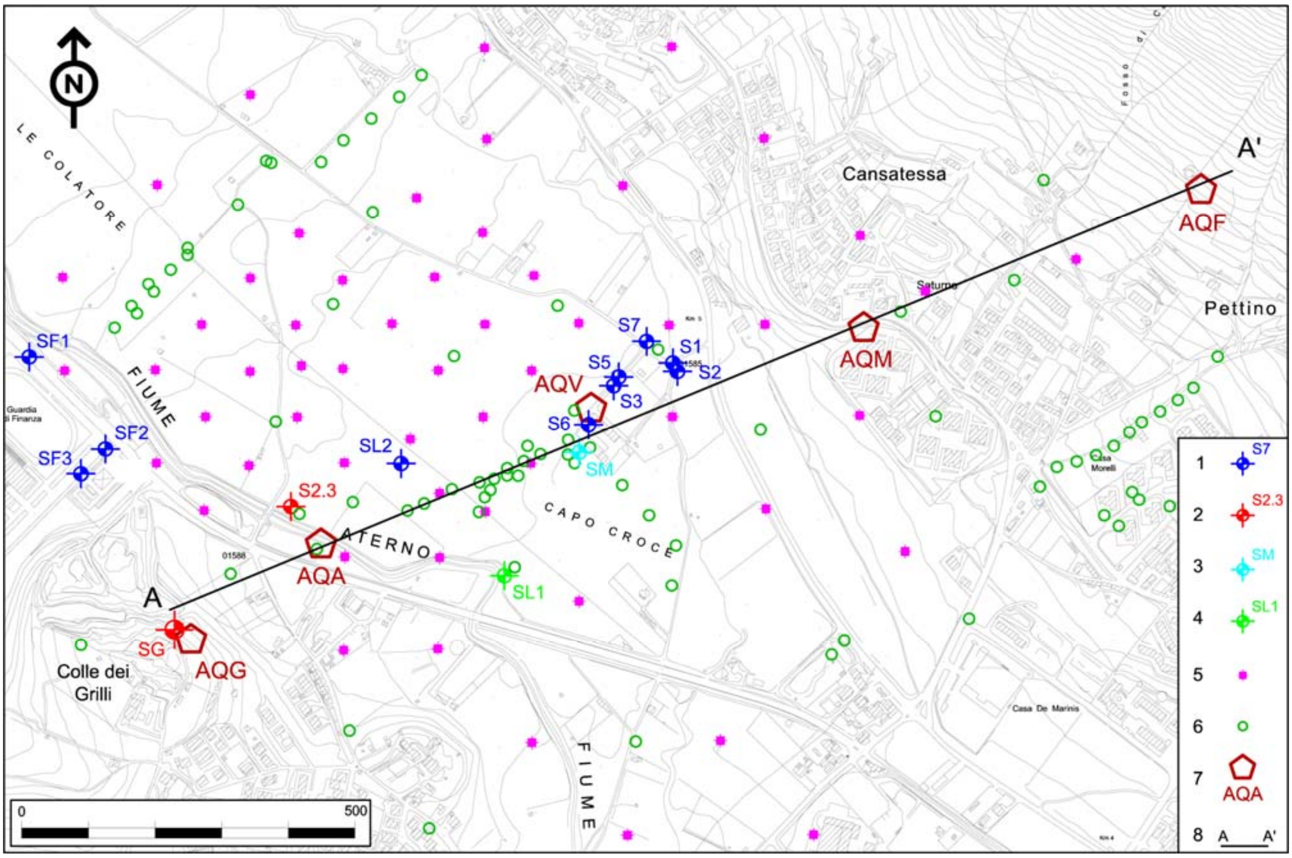

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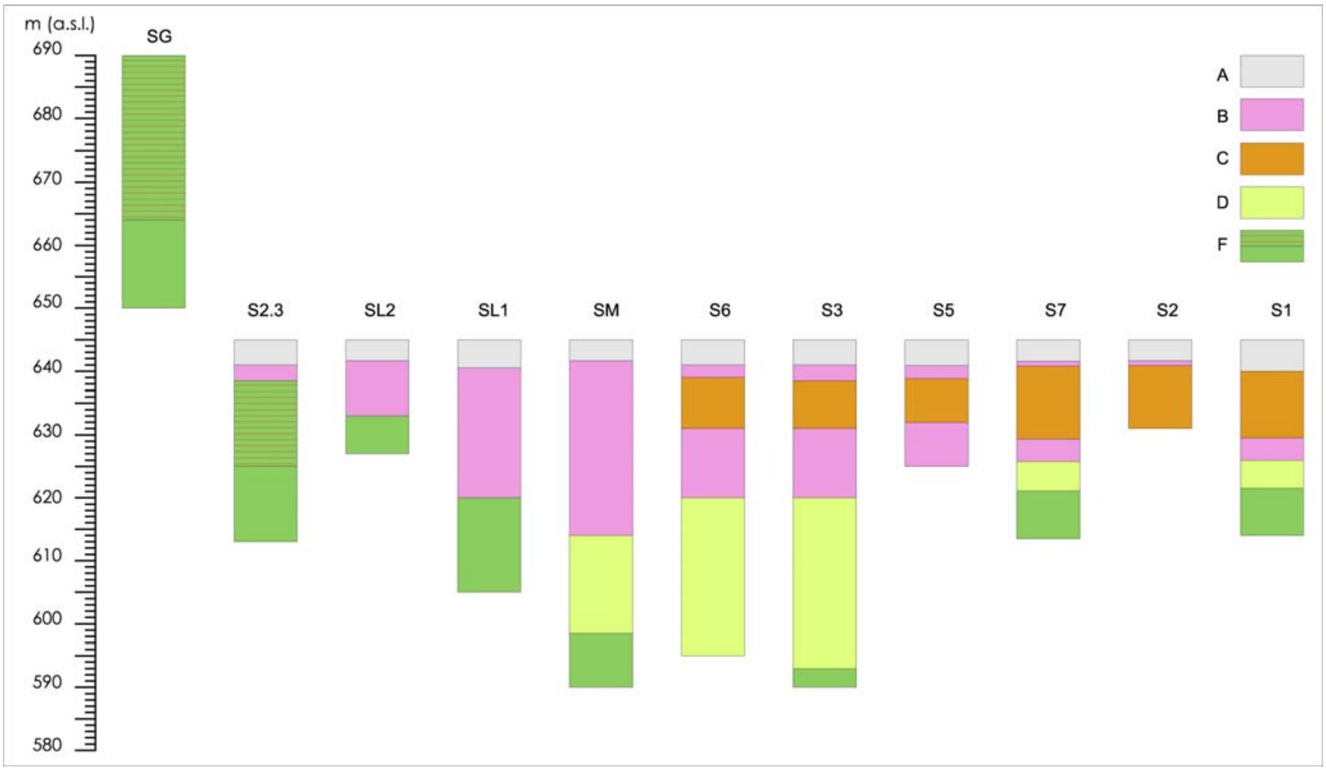

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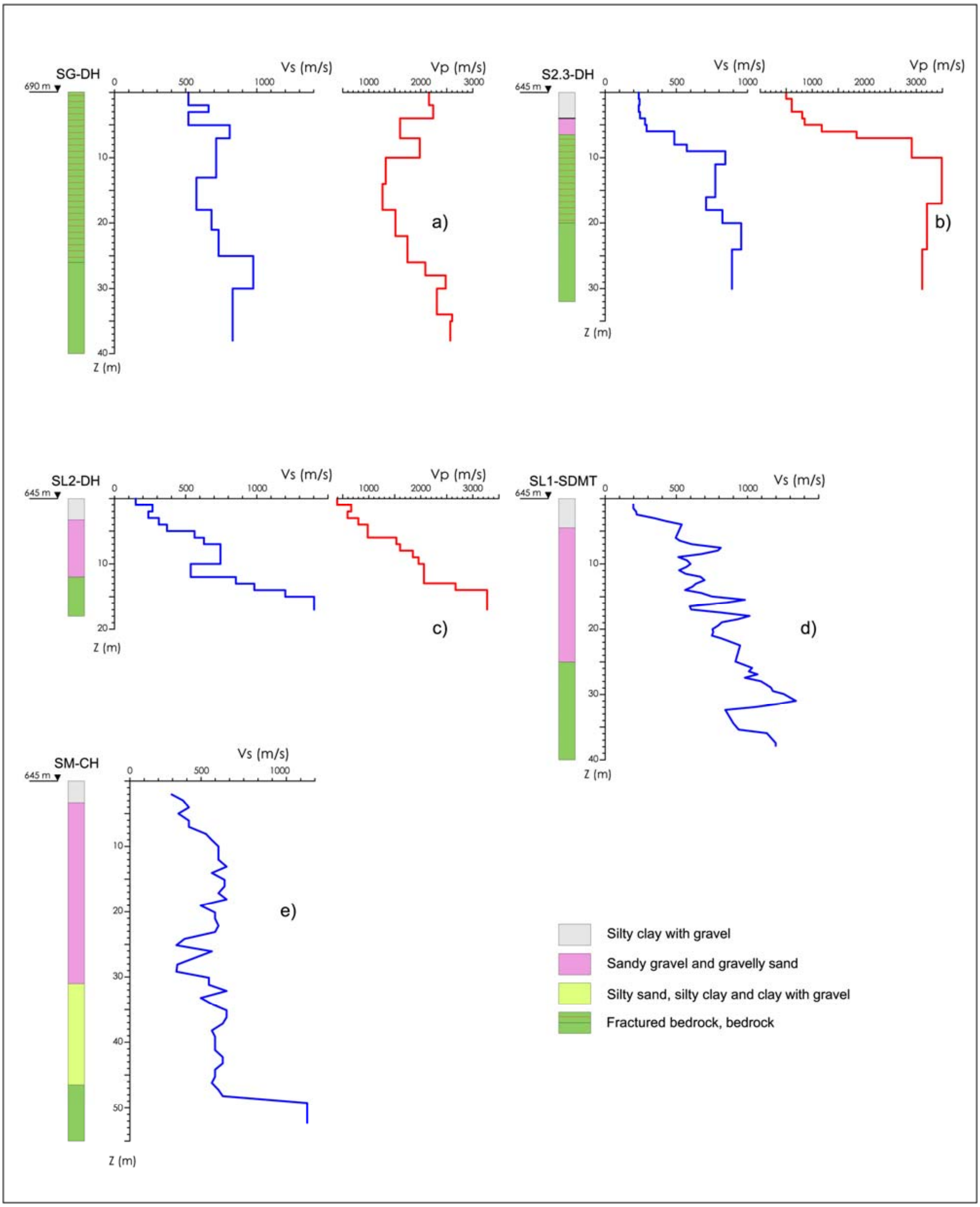

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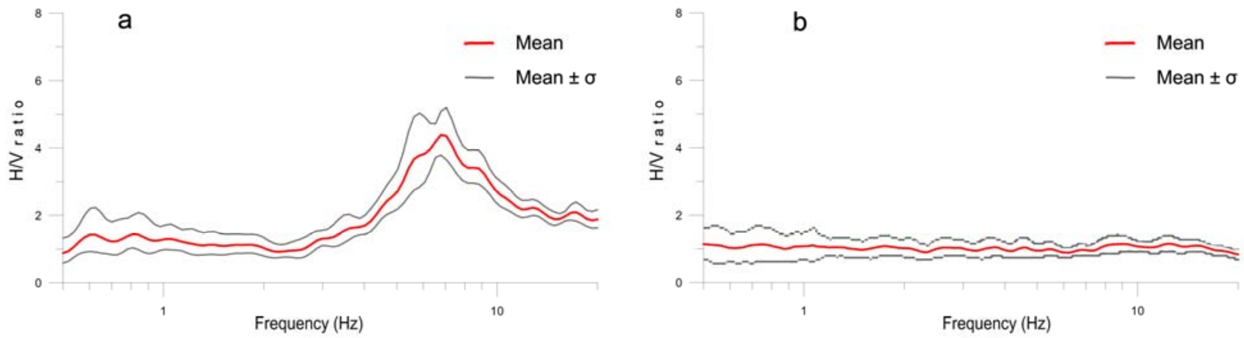

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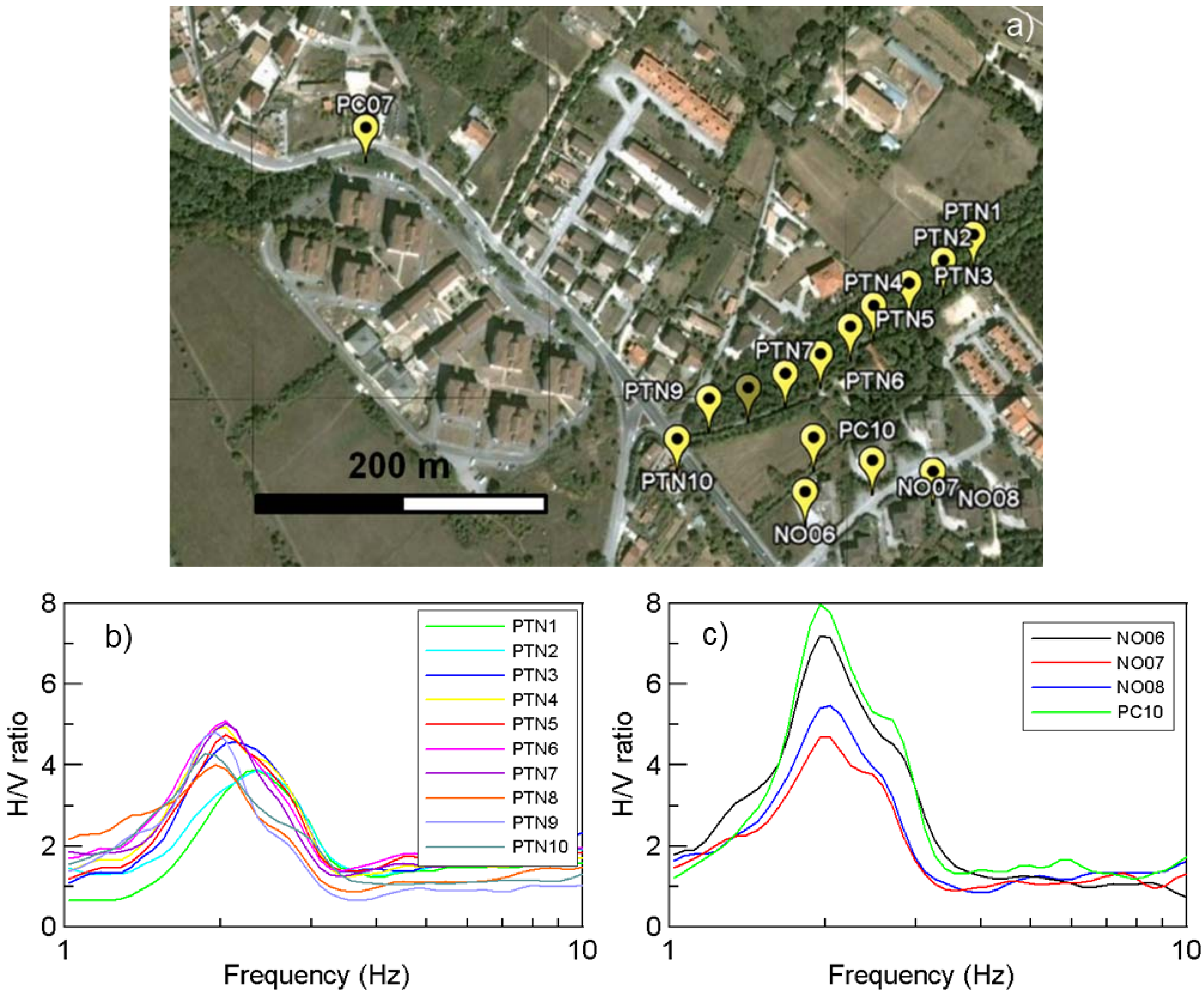

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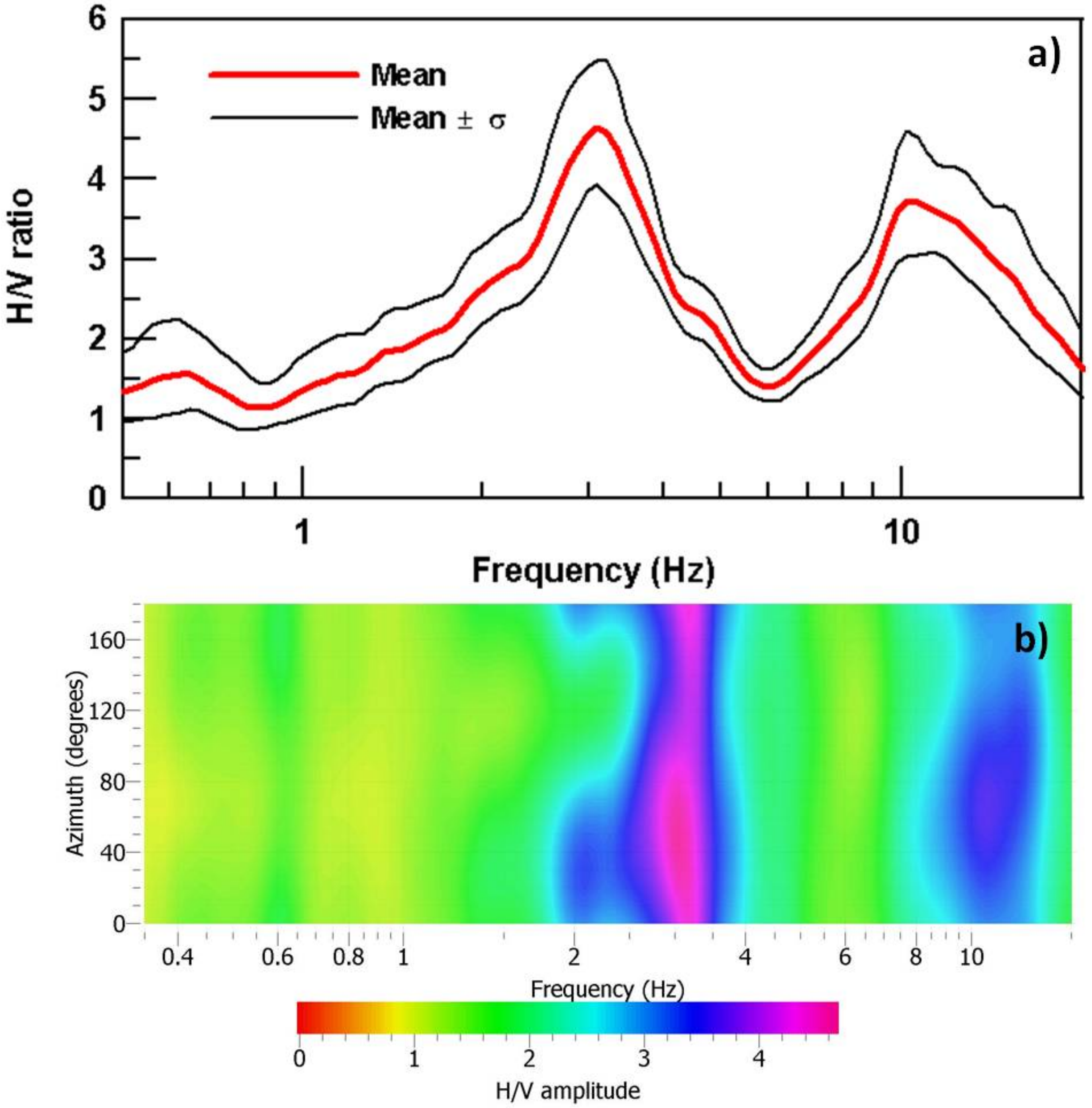
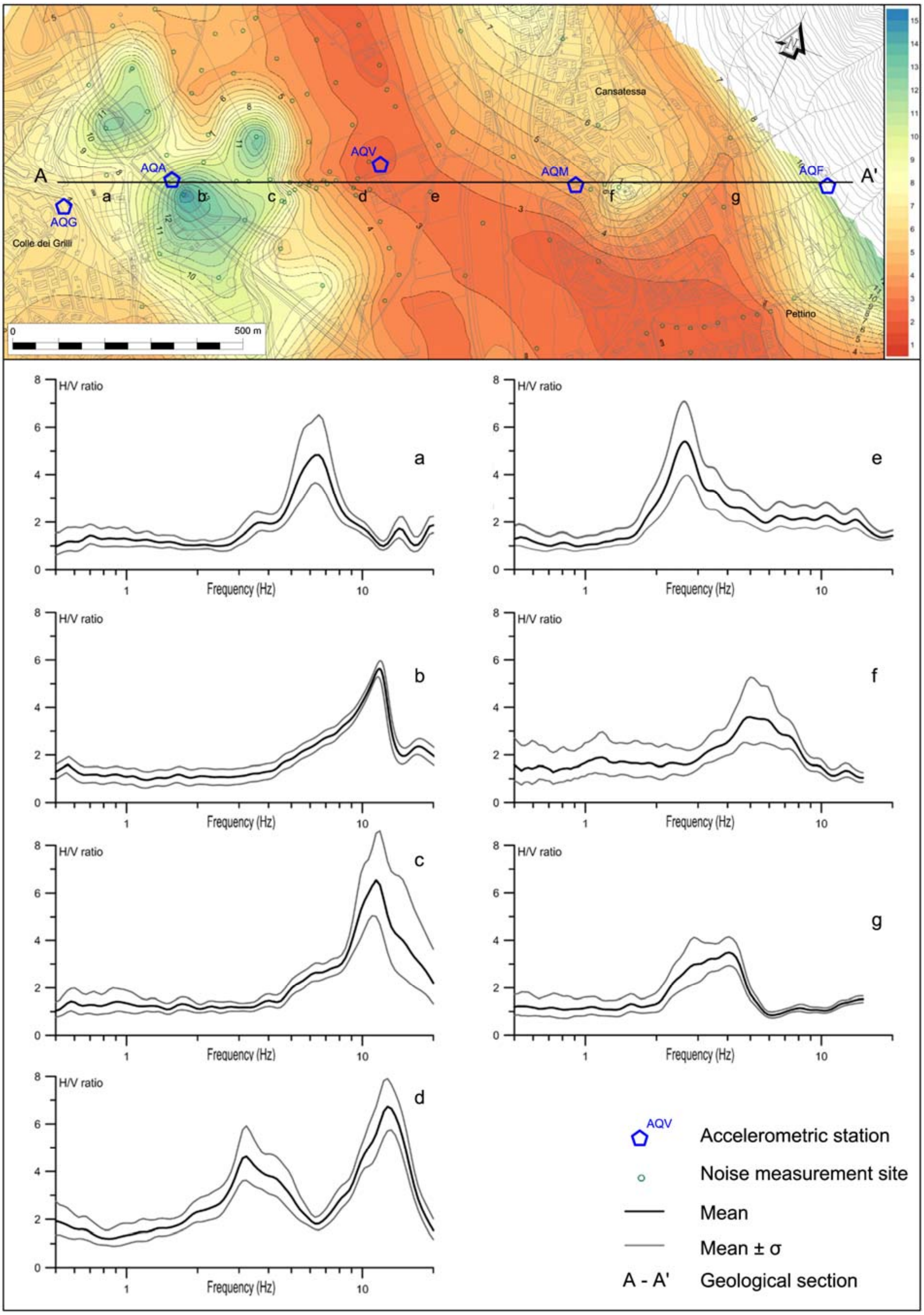


Fig. 9 – H/V curve at AQV site (a) along with directional H/V (b).



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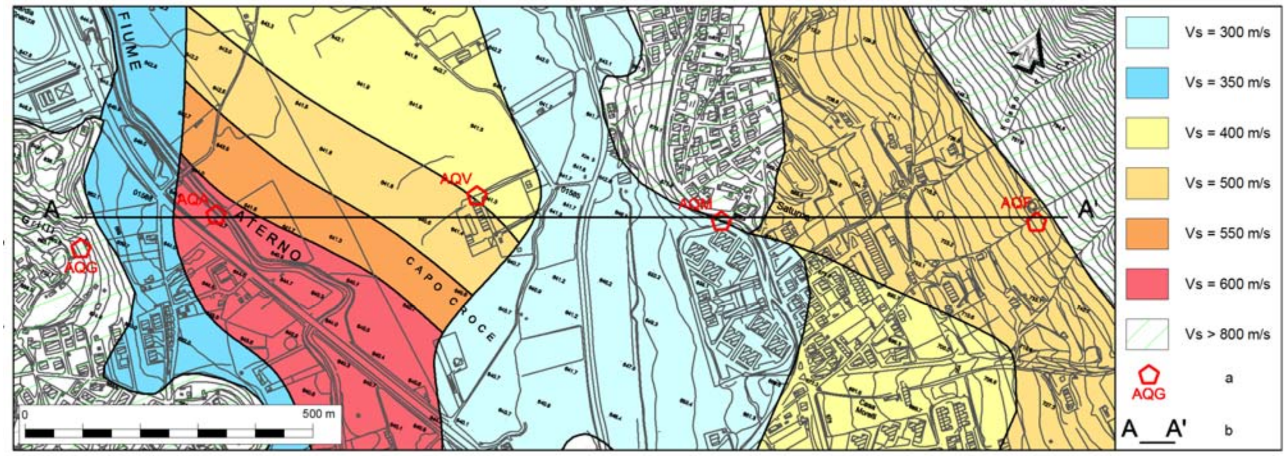
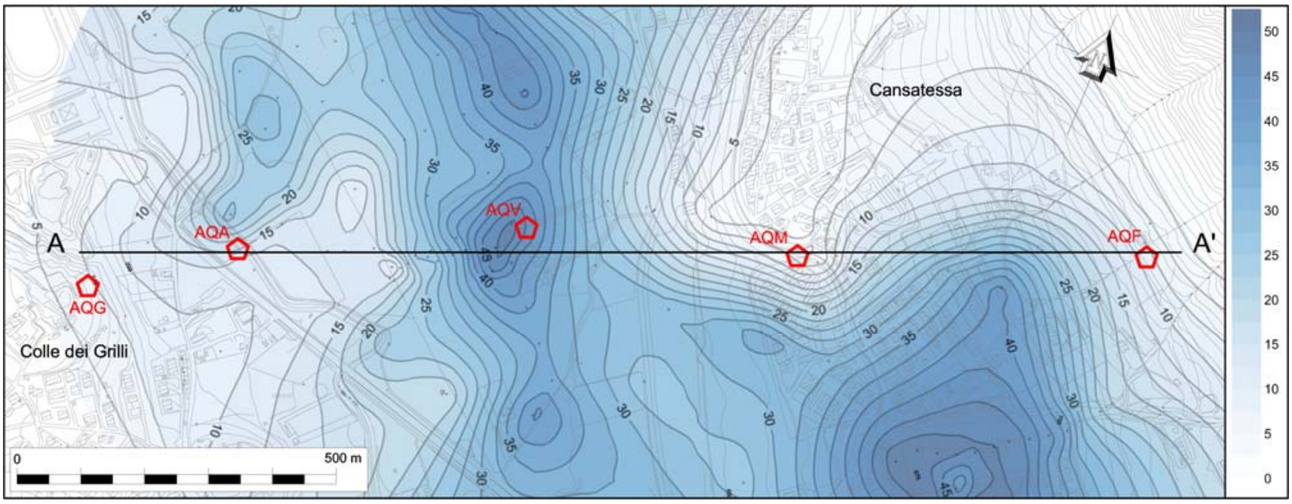


Fig. 11 – Vs values in the studied area. a- RAN station; b- geologic section.



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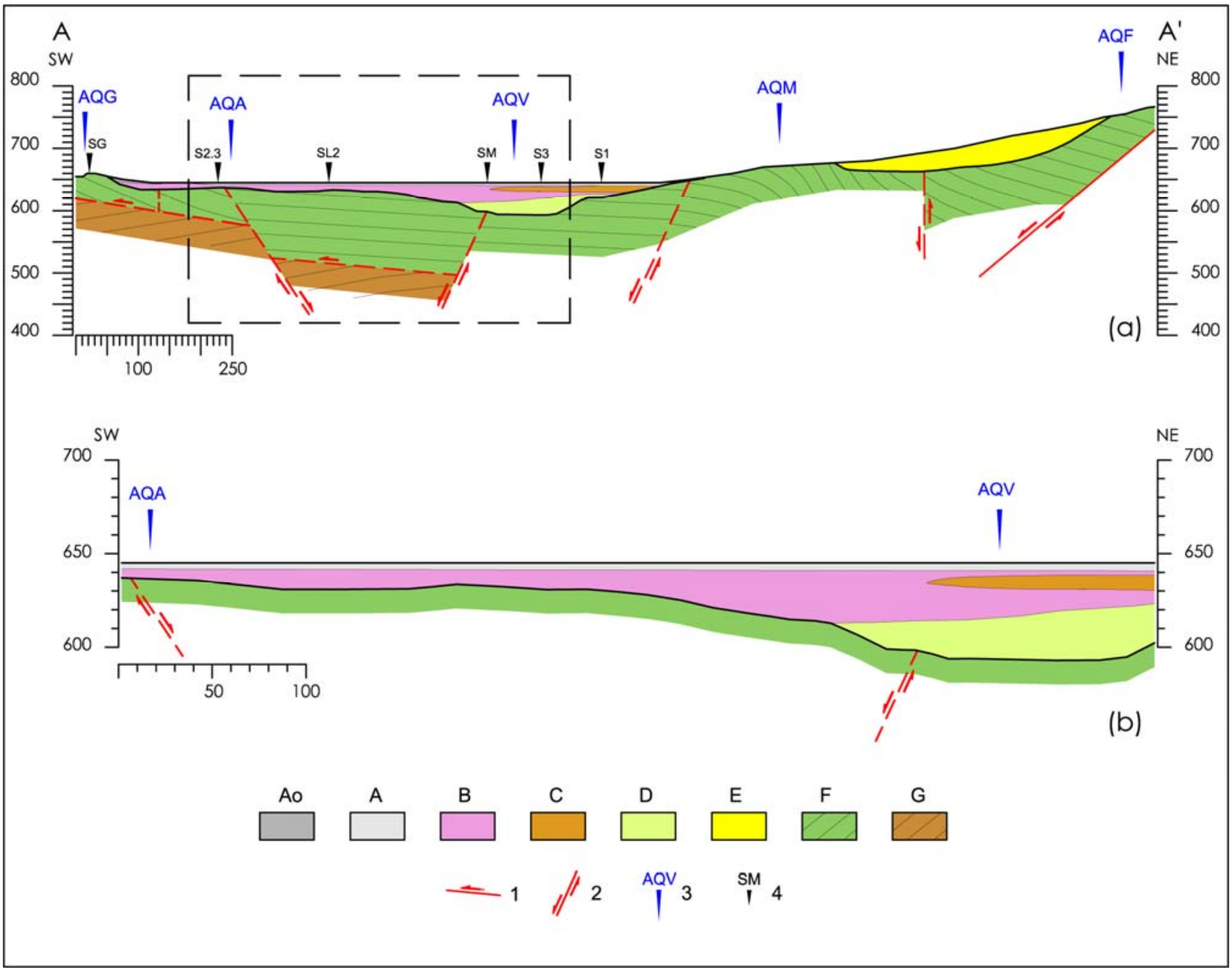

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