Imaging the three-dimensional architecture of the Middle Aterno basin (2009 L'Aquila earthquake, Central Italy) using ground TDEM and seismic noise surveys: preliminary results

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Abstract: *We present preliminary results from a multidisciplinary geophysical approach applied to the imaging of the three-dimensional architecture of the Middle Aterno basin, close to the epicentral area of the 2009 L'Aquila earthquake (central Italy). We collected several time domain electromagnetic soundings (TDEM) coupled with seismic noise measurements focusing on the characterization of the bedrock/infill interface. Our preliminary results agree with existing geophysical data collected in the area, and show that the southeastern portion of the basin is characterized by a deepening of the Mesozoic-Tertiary bedrock down to a depth of more than 450 m. We found that a joint use of electromagnetic and seismic methods significantly contributes in obtaining new insights on the 3D geometry of the Middle Aterno basin. Moreover, we believe that our combined approach based on TDEM and noise measurements can be adopted to investigate similar geological settings elsewhere.*

Key words: *Central Apennines, extensional basin, TDEM, ambient noise.*

INTRODUCTION

The Mw 6.1 April 6, 2009 L'Aquila earthquake and related sequence (Herrmann et al., 2011) struck a densely populated area in central Italy causing heavy damage in the town of L'Aquila and surrounding villages, with 309 fatalities and thousands of injured. The mainshock was related to a 12 to 19 km-long, NW-SE oriented, SW-dipping causative normal fault (Chiaraluce, 2012 and references therein), which caused coseismic surface breaks and noticeable hangingwall subsidence (Atzori et al., 2009; Emergeo Working Group, 2010 and references therein). This fault belongs to the Paganica - San Demetrio fault system (PSDFS, according to Galli et al., 2010 and Civico et al., 2014). The latter consists of a ~20 km long network of Quaternary normal faults that originated a wide intermontane continental basin (Middle Aterno basin; Pucci et al., 2014).

The PSDFS belongs to a wider system of Pliocene-Quaternary, NW-SE and NNW-SSE striking normal faults affecting the whole inner central Apennines and responsible for the generation of several intermontane continental basins (Cavinato & De Celles, 1999; Ghisetti & Vezzani, 1999).

The Middle Aterno basin is characterized by the presence of an extensive cover of lacustrine and fluvial/alluvial deposits accumulated upon a Meso-Cenozoic carbonatic and siliciclastic bedrock, and generally separated by unconformities and/or displaced by the PSDFS (Pucci et al., 2014).

The 2009 L'Aquila earthquake triggered several studies aimed at defining the subsurface geometry of the Middle Aterno basin (among the others: MS-AQ Working Group, 2010; Balasco et al., 2011; Improta et al., 2012; Santo et al., 2013).

Balasco et al., (2011) investigated the large-scale structure of the northeast part of the basin by means of a ~8 km-long, Electric Resistivity Tomography (ERT) that complemented a magnetotelluric profile (~1000 m investigation depth). Their resistivity section highlights the existence of complex lateral and vertical resistivity changes in the NE sector (between Mt. Bazzano and Paganica), that can be related to the presence of a shallow conductive alluvial filling (~200 m-thick) above a rugged carbonate substratum. In the same area, Improta et al., (2012) performed a high-resolution seismic survey over an 8 km long section. Their tomographic images define the basin structure down to a depth of ~350 m, highlighting the presence of a complex topography of the pre-Quaternary substratum, with a ~350 m deep depocenter in the Bazzano sub-basin. They evidence strong lateral heterogeneities and steps in the substratum (NE of Mt. Bazzano), suggesting the presence of buried synthetic and antithetic fault splays involving bedrock and basin infill deposits within the Paganica sub-basin.

Santo et al., (2013) present the subsurface setting of the south-easternmost portion of the basin obtained by merging existing geophysical data from microzoning activity and some old vertical electrical soundings reported by Bosi & Bertini (1970).

Although the abovementioned results provided new information of the subsurface basin geometry, they still suffer from limited areal extension and/or investigation depth, moreover the long-term reconstruction of the fault system and basin evolution is hampered by few reliable subsurface constraints covering the whole basin. To contribute to fill this gap of knowledge, we performed extensive surveys in the Middle Aterno basin by using a combined geophysical approach based on

Time-Domain Electromagnetic Method (TDEM) and ambient noise vibrations measurements. The main aim of our approach is to map the buried interface between the continental infilling deposits and the Mesozoic-Tertiary marine substratum. TDEM and noise measurements resulted a suitable strategy for defining the geometry of the Middle Aterno basin to more than 450 m in depth.

The work is still in progress, anyway we can present the areal extent of the already collected data and a preliminary reconstruction of a limited portion of the Middle Aterno basin at depth.

METHODS AND DATA ACQUISITION

Time-domain electromagnetic method (TDEM) is based on the induction of a time-varying secondary magnetic field produced by decay current in the ground. This secondary magnetic field is measured by an induction receiver coil, generally placed at the centre of a transmitter loop. As the current diffuses deeper into the ground (at later time), the signal measurements provide information on the conductivity of the lower layers. TDEM is sensitive to subsurface resistivity: the latter for near-surface earth materials can vary by several orders of magnitude, being thousands of Ωm for carbonates or crystalline rocks and few Ωm for clay and/or saturated alluvium (e.g. Palacky 1987). Although it is not possible to establish a 1:1 correlation between resistivity values and heterogeneous infill materials, TDEM soundings can offer a cheap alternative to drilling several wells in defining the depth of a gently dipping bedrock (Hobza et al. 2012; Bedrosian et al., 2013).

We used a three-component receiver coil, in conjunction with a transmitter square loop of 50 m and 100 m size, respectively. TDEM measurements were performed both in central-loop and offset receiver configuration. We adopted standards from Geonics Ltd. (Rob Harris, personal communication) for the determination of the input current, gain setting and number of stacks.

We performed our TDEM surveys taking into account local issues in order to avoid high-noise sites (related to infrastructures/lifelines). Indeed, for each site we performed initial noise tests, showing that the signal-noise level was generally low in the study area. However, since the surveys span a large geographic area, we repeated the initial noise tests for each site. It helped us in discarding some unreliable TDEM measurements due to anthropogenic noise. In addition, unreliable data distorted by 2D or 3D structure (i.e. fault) were also removed prior to inversion (Newman et al., 1986). Data processing was made with the SiTEM software, and the resistivity data were inverted with the SEMDI program (Effersø et al., 1999) to obtain 1-D resistivity model of the subsurface.

We coupled TDEM measurements with recordings of ambient seismic vibrations, in order to better constrain the depth of the seismic basement. We used the classical H/V method (Nakamura, 1989) based on the spectral ratio between the horizontal and the vertical components of ambient noise data. The resonance frequency (f0) was obtained from the peak of the H/V curves. The value of f0, for 1-D structures, is closely linked to the mean properties (thickness and shear-wave velocity Vs) of the soft soil (Bonnefoy-Claudet et al., 2006). Assuming the 1-D quarter wavelength approximation, we derived the bedrock depth (in terms of a range of possible values) from the f0 values. This implies that a reliable Vs profile of the sedimentary filling was first assumed in the valley. Indeed Vs values were provided by surveys carried out in the L'Aquila surroundings and in the Middle Aterno after the microzoning activity. Typical estimated Vs values of the sedimentary filling within the basin are 600-700 m/s (MS-AQ Working Group, 2010; Di Giulio et al., 2014). Ambient noise was recorded using 24-bit Reftek130 data loggers

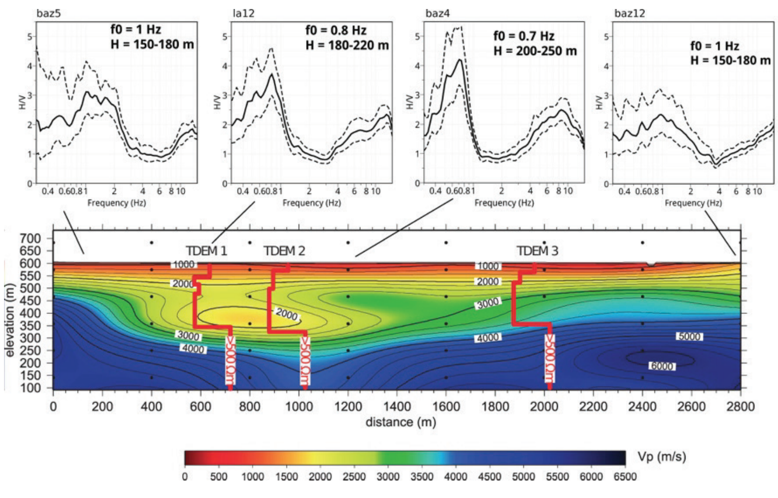

Figure 1: Vp tomogram of two merged high-resolution seismic lines across the Bazzano basin (B1 and B2, modified after: Improta et al., 2012). Three 1-D resistivity models derived from the inversion of TDEM data (solid red lines), and four H/V curves computed from noise measurements (upper panel), are also projected along the Vp model. The infill/bedrock interface displays high resistivity (> 500 Ωm) in the 1-D models, and high Vp (>3500 m/s) in the tomogram. The values of f0 and H (where H indicates a possible range for the depth of the bedrock) are also shown in the inset of the H/V curves. The blue line at 650 m distance along the tomgram indicates a 150 m deep borehole (Porreca et al., 2013) conducted as part of the FIRB Abruzzo Project.

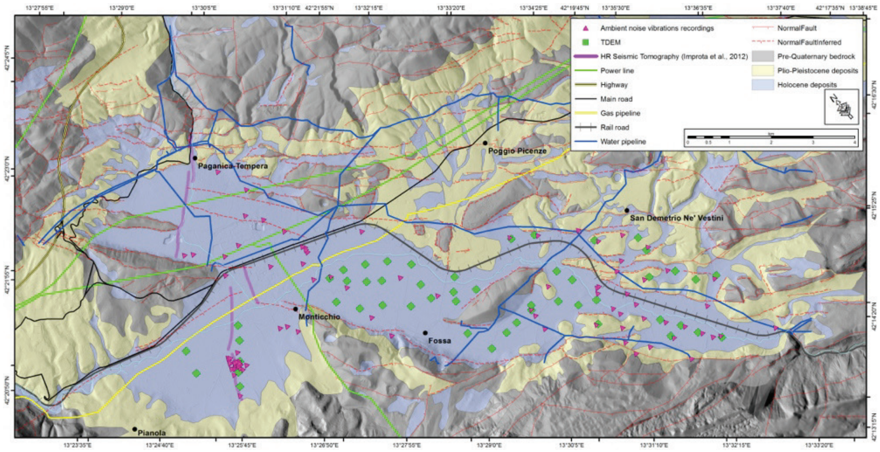

Figure 2: Location map of TDEM and seismic noise surveyed sites, showing the main infrastructures and lifelines in the Middle Aterno basin, and the trace of the seismic lines and Deep ERT. Simplified geology and main faults of the area redrawn after Pucci et al., (2014).

coupled to Lennartz LE-3D5s velocimeters with eigenfrequency of 0.2 Hz. The sampling rate was fixed at 250 Hz with recording duration of at least 50 minutes. Data processing for computing the H/V curves was performed with the Geopsy code (http://www.geopsy.org).

We successfully calibrated TDEM and ambient seismic noise data against: available wells information (MS-AQ Working Group, 2010; Porreca et al., 2013), existing geophysical investigations (Improta et al., 2012) and Deep ERT profiles (Delcher et al., in prep.). As an example, in Figure 1 we show the results of three TDEM soundings and four noise measurements collected along the high-resolution seismic tomography profile. In particular, we observe at ~230 m depth in the 1-D models a high resistivity contrast, with values larger than 500 Ωm, that we interpreted as the interface between the Quaternary infill and the Mesozoic-Tertiary bedrock.

The recovered 1-D resistivity models show a good agreement with the seismic section both in the near surface and in the deeper part of the two models. The f0 trend resulting from H/V curves is also fairly in agreement with the bedrock depth shown by the seismic section.

We then expanded our survey performing TDEM and microtremor measurements at regularly spaced intervals (about 500 m spacing between adjacent stations) and collecting so far a total of 51 TDEM and 103 seismic noise measurements respectively (Figure 2). We eventually interpolated a raster surface from depth to bedrock data points using a two-dimensional minimum curvature spline technique. The spline tool uses an interpolation method that estimates values using a mathematical function that minimizes overall surface curvature and the resulting smooth surface passes exactly through the input depth to bedrock points. As primary boundary conditions, we obviously imposed the bedrock depth to be zero along the perimeter of all the bedrock outcrops within the basin and along its margins.

PRELIMINARY RESULTS AND DISCUSSION

Despite logistical difficulties, the geophysical survey by means of TDEM and noise methods is in progress along the whole Middle Aterno basin. Here, we present a preliminary interpolation of the recovered depth of the pre-Quaternary bedrock top-surface of the southern portion of the basin, in order to reconstruct its subsurface geometry (Figure 3).

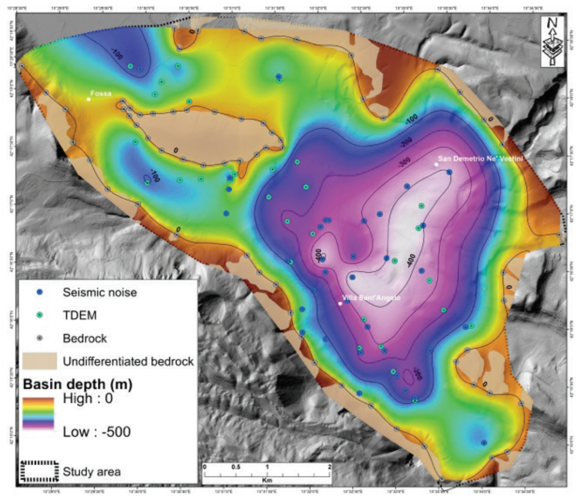

Figure 3: Interpolated top-bedrock surface in the south-eastern sector of the Middle Aterno basin (contour interval: 100 m).

Notwithstanding it might be difficult to discriminate among Meso-Cenozoic carbonate bedrock and Early Quaternary cemented carbonatic breccias (Megabrecce Fm Auct. - mainly found in the northwestern portion of the basin), our result highlights the presence of a complex basin structure formed by thresholds separating some 100-200 m-deep depocenters, with a maximum depth >450 m located between the villages of San Demetrio Ne' Vestini and Villa Sant'Angelo, at the southern end of the Middle Aterno basin (Figure 3). This deepest part of the basin has a rough triangular shape with a side paralleling the western slope of the valley and a vertex close to the San Demetrio Ne' Vestini village. As a consequence, the SE side of the depocenter is characterized by a strong topographic gradient, in coincidence with the tip of the Quaternary basin. Notably, the shape of this maximum depocenter is not coherent with the NW-trending, Quaternary normal faults affecting the eastern side of the basin. This evidence suggests that the onset of the Middle Aterno Quaternary basin was controlled by the long-term activity of a differently oriented fault system that could have played a key role before or together with the PSDFS segments through time.

This buried deep depocenter of the basin is also confirmed by a 2-D deep ERT (Delcher et al., in prep.) as well as by a low-resolution map of gravimetric anomalies (Di Filippo et al., in: MS-AQ Working Group, 2010) performed independently in the same area.

The data of the present work yield new insight to reconstruct the 3D image of the Middle Aterno basin. Indeed, our study emphasizes the utility and flexibility of combining two different methods (TDEM and ambient noise) in reconstructing the 3D geometry of the Middle Aterno Basin bottom.

The reconstruction of the physiography of the tectonic-related Quaternary basin bottom represents a critical contribution to the estimation of the fault system evolution and thus to the evaluation of the seismogenic potential of the active structures.

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