Geological and geophysical characterisation of the Paganica - San Gregorio area after the April 6, 2009 L'Aquila earthquake (M_w 6.3, central Italy): implications for site response

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ABSTRACT We present the results of a geological and geophysical investigation, aimed at the seismic microzonation for post-earthquake reconstruction, of the Paganica-San Gregorio area damaged by the April 6, 2009 L'Aquila earthquake. The area is characterised by a thick pile of lacustrine and alluvial deposits (up to 190 m thick or more) accumulated syntectonically within a NW-SE extensional tectonic basin and covering a morphologically and structurally articulated carbonate bedrock. The extensive cover of continental deposits justifies the widespread local stratigraphic amplifications of the ground motion measured by passive seismology (weak motion and noise), with some apparently contradicting results such as the absence of significant amplification peaks within the large Paganica alluvial fan. In general, we found an excellent agreement between the results from the spectral ratio analysis of the ground motion and the structural-stratigraphic setting obtained by independent geological (surface and well data) and geophysical (ERT) constraints. Besides the 1D amplification effects, spectral ratio analyses revealed significant amplifications over a broad frequency range along both the horizontal and vertical components suggesting that 2D (or possibly 3D) site effects are related to the architecture of the buried bedrock.

1. Introduction

Soon after the April 6, 2009 normal faulting L'Aquila earthquake (M_w 6.3), the Italian National Department of Civil Protection (DPC) promoted and coordinated intensive geological and geophysical investigations aimed at the seismic microzonation of the mesoseismal area (MCS intensity ≥ VII) for post-earthquake reconstruction applications. The mesoseismal area was divided into 12 macroareas (see www.protezionecivile.it under *"Microzonazione Sismica dell'area aquilana"*) with the aim of zoning these areas following the Guidelines and Criteria proposed by the Gruppo di Lavoro MS (2008).

We present part of the results pertaining to macroareas 3 and 5. In particular, we show the results from the area including the Paganica, Tempera, Bazzano (industrial area), Onna and San Gregorio localities, all belonging to the municipality of L'Aquila (Fig. 1). These localities are situated 6 to 10 km east of the April 6 epicentre and suffered damages of up to IX-X on the MCS scale [Paganica VIII, Tempera IX, Bazzano VIII, San Gregorio IX and Onna IX-X; Galli *et al.* (2009)].

The surface geology has been constrained by detailed (1:5,000 scale) geological surveys and has been integrated with pre-existing and newly-acquired well data. The pre-existing data consists mostly of stratigraphic reports of water wells linked to the Italian National Law n. 464/1984 (made available by ISPRA, the Italian Institute for Environmental Protection and Research) and several geognostic wells made available by independent professionals. We drilled six new geognostic wells for stratigraphic and mechanical characterisation of the continental cover deposits. We also acquired a number of geophysical data to characterise the sub-surface stratigraphy and the related shear wave velocities, as well as the local seismic response. The geophysical analyses included electric resistivity tomographies, multichannel analyses of seismic waves, refraction microtremor analyses, down-hole experiments and seismic recordings of both

Fig. 1 - Geological map of the Paganica - Tempera - Onna - San Gregorio area with synthesis of the results from the weak motion (squares) and ambient seismic noise (circles) measurements; the stations with significant amplification of the vertical component are highlighted by an asterisk (number in brackets indicates the frequency in Hz of the amplification peak along the vertical component). Labelled boreholes are reported in the sections of Figs. 2 and 6 (ww = water well; D = pre-existing geognostic well; DH = newly-drilled geognostic well with down-hole). PQB) Pre-Quaternary carbonate bedrock (Early Cretaceous - Miocene); Lac-s) stratified, very stiff-to-cemented white carbonate silt and sandy-silt of lacustrine environment (Early Pleistocene); Lac-g) clino-stratified, medium-to-coarse, very dense gravel and conglomerate with rounded grains in a white-greyish silty (lacustrine) matrix (Early-Middle(?) Pleistocene); Br) slope-derived, massive, coarse-to-very coarse breccia, partially etheropic with Lac-g (Middle(?) Pleistocene); Fan1) coarsely stratified, medium-to-coarse conglomerate or very dense gravel and sandy gravel with rounded/sub-rounded grains of alluvial fan environment containing paleosols and tephra horizons (Middle Pleistocene, lower part); Fan2) coarsely stratified, medium-to-coarse, dense gravel, locally cemented, with rounded/sub-rounded grains in a sandy-silty matrix of alluvial fan environment containing silty paleosols with volcaniclastic material (upper part of Middle Pleistocene - Late Pleistocene(?)); All2) Terraced fluvial deposits made up of dense gravel/conglomerate and dense sand (Middle Pleistocene); Fan3) medium-to-coarse, dense gravel, locally poorly cemented, with rounded/sub-rounded grains in sandy-silty matrix of alluvial fan environment (Late Pleistocene); All3) Terraced fluvial deposits made up of alternating, coarsely stratified, medium dense gravel and sand (Late Pleistocene); Db) slope-derived, poorly dense or loose angular gravel in silty-clayey matrix (Late Pleistocene - Holocene); Coll) eluvium-colluvium made up of soft silt and clay with scattered gravel grains (gravel increasing toward the slope foot) (Latest Pleistocene - Holocene); Fan4) fine-to-coarse, poorly dense or loose gravel with sub-angular grains in a silty-sandy matrix, with interlayers of poorly dense sand (Holocene); All4) modern and recent fluvial deposits made up of poorly dense or loose gravel, sandy gravel, sand and silty sand (Holocene); Bf) human backfill and waste material (present).
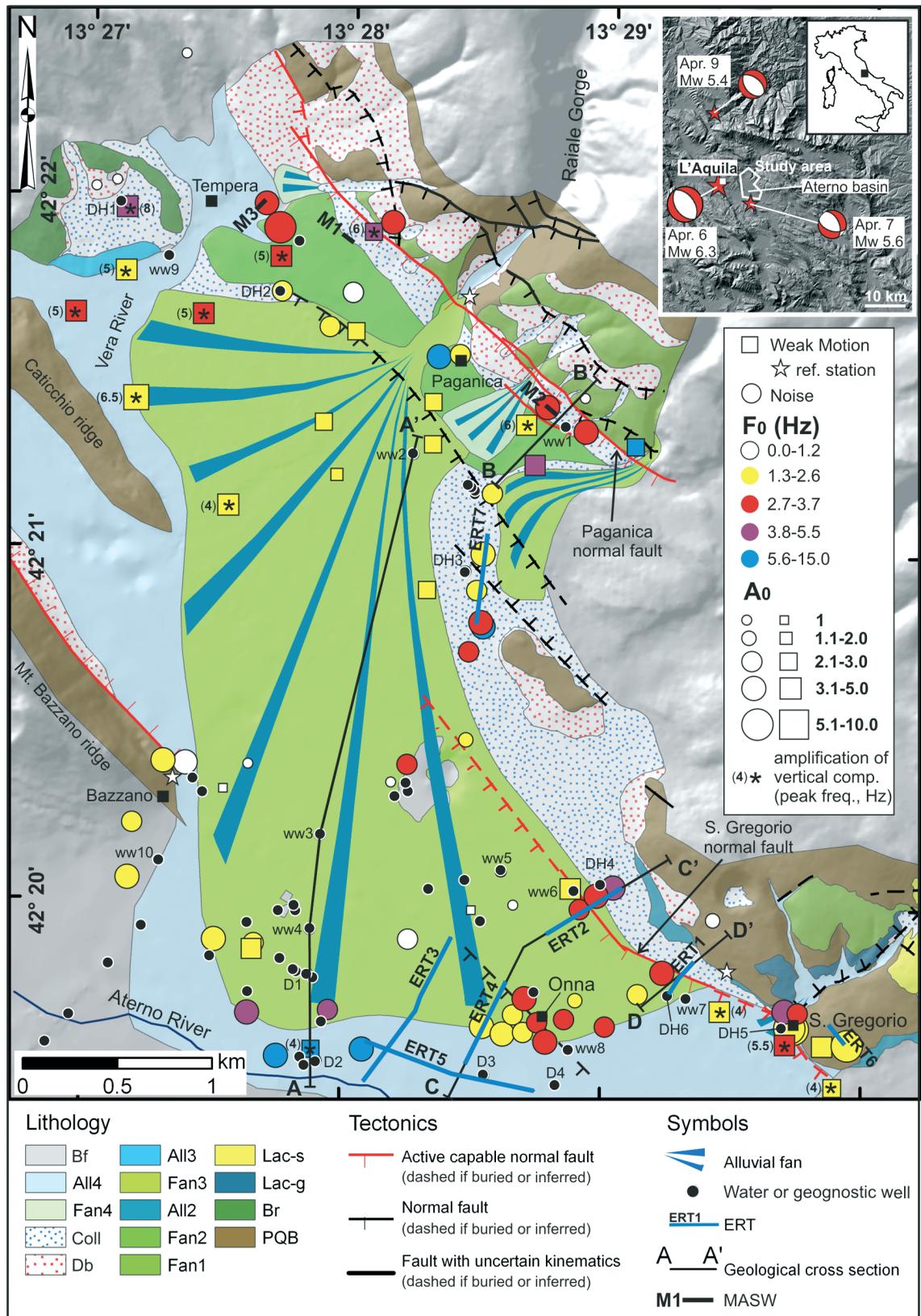
ambient noise and earthquakes.

In this note, we deal with the geological aspects of the seismic microzonation (i.e., the geological model), and we discuss the implications, in terms of site response, based on noise and earthquake recordings. The results from this study might have implications for both: a) the methodological approach to the seismic microzonation in areas of comparable geological setting and elsewhere and b) the post-earthquake reconstruction and future land-use planning of the investigated area. In fact, the geological model, such as that presented here, is the first, basic step for any subsequent quantitative estimates of the site response to ground shaking, which in turn is a useful tool for:

i)   defining priorities in the reconstruction phase;

ii) deciding the best typology of construction during the repair/reconstruction phase;

iii) identifying areas with the highest amplifications that should be excluded from new urbanisation, and

iv) urban planning in general. Examples of quantitative site response studies in the form of maps of amplification factors and acceleration response spectra for the L'Aquila area are given in Gruppo di Lavoro MS-AQ (2011) [for the macroarea 3, also Compagnoni *et al.* (2011)].

During the seismic microzonation, we also mapped a number of zones affected by local hazard due to coseismic surface faulting/fracturing along the Paganica and San Gregorio normal faults that were reactivated during the April 6 earthquake. Though this is an important aspect of the seismic microzonation, it will not be discussed here. In fact, this topic requires an adequate description/discussion, and we will deal with it in a separate note.

2. Surface geology

The Paganica - San Gregorio area is located within the Middle Aterno intramountain basin. This is a tectonic basin elongated in the NW-SE direction, which was formed during the Quaternary extensional tectonics and is bordered by normal faults (Bosi and Bertini, 1970; Bagnaia *et al.*, 1992; Bertini and Bosi, 1993; Vezzani and Ghisetti, 1998; APAT, 2005). The normal master fault, bordering the basin to the NE, is the SW-dipping Paganica normal fault, which belongs to the Mt. Stabiata - Paganica - San Demetrio fault system (Bagnaia *et al.*, 1992; Bertini and Bosi, 1993; Boncio *et al.*, 2010). This is the westernmost fault of a set of normal faults offsetting and lowering the Meso-Cenozoic carbonate units of the Gran Sasso Range towards L'Aquila (SW). Antithetic normal faults (NE-dipping) delimit the basin to the SW.

Several geological, seismological and geodetic data clearly indicate that the Mt. Stabiata - Paganica - San Demetrio fault system is the seismogenic master fault of the April 6, 2009 earthquake (Anzidei *et al.*, 2009; Atzori *et al.*, 2009; Chiarabba *et al.*, 2009; Cirella *et al.*, 2009; Falcucci *et al.*, 2009; Galli *et al.*, 2009; Pondrelli *et al.*, 2009; Walters *et al.*, 2009; Boncio *et al.*, 2010). Coseismic surface faulting occurred along the central-northern portion of the system, particularly along the Paganica segment (see Fig. 1), where the ground surface was offset with dip-slip displacements up to nearly 10 cm (EMERGEO Working Group, 2009; Falcucci *et al.*, 2009; Galli *et al.*, 2009; Boncio *et al.*, 2010; ISPRA at www.apat.gov.it). Coseismic fracturing was also observed along the San Gregorio normal fault. This fault was interpreted as a major

synthetic splay of the Mt. Stabiata - Paganica - San Demetrio system that was reactivated to nearly the ground surface during the April 6 main shock [Fig. 1; Boncio *et al.* (2010)].

The basin at the hanging wall of the Paganica fault system is filled with Quaternary continental deposits. The interior of the basin is articulated by a number of NW-SE-elongated ridges formed by pre-Quaternary carbonate rocks and emerging from the continental deposits (Fig. 1). East of Paganica, the pre-Quaternary bedrock is formed by Lower Cretaceous massive limestones passing upwards to Upper Cretaceous - Oligocene stratified limestones, marly limestones and marls and then to Miocene marly limestones. Between San Gregorio and Paganica, the bedrock is composed of Eocene - Oligocene stratified limestones passing upwards to Miocene marly limestones, marls and clayey marls (APAT, 2005).

The continental deposits of the basin infill are formed by several sedimentary units of Early Pleistocene-to-Holocene age. The oldest continental deposits (Early Pleistocene) crop out east of San Gregorio and can be referred to as the "Poggio Picenze" and "Vall'Orsa" sedimentary cycles according to Bertini and Bosi (1993). They are formed by very stiff or cemented white and greyish lacustrine carbonate silt with sand interbeds [Lac-s unit in Fig. 1; "Limi di San Nicandro" of the Poggio Picenze cycle, Bertini and Bosi (1993)], capped by clino-stratified, grain-supported, very dense gravels and conglomerates in a white silty matrix [Lac-g unit; Vall'Orsa cycle, Bertini and Bosi (1993)]. They represent the infilling of a wide tectonic lake of Early Pleistocene age that was closed upwards by coarse-grained fan deposits that prograded within the lake in the predominant ENE-WSW direction (Bosi and Bertini, 1970; Bagnaia *et al.*, 1992; Bertini and Bosi, 1993). The most widespread continental deposits are younger alluvial fan and fluvial sediments which piled syntectonically during Middle and Late Quaternary times and which covered the above-mentioned older lacustrine deposits. The prevailing texture is gravel and sandy-silty gravel, with increasing percentages and interlayers of fine-grained sediments (sand and silt) towards the Aterno River, where alluvial fan and fluvial deposits become interfingered.

We distinguished 3 fan units, cropping out between Paganica and the Aterno River. The oldest fan unit (Fan1) is tectonically uplifted at the footwall of the Paganica normal fault and is internally offset by normal faults, that originated tectonic terraces. This unit covers the carbonate bedrock and is formed by coarsely stratified conglomerates or very dense gravels and sandy gravels with interlayers of paleosols and tephra horizons of Middle Pleistocene age (Messina *et al.*, 2009). A younger fan unit (Fan2), tentatively referred to as the upper part of the Middle Pleistocene - Late Pleistocene age, crops out at the hanging wall of the Paganica normal fault and represents the unit where the largest part of the Paganica village is founded. It consists of dense sandy-silty gravels that are locally cemented and coarsely stratified. This unit is probably coeval with the terraced alluvial gravels, conglomerates and sands cropping out NW of San Gregorio (All2 unit). The widest outcropping unit, of Late Pleistocene age, corresponds to the large alluvial fan developing between the mouth of the Raiale gorge and the alluvial plain of the Aterno River (Fan3). The unit shows typical fan morphology with the upper depositional surface gently sloping (2-4%) towards the Aterno River. A number of outcrops along quarry walls show that the prevailing lithology consists of medium-to-very dense or slightly cemented gravels and sandy-silty gravels that contain thin, laterally discontinuous interlayers of yellowish sands. The outcropping thickness of the unit is ≥15 m. The available water well stratigraphies suggest that the unit is up to 30-35 m thick; it passes downwards to older gravels, probably correlated to the

fan units cropping out near Paganica (Fig. 2). Close to the Aterno River, the Fan3 gravels are covered by fluvial deposits of Holocene age (mostly sand and silt, All4 unit). These fluvial deposits pass downwards to older fluvial units of the paleo-Aterno River that are in lateral continuity with the fan deposits (sand and silt with gravel interbeds; Flu-Lac of Figs. 2 and 3, observed only in geognostic wells). Other recent fluvial deposits (mapped as All4 unit in Fig. 1) made up of gravels, sandy gravels and sand crop out along the Vera River and between the Caticchio and Mt. Bazzano ridges. Coarse-grained bodies of loose-to-variously dense, slope-derived gravels in a silty-clayey matrix (Db unit) or fine-grained eluvial-colluvial covers (Coll unit; silt and clay, with subordinate gravel) crop out at the foot of the topographic ridges. Recent alluvial fans (Fan4 unit) are located at the outlet of small valleys in the Paganica area and local covers of backfill and waste material are widespread within villages and industrial areas (Bf unit).

3. Geognostic and geophysical investigations

To characterise the sub-surface geology with particular attention to the continental deposits, we performed a number of geophysical and geognostic investigations. The choice of type, number and location of the investigations was conditioned by three main factors:

1) the identification of sites/transects considered key areas for the reconstruction of the sub-surface geological model;
2) the location of sites considered strategic for the post-earthquake construction/reconstruction strategies; and
3) the budget.

We acquired 7 electric resistivity tomographies (ERT in Fig. 1), 3 multichannel analyses of seismic waves (MASW) and 13 experiments of refraction microtremors and drilled six new geognostic wells (DH in Fig. 1). The geognostic drillings were planned in order to perform the following tasks:

1) integrate the available well data (often characterised by poor stratigraphic reports) with detailed stratigraphic logs;
2) measure the Vs and Vp variations by means of down-hole experiments;
3) calibrate the ERT profiles; and
4) collect samples of fine-grained materials for laboratory analyses.

Below, we synthesise the results from the investigations that provided the most constraining data, which are the DH, ERT and MASW analyses.

3.1. Geognostic well data and shear wave measurements

In Fig. 3, we report the synthetic stratigraphic logs of the six newly-drilled geognostic wells and the velocity profiles obtained by down-hole experiments (see Fig. 1 for location).

The DH5 (30 m deep) and DH6 (38 m) wells are particularly important for the sub-surface characterisation of the area. In fact, they reveal the presence of a thick sedimentary unit of likely fluvial-lacustrine environment not exposed at the surface and probably related to the sedimentary history of the paleo-Aterno River valley (Flu-Lac unit). This unit is mostly composed of brown silty sand and clayey silt containing volcaniclastic material with gravel interbeds and with a general fining-upward arrangement. Along the DH6 well, the Flu-Lac unit is ~28 m thick and is
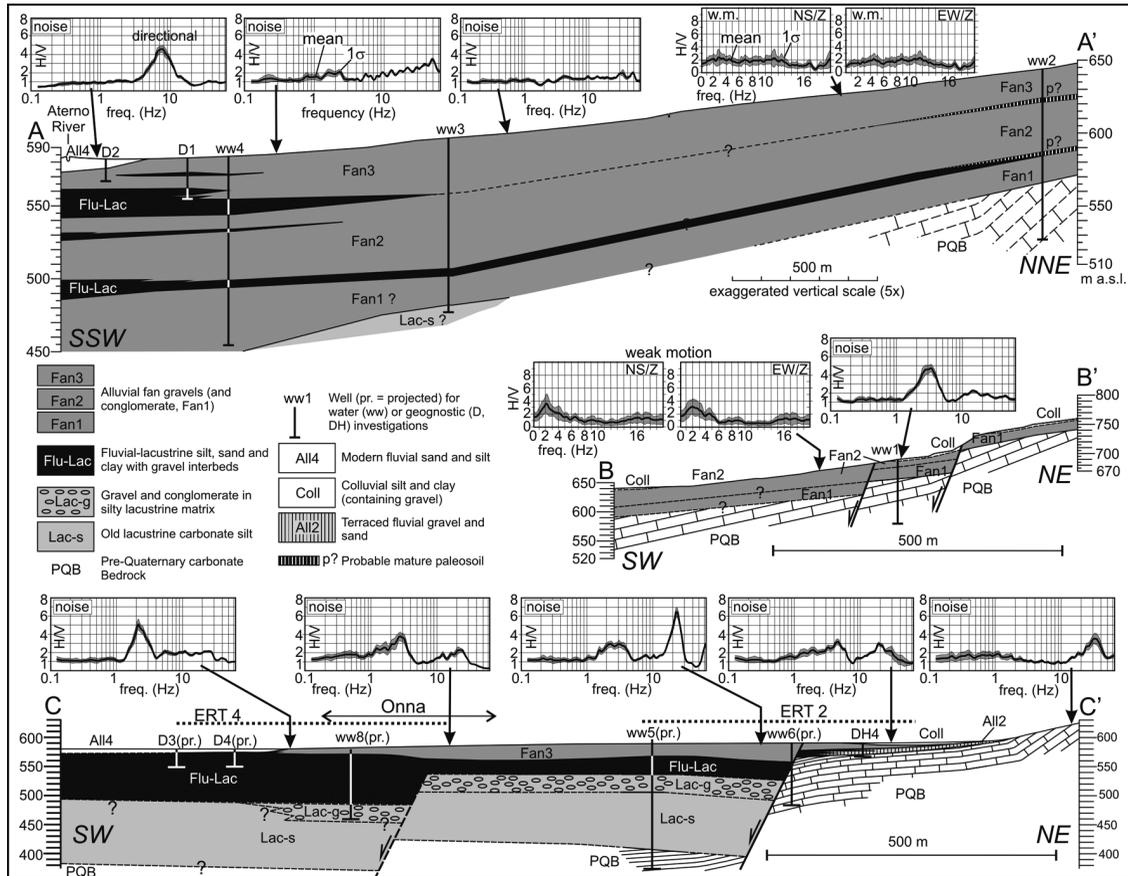
Fig. 2 - Geological sections across the Aterno River - Paganica (A-A', B-B') and San Gregorio-Onna (C-C') areas with examples of HVSR measurements from ambient seismic noise or weak motion (location in Fig. 1). Note that the vertical scale of the A-A' section is exaggerated 5 times.

covered by ~9 m of alluvial fan gravels (Fan3 unit). Downwards, it changes sharply to dense gravels in an abundant whitish silty matrix that can be correlated to the Lac-g unit cropping out east of San Gregorio (see Fig. 1). The DH6 well was used to calibrate the ERT1 profile (see Figs. 1 and 6). Along the DH5 well, the Flu-Lac unit is ~17 m thick and is covered by ~9 m of recent alluvial fan deposits (mostly sands and gravels; Fan3-4 units). The transition to the Lac-g unit was drilled at an ~26 m depth.

The DH4 well (24 m deep) was drilled at the footwall of the San Gregorio normal fault, close to the trace of the ERT2 profile. The well penetrated ~10 m of alluvial fan gravels (Fan3 unit) overlaying a ~10 m-thick interlayering of gravels and fine sediments (clay, silt and sand) that probably represent the interfingering between a coarse-grained fluvial unit (All2, see Fig. 1) and the fluvial-lacustrine deposits of the Flu-Lac unit. At depths of 20.5 m, the well penetrated the top of the pre-Quaternary bedrock (Oligocene-Miocene stratified limestone). This well confirmed that the bedrock at the footwall of the San Gregorio normal fault is relatively shallow.

The DH2 (42 m deep) and DH3 (51 m) wells were drilled at the northern and eastern

terminations of the Paganica alluvial fan, respectively. The DH2 well probably crossed the 3 alluvial fan units recognised in outcrops near Paganica (Fan1, Fan2 and Fan3 units). The Fan3-Fan2 boundary, marked by a thin red pedogenic horizon, was drilled at an ~5 m depth. The Fan2-Fan1 boundary, at an ~35 m depth, was interpreted as corresponding to a sandy horizon, rich in volcaniclastic material. Below this depth, very dense gravels and conglomerates were drilled (Fan1 unit). The DH3 well revealed a few meters of colluvial deposits and then a 42 m-thick pile of dense gravels and sandy-silty gravels. We interpreted these deposits as belonging to the Fan3 and Fan2 units, but a stratigraphic boundary between the two units was not recognised. The well ended within brown sandy-silty sediments that probably represent an interlayer of fine-grained deposits in the coarse-grained alluvial fan succession (possibly correlated to the Flu-Lac unit; see section A in Fig. 2).

The DH1 well (40 m deep) was drilled west of the Tempera village and penetrated a stratigraphy significantly different from that of the DH2 and DH3 wells. Colluvial deposits, ~5 m thick, cover an 11-12-m thick sedimentary unit composed of brown fine-grained sediments, containing volcaniclastic material, likely of a fluvial-lacustrine environment that we tentatively correlate to the Flu-Lac unit. This unit covers an ~8 m-thick body of well cemented breccia in a pink matrix that can be correlated to the outcropping Br unit (Fig. 1). Then, the well crossed more than 15 m of dense gravels, in an abundant whitish silty matrix that is lithologically similar to the Lac-g unit seen in outcrops near San Gregorio and recovered from the bottom of the DH5 and DH6 wells.

The Vs and Vp curves, shown in Fig. 3, were obtained by means of down-hole experiments. The errors were determined by taking into account that the measurements were executed from the top to the bottom of the borehole and in the opposite direction (from bottom to top) using 4 m interval spacing. The down-hole survey time errors were always lower than 5% (~0.5 ms), which corresponds to the sampling interval.

The Vs values measured along the six wells can be grouped in three classes:

1) the first class is characterised by low Vs (<300-350 m/s) and corresponds to the top few meters of the sedimentary cover or to the Flu-Lac unit; the latter can have Vs values as low as 100-200 m/s (e.g., DH6). Peaks in the Vs profile within the Flu-Lac unit (up to 500-600 m/s at depths >15 m) are related to the presence of gravel beds;

2) the second class corresponds to the upper alluvial fan units (Fan2, Fan3), with Vs increasing progressively with depth, to values of ~500-600 m/s at depths of > 3-5 m and up to 600-750 m/s for depths of > 10 m (DH2, DH3 and DH4). Variations along the Vs profile and peaks up to 800 m/s can be related to different degrees of compactness/cementation (e.g., DH3); and

3) the third class is characterised by high Vs (>750-800 m/s) and corresponds to the pre-Quaternary carbonate bedrock (Vs up to 1150-1200 m/s at depths of 22-24 m; DH4) or to very dense/cemented continental coarse granular deposits such as the well cemented breccia (e.g., Br in DH1), the very dense or cemented gavels of the Fan1 unit (e.g., DH2) and the very dense gravels in the white silty matrix of the Lac-g unit (e.g., DH1 and DH5).

The Vp/Vs ratio, that evaluates the porosity and degree of fracturing and lithification of the deposits is particularly interesting. Based on the assumption that the pore structure influences the Vp and the Vs differently, Vp/Vs can be used to extract various rock properties. It is evident that
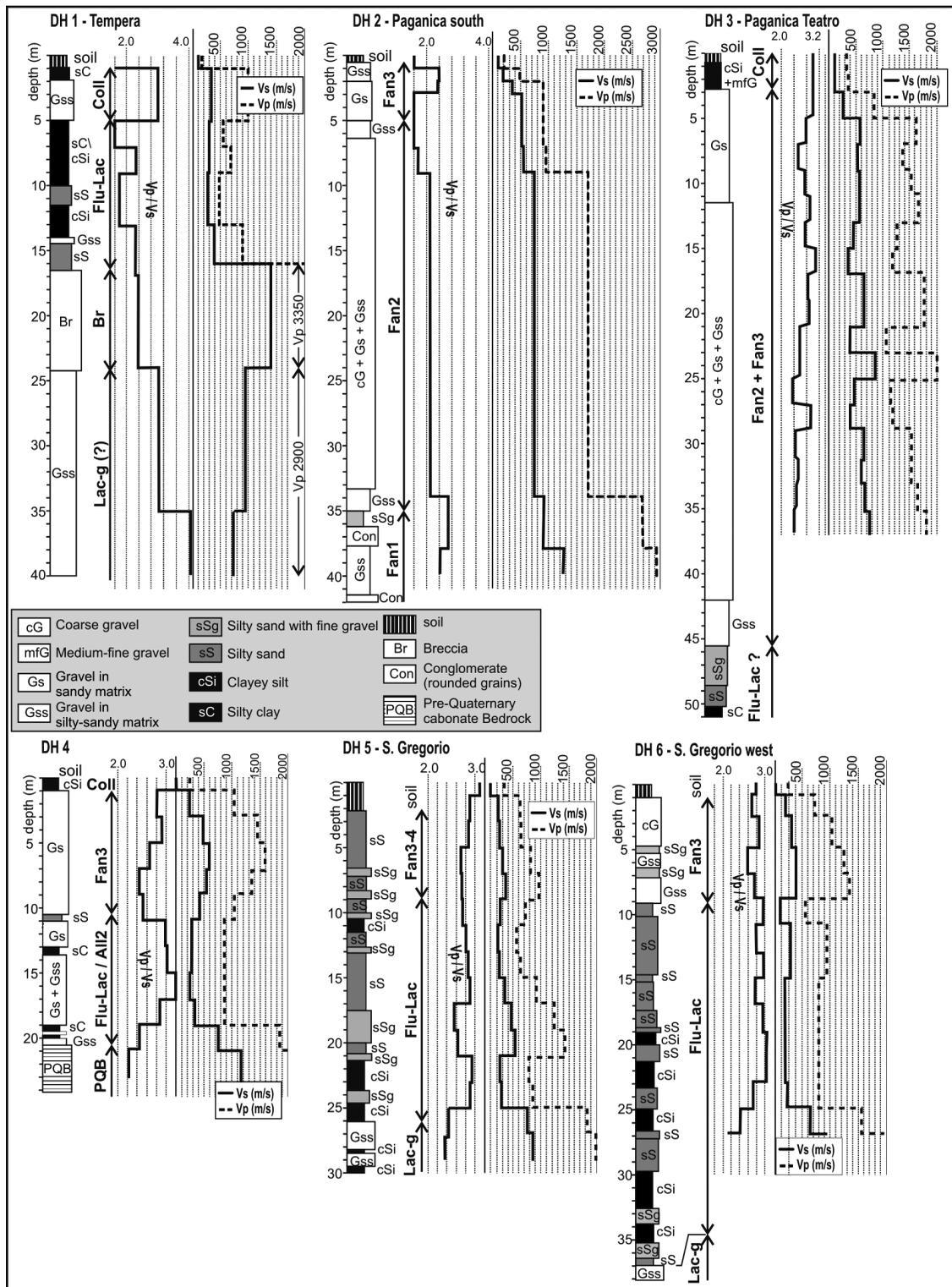
Fig. 3 - Stratigraphic logs for the six newly-drilled, geognostic wells and associated Vs, Vp and Vp/Vs profiles from down-hole experiments (location in Fig. 1); abbreviations for geologic units are as in Figs. 1 and 2.
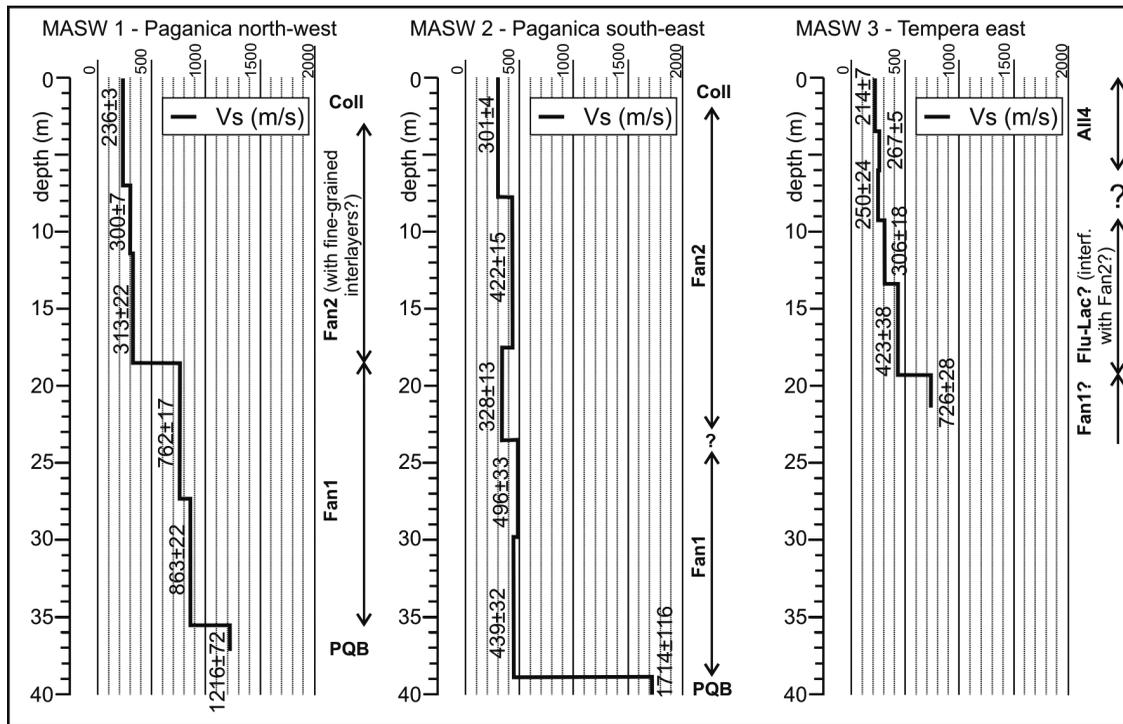
Fig. 4 - Vs profiles from multichannel analysis of seismic waves (MASW) in the Paganica and Tempera villages (see Fig. 1 for location) and possible correlation to the geological units (see Figs. 1 and 2).

in the DH1, DH3, DH4 and DH5 profiles, there are several Vp/Vs anomalies. These anomalies can be characterised by a low Vp/Vs (DH4, 7-11 m depth; DH5, 17-21 m depth) that probably indicates a low porosity medium under dry conditions or a high Vp/Vs (DH1, 1-5 m depth; DH4, 15-17 m depth) that can be ascribed to a high porosity, saturated medium.

Additional data about the Vs profile for the alluvial deposits was derived from three MASW experiments performed between the Paganica and Tempera villages (Fig. 4; see Fig. 1 for location). The root-mean-square (RMS) error was used as an indicator of the closeness between the two dispersion curves (measured and theoretical), and the final solution was chosen as the 1D Vs profile resulting in a preset (small) value of RMS (Xia *et al.*, 1999):

$$\varepsilon_i = \alpha_M - \alpha_T$$

where α_M and α_T are the phase velocities of measured and theoretical dispersion curves, respectively. The ε_i value determined for our data was lower than 1 %.

The MASW1 Vs profile, measured on the north-western side of the Paganica village, suggests the presence of two units overlaying a high velocity substratum ~35 m deep (Vs=1216 m/s). The upper unit, capped by a thin cover of colluvial deposits, is ~15 m thick, has a Vs of 240-310 m/s and can be correlated to the Fan2 unit. This unit probably contains interlayers of fine-grained

sediments (sand, silt), which reduce the overall average Vs compared to prevailing gravels (e.g., MASW2). The lower unit is ~17 m thick with a Vs of 760-860 m/s and is probably correlated to the Fan1 unit.

The MASW2 Vs profile, measured on the south-eastern side of the Paganica village, suggests the presence of continental cover deposits overlaying a high velocity substratum ~39 m deep (Vs=1714 m/s). This substratum depth is fairly consistent with the depth of the carbonate bedrock as reported by the stratigrafic log of the ww1 water well (carbonate bedrock at 33 m depths; see section B in Fig. 2). There are no sharp Vs variations within the cover deposits and the correlation to the Fan2 and Fan1 units can only be inferred. The first 23 m, that are possibly correlated to the Fan2 unit, are characterised by a Vs of 320-420 m/s. The underlying 15 m of cover deposits have a higher Vs (440-500 m/s) and can be tentatively correlated with the Fan1 unit, even if the Vs values obtained seem significantly lower than those measured along both the MASW1 Vs profile (> 750 m/s at depths > 18 m) and the DH2 down-hole profile (> 900 m/s at depths > 33 m).

The MASW3 Vs profile was measured east of the Tempera village, on the fluvial deposits of the All4 unit. The first 6-9 m can be interpreted as the All4 unit, with a Vs of 210-270 m/s. Below a 9 m depth, the Vs increases to 300-420 m/s and then, at a 19 m depth, to 725 m/s. The available wells suggest that the sediments between a 6-9 and 19 m depth are correlated with the Flu-Lac unit drilled by the DH1 well and may be interfingered with the gravels of the Fan2 unit. The sediments below a 19 m depth could be correlated with the Fan1 unit.

3.2. Electrical resistivity tomographies

The electrical resistivity tomography (ERT) is an active geoelectrical method widely applied to obtain 2D and 3D high-resolution images of the resistivity sub-surface patterns in areas of complex geology (Griffiths and Barker, 1993; Dahlin, 1996). It has been proved useful to characterise the geological and structural setting of sedimentary basins in seismogenic areas (Giano *et al.,* 2000; Suzuki *et al.,* 2000; Caputo *et al.,* 2003; Galli *et al.*, 2006; Giocoli *et al.*, 2008). In this work, seven ERT surveys were carried out to characterise the sub-surface stratigraphy. Below, we describe three ERT profiles, acquired between the San Gregorio and Onna villages, that are considered the most representative profiles for the reconstruction of the sub-surface geological model of the area (ERT1, ERT2 and ERT4, see Fig.1 for location). The ERT1 was calibrated with the DH6 well. The ERT2 and ERT4 were calibrated by the DH4 well and by a number of pre-existing water well stratigraphies and geognostic drillings located a few hundred meters away from the ERT profiles (see Fig. 1). ERT2 and ERT4 were used to build the C-C' geological section, whereas the ERT1 was used for the D-D' geological section (see next section and Figs. 2 and 6).

Apparent resistivity data were collected with two different arrays (Wenner-Schlumberger and Dipole-Dipole) using a Syscal Pro (Iris instruments) Earth resistivity meter coupled with a multielectrode system (48 electrodes). An electrode spacing range from 5 to 10 m was used and resulted in an investigation depth of approximately 40 and 80 m, respectively. The RES2DINV resistivity inversion software (Loke and Barker, 1996) was used to automatically invert the apparent resistivity data. In all cases, the number of iterations was three with RMS errors ≤5%.

Fig. 5 shows the interpreted inverse model resistivity sections related to the 3 ERT profiles. Overall, the electrical images show a relatively low resistivity range, from 50 to over 566 Ω·m, and a resistivity pattern characterised by relatively strong lateral and vertical gradients (especially
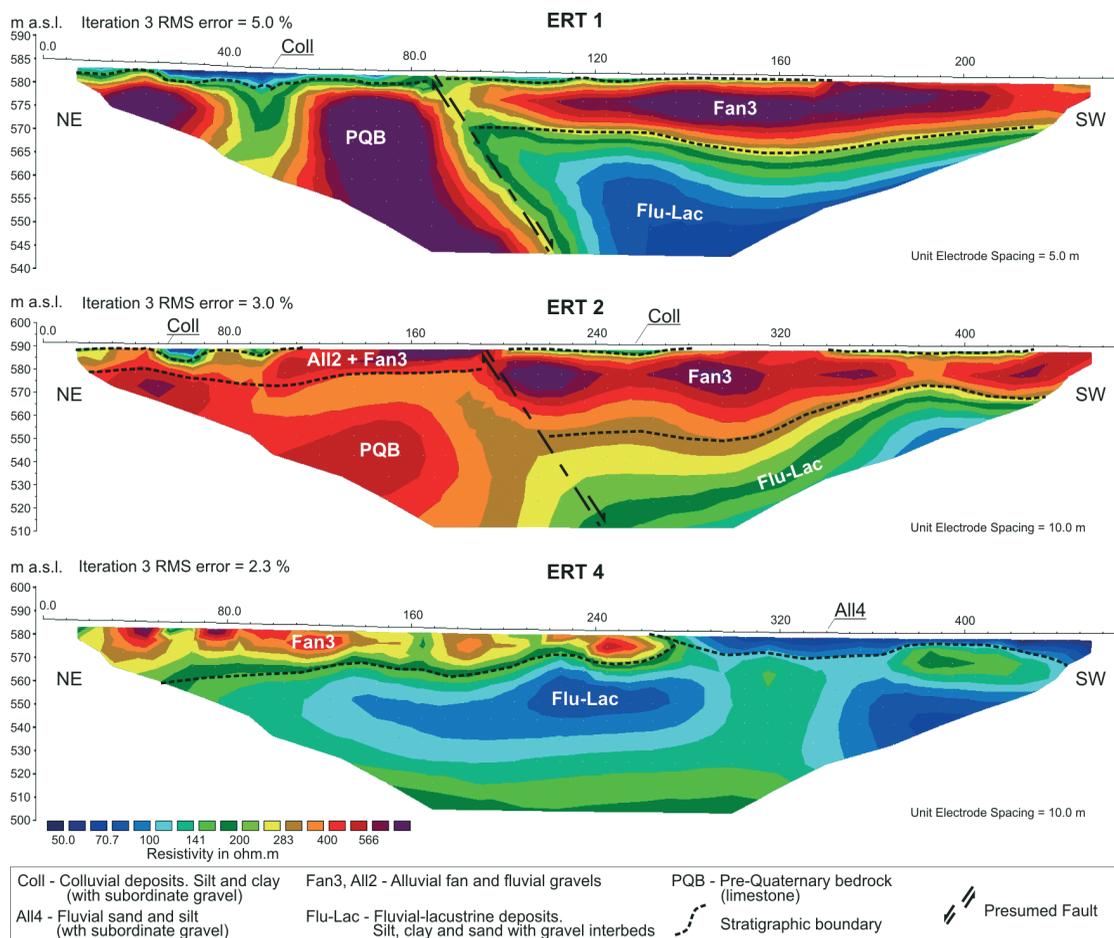
Fig. 5 - Interpreted electrical images across the San Gregorio (ERT1 and ERT2) and Onna (ERT4) areas (see Fig. 1 for location).

in ERT1). On the basis of geological and geognostic data, low electrical resistivity values (from 50 to 140-170 Ω·m) can be associated with sandy-silty fluvial-lacustrine deposits (Flu-Lac unit) and/or colluvial-alluvial deposits (Coll, All4 units), and relatively high electrical resistivity values (> 170 Ω·m) can be related to gravel deposits (Fan3, All2 units) and/or pre-Quaternary carbonate bedrock (PBQ). Finally, the occurrence of strong lateral discontinuities in the resistivity distribution in ERT1 and ERT2 could be due to the presence of the SW-dipping San Gregorio normal fault.

4. Sub-surface geological model

The sub-surface geological and geophysical data allowed us to assess the geometry of the sedimentary bodies filling the basin and their relations with the pre-Quaternary bedrock. The sub-surface geology of the area is synthesised along three geologic sections (Fig. 2). Sections A
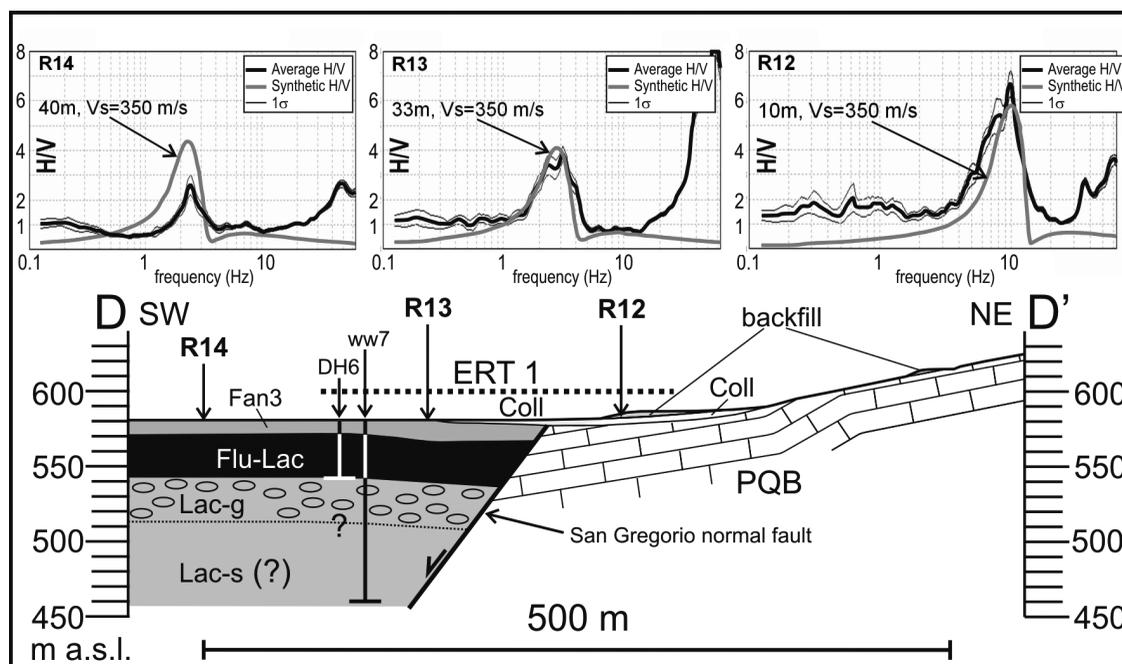
Fig. 6 - Geological section across the San Gregorio normal fault constrained by surface geology, newly-acquired geognostic well with down-hole experiment (DH6) and electrical tomography (ERT1) (see Fig. 1 for location). R12 to R14 indicate HVSR curves from seismic noise measurements; the gray curve indicates the synthetic HVSR obtained from the inversion method by Castellaro and Mulargia (2009) (string on the left side indicates the inverted bedrock depth and average Vs of the sedimentary cover).

and B, cross the fan units longitudinally from the Aterno Valley to the town of Paganica. Section C, crosses the flat alluvial plain near Onna, the lateral termination of the Paganica fan and the western border of the San Gregorio carbonate ridge. An additional section (section D, Fig. 6) shows details across the San Gregorio normal fault.

The Quaternary continental deposits, progressively thicken from NNE to SSW, mostly due to the tectonic setting. At the footwall of the Paganica normal fault (section B), the Fan1 unit has an estimated thickness of ~20 m close to the normal fault and thins progressively to the NE. At the hanging wall of the normal fault, a water well (ww1 in Figs. 1 and 2) penetrated the carbonate bedrock at a depth of 33 m, below a cover of fan gravels (Fan1 and Fan2 units). Moving to the SW, synthetic normal faults down-fault the bedrock (see Fig. 1) to the SW, determining a progressive step-like thickening of the continental deposits. Close to the south-western side of the town of Paganica, near the apex of the Paganica fan (section A), the top of the bedrock (limestone) was drilled by a water well to a depth of 78 m (ww2 in Figs. 1 and 2) at the hanging wall of a synthetic splay of the Paganica normal fault (see Fig. 1). Along the central-southern part of section A (industrial area), the water wells show a deepening of the top of the bedrock to depths exceeding 120-130 m. The borehole stratigraphies also show an increase of fine-grained sediments (mostly sandy silt and clayey silt), toward the SSW, that form interlayers within the fan gravel deposits up to >10 m thick. This overall increase of fine-grained sediments towards the

Aterno River suggests a transition from coarse-grained proximal fan facies to distal fan facies or fluvial facies.

The sub-surface geology between Onna and San Gregorio is more articulated because of the SW-dipping San Gregorio normal fault (section C). The fault borders the San Gregorio carbonate ridge to the SW. At the footwall of the fault, the carbonate bedrock is outcropping or buried by a thin cover of alluvial, colluvial and slope-derived deposits. Along section C, the carbonate bedrock is ~20 m deep at borehole DH4 (Figs. 2 and 3) and is progressively shallower towards the NE. Along the ERT1 profile, the bedrock at the footwall of the fault is estimated to be as deep as ~5 m (Figs. 5 and 6). At the hanging wall of the fault, the continental deposits sharply thicken. Water well stratigraphies indicate a maximum depth of the carbonate bedrock of ~190 m (well ww5 in section C). More specifically, the stratigraphy of the continental deposits at the hanging wall of the fault, constrained by both pre-existing and newly-drilled wells, is characterised by:

1) a shallow unit made up of gravels (Fan3 unit, 10-20 m thick) that become progressively thinner towards the South and SE. Along the ERT profiles, these deposits are characterised by high resistivity values (>170 Ω·m, Fig. 5);

2) below the Fan3 unit, there are fine-grained deposits of fluvial-lacustrine environment composed of sand and silt containing abundant volcaniclastic material with interbeds of gravels (Flu-Lac unit). Along the ERT profiles, these deposits are characterised by relatively low resistivity values (from 50 to 140 Ω·m, Fig. 5). Moving from section C to the NW, halfway between sections C and A, the unit Flu-Lac probably starts to be heteropic with the fan gravels of the Fan2 unit;

3) below the Flu-Lac unit, there is a unit made up of gravels in an abundant white silty matrix, drilled by the DH5 and DH6 wells (Figs. 2 and 3) that can be correlated to the gravels and conglomerates of the Vall'Orsa cycle, cropping out near San Gregorio [Bertini and Bosi (1993); Lac-g unit in Fig. 1]. According to the well ww5, the total thickness of the unit is ~30 m; and

4) considering both the stratigraphy of the well ww5 and the overall stratigraphic setting of the Middle Aterno basin (Bosi and Bertini, 1970; Bertini and Bosi, 1993), it is reasonable to believe that the Lac-g unit is followed downwards by the Lac-s unit [Limi di San Nicandro of Bertini and Bosi (1993); Fig. 1]. Interpreting the stratigraphy of the ww5 well, the estimated thickness of the Lac-s unit is ~100 m, resulting in a total thickness of the continental succession at the hanging wall of the San Gregorio normal fault of ~190 m.

Between the trace of section D and San Gregorio village, the estimated dip-slip offset of the top of the Lac-g unit across the San Gregorio normal fault is ~60 m.

Beneath the village of Onna and westwards, the absence of detailed stratigraphic logs from deep wells prevents reliable reconstructions of the sub-surface. The interpretation proposed in section C is mostly based on the extrapolation of the stratigraphy constrained along the eastern part of the section, with the help of the ERT profiles.

5. Weak motion and ambient seismic noise measurements

To estimate the seismic response of the Paganica-San Gregorio area, we carried out an extensive campaign of weak motion and ambient seismic noise measurements (see Fig. 1 for

location of measuring points).

Three temporary networks of velocimetric stations were installed to collect weak motion measurements. Each station consisted of a Lennartz LE-3D/5s enlarged-band seismometer connected to either a MarsLite datalogger with 20 bits of dynamic range and a sampling rate of 125 Hz or a Taurus Nanometrics datalogger with 24 bits of dynamic range and a sampling rate of 100 Hz. Between April 20 and 27, 2009 and between June 8 and 23, 2009, 17 seismic stations were installed in the Paganica-Tempera areas. During this period, more than 550 earthquakes were recorded. 329 of them with a local magnitude (M_L) between 1.6 and 4.0 and a signal-to-noise ratio (S/N) greater than 15 dB were selected for analysis. To estimate the seismic response of the area between the eastern side of L'Aquila and the industrial area of Bazzano, a temporary network of nine velocimetric stations was installed from June 23, 2009 to July 2, 2009 that recorded more than 290 earthquakes. Of these earthquakes, 105 events with M_L between 1.8 and 3.9 and S/N > 15 dB were selected for analysis. Finally, five stations were installed in the San Gregorio area from June 9 to 24, 2009, and these stations recorded 92 seismic events with S/N > 15 dB.

The weak motion data were analyzed using standard spectral ratio methods including "reference" and "non-reference" site techniques. The Reference Site Method (RSM) evaluates site amplification as the ratio of Fourier spectral ordinates of the motions recorded on soil to the motions recorded by a reference seismic station at the bedrock. Non-reference site methods, also called HVSR (Horizontal-to-Vertical Spectral Ratio) techniques, consist of calculating the horizontal-to-vertical Fourier spectral ratio, or H/V, of earthquake and/or microtremor (noise) recordings. Local earthquake recordings were processed by filtering the signals between 0.2 Hz and 20 Hz and computing the smoothed (applying both a Hanning and a Konno-Ohmachi function) Fourier spectra for signal windows including the S-phase arrival and the majority of the phase energy. Finally, for each site, the H/V ratios and the RSM curves (or H/H_{REF} curves) were derived as the average of all spectral ratios. For each temporary network, a reference station, installed on bedrock outcrop (e.g., limestone), was carefully selected and checked (i.e., flat H/V curve).

The errors associated with the H/V and H/H_{REF} curves and, therefore, with the fundamental frequency and relative amplitude level values, are defined in terms of standard deviation as derived by averaging the spectral ratios. In Fig. 2, in the panels showing the HVSR measurements, the mean values of the H/V curves and the ± 1 standard deviation are indicated. The reliable H/V and H/H_{REF} peak frequencies (F_0) are generally characterised by a standard deviation lower than a factor of 2 (e.g., for a frequency greater than 0.5 Hz) over a frequency range between 0.5 F_0 and 2 F_0.

The results summarised in Fig. 1 point out that significant site effects can be recognised for the Paganica-Tempera and San Gregorio areas and that the value of the fundamental frequency (F_0), as derived from both the H/V and the H/H_{REF} curves, spans between 1.5 and 3.0 Hz for Paganica West and Tempera South, between 2.5 and 3.0 for San Gregorio East and between 2.0 and 3.0 Hz for San Gregorio West. The resonant peak is shifted towards a higher frequency (4.5-8.0 Hz) at sites close to the foot of carbonate ridges and close to the Aterno River. In correspondence with the central body of the Paganica fan, almost negligible site amplification phenomena can be identified at only ~2 Hz. However, the H/H_{REF} curves reveal that most of the

sites, for which the H/V curves indicate a significant amplification effect at the fundamental frequency, have a broad amplification band rather than a single well defined resonant peak. Generally, the H/H_{REF} curves show significant amplification (up to around 5) from the fundamental frequency to frequencies greater than 4 Hz (up to about 9 Hz). Moreover, besides the amplification affecting the horizontal component of motion, the reference site method applied to the weak motion recordings allowed us to discover significant amplification effects along the vertical component (stations denoted by asterisk in Fig. 1) as well. For almost all of the sites characterised by significant site effect, the amplification curves for the vertical component assume values greater than unity over a broad frequency range, which starts from a frequency greater than F_0 and has maximum amplifications between 4.0 and 6.0 Hz.

The ambient seismic noise was measured on 58 sites for an acquisition time of at least 15 minutes with a digital tri-directional trommometer, a high-resolution seismometer whose 24-bit dynamics targets the very low amplitude range, starting from the Brownian motion of the sensor. The HVSR curves were calculated by averaging the HVSR obtained by dividing the signal into non-overlapping windows of 20 s. Each window was detrended, tapered, padded, FF-transformed and smoothed with triangular windows with a width equal to 5% of the central frequency. The average was used to combine E-W and N-S components in the single horizontal (H) spectrum. Average single component spectra were obtained using the same procedure. For each HVSR curve, the relative ± 2 confidence interval is given. Therefore, the errors associated with the fundamental frequency and relative amplitude level values are defined in terms of the standard deviation as derived by averaging the spectral ratios. Moreover, to assess the reliability of the measures, we compared our data not only to the SESAME Project (2004) criteria, but also to the more rigid criteria proposed by Albarello *et al.* (2011). These other comparative criteria include the total duration of the recordings, the temporal stationarity of the spectral ratios, the isotropy of the signal in terms of spectral ratios, the absence of electromagnetic noise, and the overall trend of the HVSR curve.

In the investigated area, the results can be grouped in three main categories (see Figs. 1, 2 and 6):

1) the bedrock outcrops showed flat HVSR curves, as expected, or had limited amplification in the high frequency range (e.g., San Gregorio village);
2) the continental deposits covering the carbonate bedrock had clear peaks at decreasing frequency with increasing sediment thickness; and
3) the central body of the Paganica alluvial fan did not have statistically significant peaks, in agreement with weak motion measurements.

More detailed analyses along the geological sections revealed how the frequency changes are closely connected to the thickness variation of the sedimentary cover (Figs. 2 and 6). Where independent information was available (e.g., along ERT sections), we performed constrained inversions of HVSR following the approach proposed by Castellaro and Mulargia (2009). The velocity estimated using this approach was in agreement with those later retrieved from the down-hole measurements. This indicates that the average velocities so obtained can be used to estimate the sediment thickness when only HVSR measurements are available. Fig. 6 shows an example of such a procedure for a geological section crossing the San Gregorio normal fault and constrained by the DH6 geognostic well and ERT1 profile.

6. Discussion

The Paganica - San Gregorio area is characterised by extensive covers of continental deposits that justify the widespread local stratigraphic amplifications measured by passive seismology. The lithology of the near-surface, cover deposits is certainly dominated by coarse-grained, alluvial sediments (gravels). Nevertheless, in spite of this relatively homogeneous textural characteristic, we observed significant lateral variations of the site response that can be reasonably explained only if we adequately consider:

1) the different degrees of cementation/compactness of granular materials, and most importantly;
2) the sub-surface structural-stratigraphic setting, such as the 3D geometry of the sedimentary bodies, their reciprocal lateral correlations/heteropies and their relations with the architecture of the underlaying carbonate bedrock.

The fan gravels cropping out between the town of Paganica and the Aterno River have different site responses. The oldest fan unit (Fan1), uplifted at the footwall of the Paganica normal fault, has no site amplification because of the high degree of cementation that makes this unit equivalent to seismic bedrock. In contrast, the adjacent Fan2 unit is characterised by significant site amplifications ($2 < A_0 \leq 3.5$) at frequencies (F_0) ranging mostly between 1.5 and 3 Hz, depending on the depth of the bedrock (20 to 40 m). In the central body of the wide Paganica fan (Fan3 unit), the spectral ratio analyses do not show statistically significant amplification peaks. This unexpected result might be explained by both the nearly-constant lithology with depth (grain-supported gravels) and the large sediment thickness (> 75 m) that together determine a lack of significant impedance contrasts with depth. In fact, under these conditions, the spectral ratio methods might be unable to point out the possible expected effects of site amplification. Significant site amplifications were instead pointed out by spectral ratio analyses on the lateral terminations of the fan, where the presence of finer material imbedded within the gravels (distal fan facies) probably determines the more pronounced contrasts of impedance with depth.

Prominent peaks at high frequency (4.5-11 Hz, $3 < A_0 < 5$) are characteristics of the thin sedimentary bodies ($\leq$10 m thick) of colluvial, fine-grained alluvial and slope-derived deposits which may cover both the carbonate bedrock and the alluvial units. Examples are the Aterno River plain west of Onna (soft sandy fluvial deposits covering the alluvial gravels) and the eastern border of the Paganica fan (soft clayey-silty colluvia covering the fan gravels).

Significant variations of the site response occur across the San Gregorio normal fault, due to the variations of both the depth of the carbonate bedrock and the stratigraphy of the continental deposits. At the footwall of the fault, the thin covers of alluvial gravels and colluvial deposits (up to a maximum of 20-25 m) produce amplification peaks at frequency $\geq$ 3.5 Hz (A_0 >3). At the hanging wall of the fault, the carbonate bedrock is much deeper (~190 m). Nevertheless, the seismic bedrock seems not to be represented by the carbonate bedrock, but by the very dense/cemented gravels of the Lac-g unit that is intercepted by the geognostic wells at the hanging wall of the San Gregorio normal fault at depths of 30 to 60 m below the ground surface and deepening north-westwards. The behaviour of the Lac-g unit as a seismic bedrock is supported by both the textural features observed in the outcrop (very dense gravels and

conglomerates) and the geophysical data from the down-hole experiments (DH5 and DH1, Vs > 800 m/s). The frequency of the amplification peaks at the hanging wall of the San Gregorio normal fault (2.5-3 Hz, $2.5 < A_0 < 6.5$) is systematically lower than those measured at the footwall of the fault, which is in agreement with a deeper seismic bedrock.

A further deepening of the seismic bedrock (the top of the Lac-g unit) to depths $\geq$ 60 m, probably due to a SW-dipping normal fault (dashed fault in section C of Fig. 2), might explain the sharp variation in the vibration frequency observed across the Onna village (from 3.0-3.3 to ~2.2 Hz moving from east to west; Fig. 1).

The Lag-g unit is followed downwards, by lacustrine silt that might have thicknesses of up to 100 m (Lac-s unit; see Fig. 2). In the outcrop, the Lac-s unit is characterised by stratified, very stiff/cemented carbonate silt, suggesting a possible behaviour as seismic bedrock. However, direct mechanical characterisations of the Lac-s unit at various depths are lacking, and future site response studies should plan deep geognostic drillings to intercept and characterise this unit (i.e., depths > 60-70 m between San Gregorio and Onna).

It is worth noting that, mainly in the areas towards the north-western border of the Paganica fan and across the San Gregorio normal fault, while the HVSR method applied to earthquakes or microtremors identifies the site's fundamental frequency, the reference site method reveals amplifications within a broader frequency range and indicates the presence of probable multi-dimensional (2D or possibly 3D) site effects. Moreover, as derived from RSM curves, such areas show a significant amplification of the seismic motion along the horizontal components and also along the vertical one (amplifications between 4 Hz and 6 Hz). While 1D amplification effects can be related to the seismic impedance contrast between the bedrock and the overlying alluvial deposits and, in some cases, also to the response of the soil layered system, 2D effects may be attributed to the buried morphology of the study area that is clearly related to the Quaternary synsedimentary activity of the SW-dipping normal faults (i.e., Paganica and San Gregorio faults).

7. Summary and conclusions

From the geological-geophysical investigation of the Paganica-San Gregorio area, we can draw a number of conclusions that are of both local and general interest.

The local conclusions are strictly related to the geological setting of the investigated area and in particular to the basic surface and sub-surface geological model to be used for numerical quantifications of the site response (e.g., amplification factors, acceleration response spectra). These have evident implications in terms of future land-use planning and post-earthquake reconstruction (e.g., definition of priorities and best typology of construction during the repair/reconstruction phase; identification of areas with high amplifications that should be excluded from new urbanisation).

- The geology of the Paganica-San Gregorio area is characterised by a thick pile of Quaternary deposits syntectonically accumulated within an extensional basin and covering pre-Quaternary carbonate bedrock, the top of which is rather articulated due to normal faulting. The normal faults dip mostly to the SW (e.g., Paganica and San Gregorio fault) and determine a general step-like thickening of the continental succession moving from NNE to SSW (i.e., towards the Aterno River), from a few meters to about 190 m or more.

- The continental stratigraphy can be synthetically divided into: 1) old (Early Pleistocene) fine-grained lacustrine deposits (Lac-s) capped by gravels and conglomerates (Lac-g); 2) a Middle-Upper Pleistocene sequence of coarse-grained alluvial fan (Fan1, Fan2 and Fan3), fluvial (All2 and All3) and slope-derived (Br) deposits and fine-grained, fluvial-lacustrine (Flu-Lac) deposits; and 3) thin covers of Upper Pleistocene-Holocene fine-to-coarse-grained alluvium (All4), coarse-grained slope-derived debris (Db), fine-grained, eluvial-colluvial accumulations (Coll) and human backfill and waste material (Bf).

- The seismic bedrock (Vs ≥800 m/s) is represented not only by the pre-Quaternary carbonate rocks, but also by the old (Early-Middle Pleistocene) coarse-grained, very dense/cemented continental alluvial deposits (Br, Fan1 and Lac-g units), provided that their original degree of compactness/cementation is preserved from significant weathering/fracturing. The mapped distribution of these units and their depths below the younger continental units, as well as their lateral continuity, are important targets in planning site response studies. Future site response studies should also plan deep geognostic drillings (> 60-70 m) to intercept and characterise the old lacustrine unit (Lac-s), which represents the lower unit of the continental basin infill and that might have thicknesses up to 100 m or more.

- The mechanical properties of the young fan units (Fan2 and Fan3) are typical of dense gravels, with Vs increasing progressively with depth from 200-300 m/s in the near surface to 500-600 m/s at depths > 3-5 m and up to 600-750 m/s at depths >10 m. The mechanical properties of the fluvial-lacustrine deposits (Flu-Lac) are rather poor, with average Vs generally< 300 m/s and with higher velocities (up to 500-600 m/s at depths >15 m) only corresponding to gravel interbeds.

- The widespread site amplifications highlighted by spectral ratio analyses of both weak motion and noise are mostly due to the stratigraphy of the continental deposits, especially the stratigraphy of the upper part of the continental succession (above the Lac-g and Fan1 units), with some exceptions.

- The negligible amplifications recorded by the spectral ratio analyses in situations that from surface geology alone might be considered preferential sites for local amplifications, such as the central body of the large Paganica alluvial fan, may be explained in the context of large thicknesses (> 75 m) of relatively homogeneous gravelly textures that determine a lack of marked contrasts of impedance with depth.

- The most significant amplification peaks (between 2 and 3 Hz) mostly occur: 1) where fine-grained fluvial-lacustrine sediments (Flu-Lac) prevail in the shallow sub-surface stratigraphy (within the first 15-30 m; e.g., San Gregorio at the hanging wall of the normal fault; Tempera West) or where this unit represents a thick interlayer (≥20 m) within the alluvial gravels (e.g., between San Gregorio and Onna); 2) along the marginal parts of the Paganica fan, where interlayers of fine-grained sediments within the alluvial gravels become an important percentage of the lithology (distal alluvial fan facies); and 3) where the dominant lithology is coarse-grained fan gravels but the bedrock is shallower than 20-40 m (e.g., Fan2 unit at Paganica).

- The weak motion analyses, using the reference site method, revealed significant amplification effects over a broad frequency range along both the horizontal and vertical components. This suggests that multi-dimensional (2D or 3D) site effects are related to the geometry of the buried carbonate bedrock, which in turn is related to the synsedimentary activity

of Quaternary normal faults.

General conclusions concern the successful methodological approach to the seismic microzonation of the area, which might represent an additional example as to how site response studies should be pursued in comparable geological settings and elsewhere [see also Bianchi Fasani *et al.* (2008), Cardarelli *et al.* (2008), Pace *et al.* (2008) and Pergalani *et al.* (2008) for an example of multidisciplinary seismic microzonation under ordinary conditions, i.e., non post-earthquake emergency].

- The extensive covers of continental deposits justify the widespread local stratigraphic amplifications measured by passive seismology. Nevertheless, if we look at the dominant lithology cropping out near the surface (alluvial gravels), the observed lateral variations in both frequency and amplitude of the amplification peaks revealed by weak motion and ambient seismic noise measurements might seem poorly correlated with the geological map. This apparent contradiction can be solved by considering two basic aspects that must be addressed during geologic investigations for seismic microzonation:

1) only careful and very detailed field surveys (e.g., 1:5,000/2,000 scale) may provide an adequate characterisation of the lithology (e.g., texture, degree of cementation/compactness of granular materials, degree of weathering/fracturing); and

2) the 3D reconstruction of the sedimentary bodies and their lateral correlations/heteropies is fundamental. This implies an integrated analysis of surface and sub-surface geological data over areas of significant lateral extent (e.g., at least as wide as the lateral extent of the depositional environment/sedimentary bodies).

- The use of rapid, non-invasive and relatively low-cost geophysical analyses such as ERT proved to be a powerful tool, especially in defining the geometry of the sedimentary bodies and the presence of lateral lithologic (electric) contrasts due to sub-surface faults. The use of these analyses, in conjunction with structural-stratigraphic data, was fundamental for planning geognostic drillings.

- Once a geologically reasonable sub-surface model is built, one can realize that there is an excellent fit between the results from the spectral ratio analysis of the ground motion and the structural-stratigraphic setting obtained by independent geological data. This suggests that the widespread use of weak motion and ambient seismic noise measurements, in conjunction with structural-stratigraphic data, are powerful tools for seismic microzonation.

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