Electrical Resistivity Tomography investigations in the Ufita Valley (Southern Italy)

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Abstract
Several Electrical Resistivity Tomography (ERT) surveys have been carried out to study the subsurface structural and sedimentary setting of the upper Ufita River Valley, and to evaluate their efficiency to distinguish the geological boundary between shallow Quaternary sedimentary deposits and clayey bedrock characterized by moderate resistivity contrast.
Five shallow ERT were carried out across a morphological scarp running at the foot of the northeastern slope of the valley. This valley shoulder is characterized by a set of triangular facets, that some authors associated with the presence of a SW-dipping normal fault. The geological studies allow us to interpret the shallow ERT results obtaining a resistivity range for each Quaternary sedimentary deposit. The electrical images showed the geometrical relationships of alluvial and slope deposits, having a maximum thickness of 30-40 m, and the morphology of the bedrock.
The resistivity range, obtained for each sedimentary body, has been used to calibrate the tomographic results of one 3560 m long deep ERT carried out across the deeper part of the intramountain depression with an investigation depth of about 170 m. The deep ERT highlighted the complex alluvial setting, characterized by alternating fine grained lacustrine deposits and coarser gravelly fluvial sediments.

Key words *Shallow ERT – Deep ERT – Ufita River Valley – Southern Italy*

1. Introduction

Electrical Resistivity Tomography (ERT) is a geoelectrical method widely applied to obtain 2D and 3D high-resolution images of the resistivity subsurface patterns and it has been applied to solve a wide class of geological problems: to determine the position of active faults and quantify displacements in Quaternary formations, before performing trenching paleoseismological studies (*e.g.* Storz *et a*l., 2000; Suzuki *et al*., 2000; Demanet *et al*., 2001; Caputo *et al*., 2003; Nguyen *et al*., 2003; Wise *et al*., 2003; Nguyen *et al*., 2005; Galli *et al*., 2006); to infer some characteristics of the fault zones, such as the presence of fluids, and to estimate the width of the damage zone (Diaferia *et al*., 2006); for the delineation of the structur-

al setting of geological sedimentary basin (Rizzo *et al.*, 2004) and volcanic areas (Di Maio *et al*., 1998, Finizola *et al*., 2006).

Several ERT surveys were acquired to study the shallow subsurface structural and sedimentary setting of the upper Ufita River Valley.

The Ufita River Valley is located in Irpinia, in the axial zone of the Southern Apennines in Italy (fig. 1). The Irpinia region is one of the most active seismic areas with the highest seismic moment release in Italy, having experienced in historical and instrumental times several destructive earthquakes with $I_{max} \geq IX$ MCS. The Ufita River Valley is located NW of the epicentral region of the M 6.9, 1980 Irpinia earthquake, and it was the epicentral area of the M 6.6, 1732 earthquake (Working Group CPTI, 2004).

In the upper Ufita Valley, five shallow ERT were carried out, using the Wenner-Schlumberger array, to study the geometries of the Quaternary alluvial and colluvial bodies across a small morphological scarp, located at the foot of low dipping triangular facets, on the northeastern valley slope (figs. 1 and 2).

The shape, geometry, and thickness changes of the deposits, across and near the scarp, were reconstructed with the aim of interpreting it either as a tectonic (*i.e*. fault scarp) or as a morphological feature (*i.e.* back-edge of a fluvial terrace).

Besides, one 3560 m long deep ERT profile, joining 11 roll-along profiles using the Wenner array, was carried out across the valley (fig. 2c), and about 5000 resistivity data were collected. This elecrtical section crossed the deeper part of the intramountain depression, with an investigation depth of about 170 m, and aimed to study the geometry and maximum thickness of the sedimentary deposits in front of the scarp.
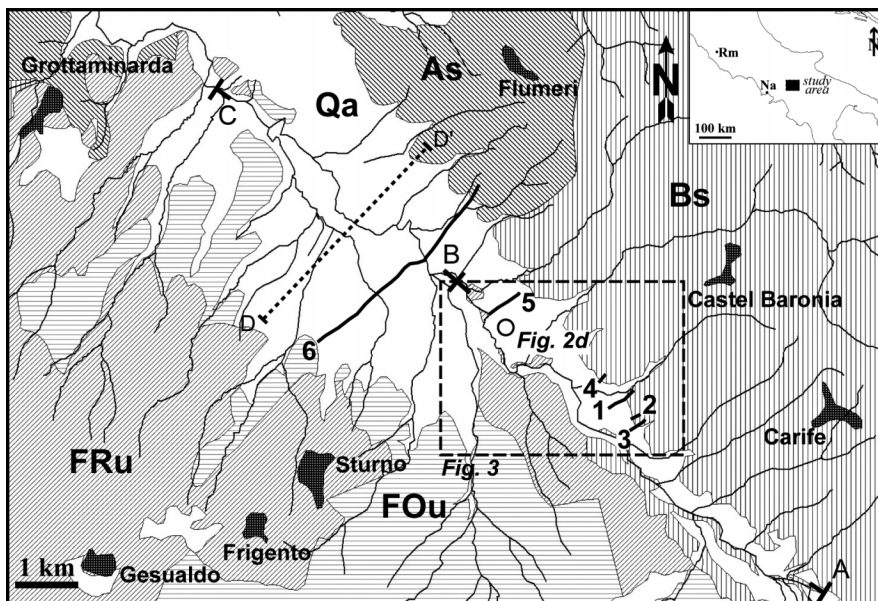
Fig. 1. Geological scheme of the study area (modified from Di Nocera et al., 2006) with traces of the ERT profiles: 1 - Isca Ciampone; 2 - Renazzo II; 3 - Renazzo I; 4 - Serritiella; 5 - Piani; 6 - Deep ERT. White circle is the location of fig. 2d. FOu: Fortore Unit; FRu: Frigento Unit; As: Altavilla supersynthem; Bs: Baronia synthem; Qa: Quaternary deposits. A-B: erosive reach of the Ufita River; B-C: depositional reach. D-D': trace of the geological profile of fig. 6.
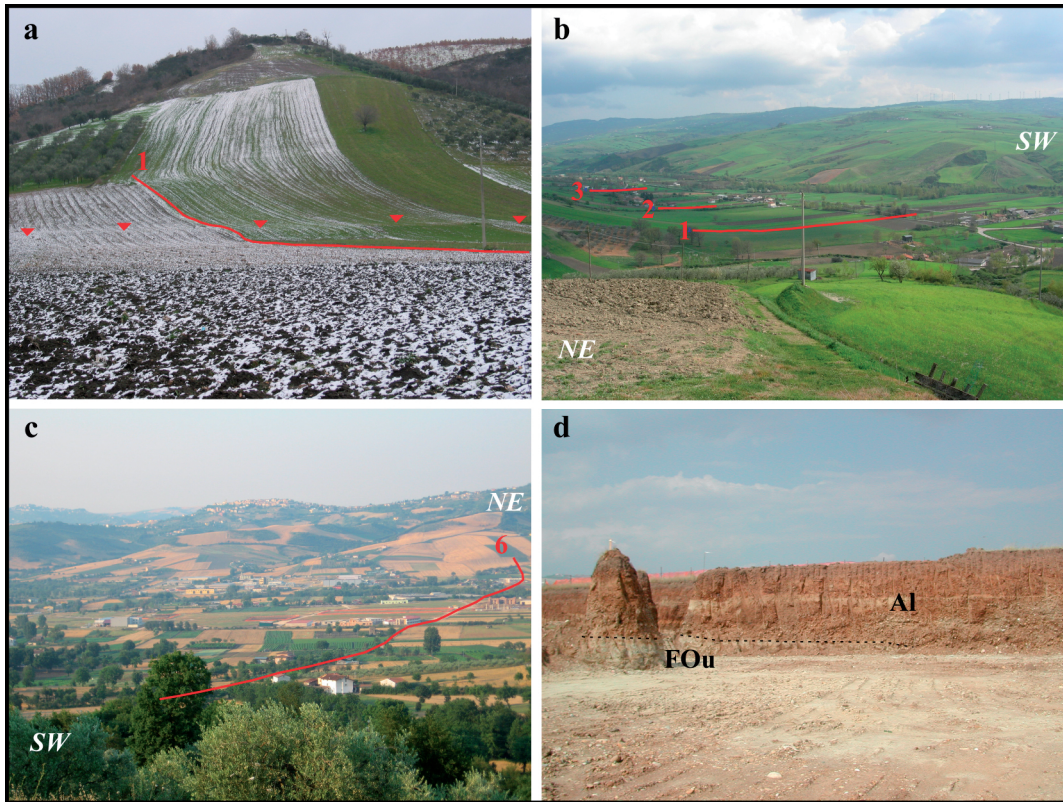
Fig. 2a-d. Photos showing the study area: a) trace of Isca Ciampone profile (1). The scarplet at the base of the triangular facet is highlighted by red triangles; b) traces of Isca Ciampone (1), Renazzo II (2) and Renazzo I (3) profiles, on the north-eastern valley shoulder. View is towards the upstream section of the Ufita River (reach AB in fig. 1); c) trace of the deep ERT profile (6) running across the valley. View is towards the north-eastern shoulder of the valley, and shows also two of the low-dipping triangular facets that characterize this margin; d) photo taken near Piani profile (location in fig. 1) showing the erosive contact (dashed black line) between coarse alluvial fan deposits (Al) and the marly limestone of the Fortore Unit (FOu). In this site, the alluvial fan is few meters thick.

2. Geological and geomorphological setting

The study area falls in the Irpinia-Daunia sector located in the eastern margin of the southern Apennines (fig. 1). The intramountain morphological depression of the upper Ufita River Valley separates two areas characterized by different tectonic and geological units, deformed and thrust eastwards starting from Middle Miocene (Basso *et al.*, 2002; Di Nocera *et al.*, 2006) (fig. 1). The southwestern valley shoulder is composed of tectonostratigraphic units originally belonging to the Lagonegro-Molise basinal domain. Two units can be distinguished: 1) the Fortore Unit (Pescatore *et al.*, 2000), composed of basinal facies, ranging from Late Cretaceous to Langhian; and 2) the Frigento Unit (Di Nocera *et al.*, 2002), composed of basinal and shelf margin facies, ranging from Middle Triassic to Middle Miocene, and overthrusting the Fortore Unit (for a detailed description of the two units see Di No-

cera *et al.*, 2006). To the first unit belong the Lower Cretaceous «Flysch Galestrino» and the Upper Cretaceous-Burdigalian «Flysch Rosso» formations, outcropping along the southwestern Ufita Valley side, that are composed of cherty claystone, fine grained calcarenites and marls, and by massive clastic limestones, and pelagic calcarenites and marls (Di Nocera *et al.*, 2006).

Conversely, the Baronia ridge, forming the northeastern valley shoulder (fig. 1), is made up of synorogenic Mio-Pliocene units, deposited in wedge-top basins, separated by angular un-conformities from the older rocks (Basso *et al.*, 2002; Di Nocera *et al.*, 2006). The northern sector of the ridge is characterized by the out-crop of the Upper Messinian «Altavilla super-synthem», composed of fluvio-lacustrine con-glomerates and clays, and of claystones to sandstones turbiditic deposits. In central-south-ern sector there are outcrops of the Lower Pliocene «Baronia synthem», which shows a complete regressive sequence from near-shore to continental deposits, with at the base a thick sandy-conglomeratic continental deposit (Di Nocera *et al.*, 2006).

Finally, the valley is filled with a Quater-nary fluvial and lacustrine deposits of variable thickness, interfingered along the margins with slope deposits and, especially along the eastern side, with coarse sediments deposited by the right tributaries of the Ufita River in alluvial fans of various size (figs. 1 and 2d). These are composed of a variable thickness of coarse grained loose deposits, originated from the Pliocene sands and gravels of the «Baronia syn-them».

The thickness of the recent alluvial deposits varies from a few meters, along the upstream section of the Ufita River (A-B in fig. 1), where the river flows directly on the pre-Quaternary bedrock, to a maximum thickness of about 150 m (Basso *et al.*, 1996) downstream point B (in fig. 1). This reach is a small basin, about 4 km wide and 5 km long, filled by a sequence of al-luvial and lacustrine-palustrine deposits.

Different orders of fluvial terraces are pres-ent on both sides of the valley, but only the younger orders are well preserved. Few rem-nants of older and higher paleosurfaces are perched along the southwestern slope of the

valley, while wider paleosurfaces are located on the Baronia, northeastern side of the valley. Along this side, a set of triangular facets have been recognised along a distance of more than 10 km (fig. 2). These 100-m-high facets, devel-oped on the Lower Pliocene soft rocks, are very gently inclined (less than 10°), and were con-sidered as the surface expression of a NW-SE striking, SW-dipping active normal fault (Bran-caccio *et al.*, 1981; 1984; Basso *et al.*, 1996).

This fault was assumed to be 22 km long with a vertical slip rate of 0.2 mm/yr since the last glacial maximum (Cinque *et al.*, 2000). It was also hypothesised to be the seismogenic source of the 1732 earthquake (Meletti *et al.*, 2000). But other studies are in disagreement with this identification of the fault (Valensise and Pantosti, 2001; DISS Working Group, 2006). The scarplet explored during this work is found at the foot of the triangular facets, reach-es a maximum height of about 2 m, and dissects both bedrock and recent alluvial and colluvial sediments (fig. 2a).

3. Electrical Resistivity Tomography (ERT)

Electrical Resistivity Tomography (ERT) is a 2D and 3D geophysical technique showing the resistivity ground variations along a cross section or volume. In the geoelectrical method a controlled current (I) is injected into the ground by two steel electrodes and the potential drop (V) is acquired by two others. The appar-ent resistivity (ρ_a) is determined as follows: $\rho_a = K \cdot V/I$, where K is a geometric factor de-fined by the electrode configurations on the sur-face. During the geoelectrical survey, a multi-electrode system (Syscal R2, Iris Instruments) has been used for data acquisition (ρ_a). In this work, the apparent resistivity data were invert-ed by the RES2DINV software (Loke, 2001) to obtain a subsurface image of the electrical re-sistivity pattern. The 2D inversion routine ap-plies a Gauss-Newton least squares method (Loke and Barker, 1996), based on the finite-difference model of the subsurface, automati-cally adjusted in an iterative process. The latest is obtained comparing the measured apparent resistivities and the calculated apparent resistiv-
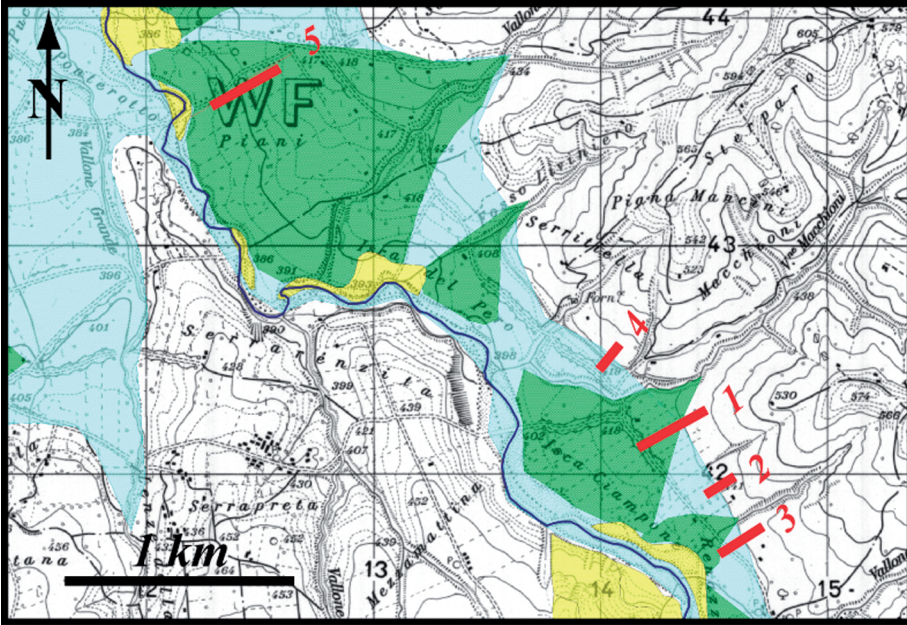
Fig. 3. Location map of the shallow ERT profiles, numbered the same as in fig. 1. The figure shows the alluvial fans (green), the recent alluvial deposits (light blue), and the bedrock outcrops along the Ufita River (yellow). Area covered by this figure is shown in fig. 1 with dashed rectangle.
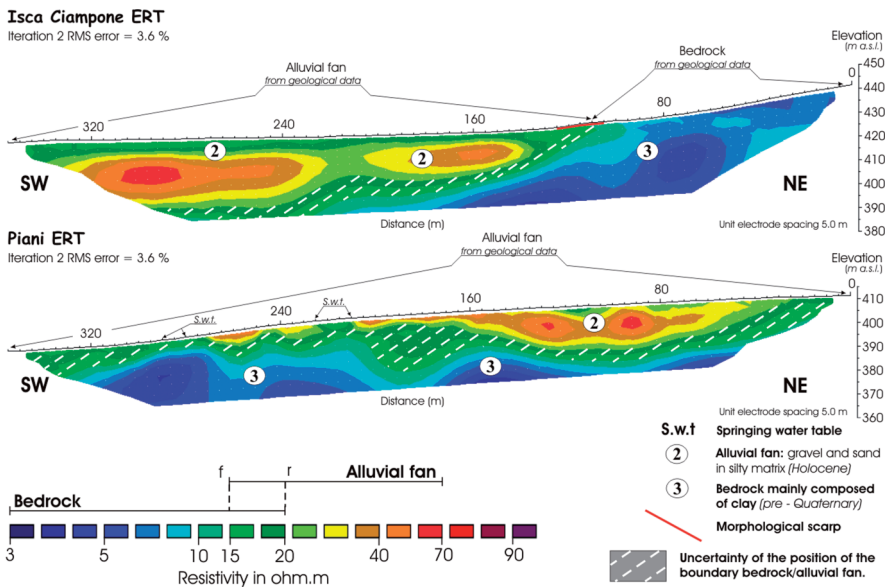

Fig. 4. Isca Ciampone and Piani electrical images (profiles 1 and 5 in figs. 1 and 3).

ities obtained from an inverted resistivity model. The Root Mean Squared (RMS) error provides a measurement of this difference as an indicator of the goodness of fit.

3.1. *Shallow ERT*

In this work, ERT method was applied to study the geometry of the Quaternary alluvial and colluvial bodies across a morphological scarp, running at the foot of the northeastern slope of the Ufita Valley (figs. 2a, 2b and 3).

A multielectrode system was used to obtain shallow ERT, using a Wenner-Schlumberger array with a minimum electrode spacing of 5 m, along five electrical profiles (*Piani*, *Renazzo I*, *Renazzo II*, *Isca Ciampone*, *Serritiella*) arranged along NE-SW direction (fig. 3). *Piani* and *Isca Ciampone* profiles crossed bedrock (mainly composed of clay) and alluvial fan deposits (gravel and sand in silt matrix), while *Renazzo I/II* and *Serritiella* profiles crossed bedrock and alluvial deposits (fine grained alluvium).

Due to the low-to-moderate resistivity contrasts characterizing the field data, the l_2 - norm inversion method was used for the inversion of the five collected data sets, being best suited to represent smooth discontinuities (Loke, 2001). The obtained resistivity sections are shown in figs. 4 and 5.

In all cases the RMS error is less than 5%, and the resistivity range is between 3 and 90 Ωm. Due to the good quality of the data (low RMS errors and high homogeneity of the resistivity values), one iteration was enough to reach the final inverse model, which was also in agreement with the available geological information.

Correlating the surface lithologies with the five shallow ERT results, resistivity ranges have been assigned to the bedrock (from 3 to 20 Ωm), to the alluvial deposit (from 10 to 20 Ωm) and to the alluvial fan deposit (from 15 to 70 Ωm).

Hereinafter, a detailed description of the features highlighted by the shallow ERT is given.

3.1.1. Isca Ciampone and Piani ERT

The *Isca Ciampone* and *Piani* ERT (1 and 5 in figs. 1 and 3) were used to characterize the geoelectrical signature of the alluvial fan deposits, and to constrain their geometry. The 350 m long *Isca Ciampone* ERT (1) crosses both outcropping bedrock and alluvial fan deposits (figs. 2a, 2b and 3). Locally, the bedrock is composed of Lower Pliocene silty-marly clays and silty sands of the Baronia synthem. The *Piani* ERT (5) crosses only alluvial fan sediments for a length of 350 m (figs. 1 and 3). However, constrains to the depth of the bedrock are given by artificial outcrops, showing a very shallow bedrock overlained by thin sequence of alluvial fan sediments (fig. 2d), and by the observation that the Ufita River flows directly on the Upper Cretaceous-Burdigalian «Flysch Rosso» formations of the Frigento Unit, about 100 m away from the southwestern end of the ERT profile (see fig. 3).

In the *Isca Ciampone* and *Piani* ERT the resistivity values lower than 15 Ωm («f» limit in fig. 4) were associated with the bedrock, while the resistivity values higher than 20 Ωm («r» limit) are related to the alluvial fan (fig. 4). The resistivity values included between the «f» and «r» limits are common to the two rock types (bedrock and alluvial fan deposits). In the *Isca Ciampone* ERT this could be due to the rather similar lithologies of the upper part of the bedrock and of the lower portion of the alluvial fan body (sourced from the Baronia synthem outcrops). Furthermore, along the *Piani* ERT, the low resistivity values of the coarse alluvial deposits could be also explained by the presence of the shallow water table (s.w.t. in fig. 4). During the survey of the *Piani* profile, performed in July, we noticed springing groundwaters between 210-215 m, and 280-290 m (fig. 4) along the profile.

Since we could not precisely locate the contact between the bedrock and the alluvial fan deposits, we were forced to represent with a diagonal pattern in fig. 4 the uncertainity of its location.

The estimated thickness of the alluvial fans is extremely variable. In the *Isca Ciampone* ERT (1), the alluvial fan deposits are more than

Electrical resistivity tomography investigations in the Ufita Valley (Southern Italy)
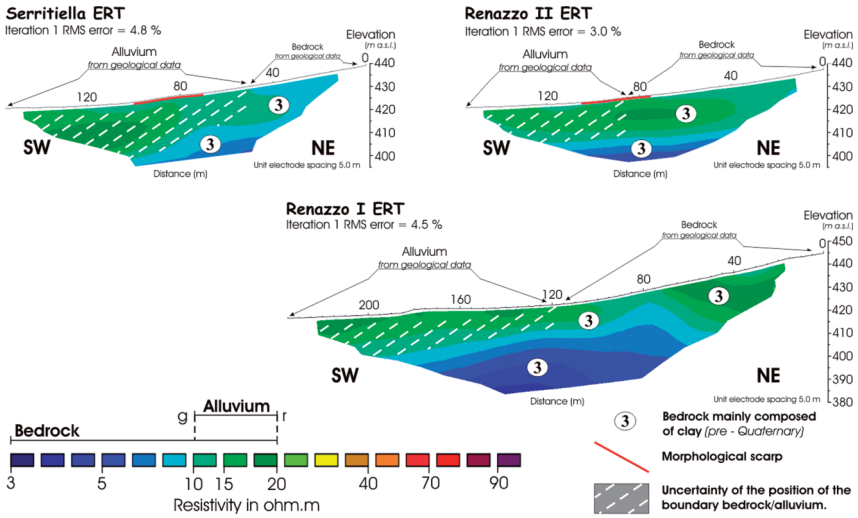

Fig. 5. Serritiella, Renazzo II and Renazzo I electrical images (profiles 4, 2 and 3 in figs. 1 and 3).
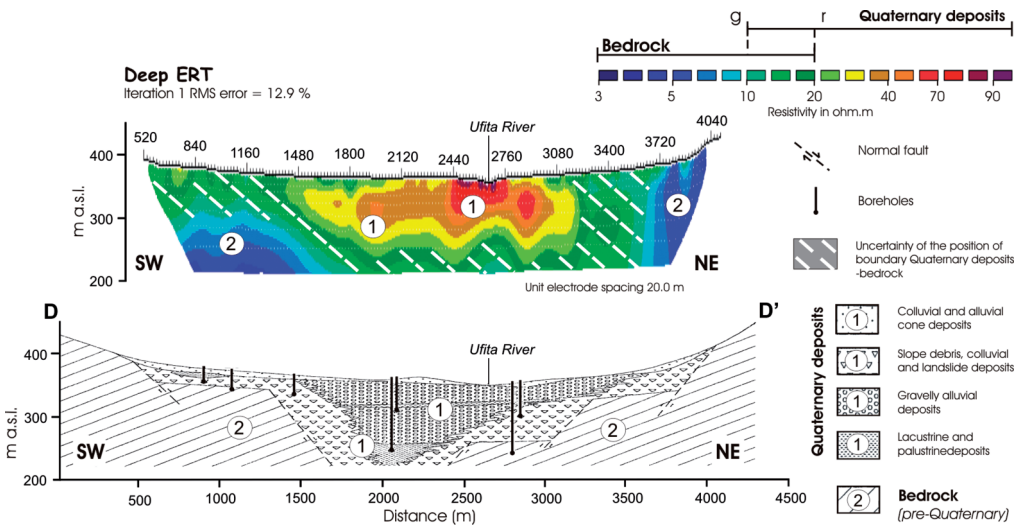

Fig. 6. Deep ERT carried out along the profile 6 of fig. 1 and fig. 2c. D-D' Geological cross-section carried out along the profile D-D' of fig. 1. The resistivity and geology models are to the same metric scale.

40 m thick below the ground surface towards the valley (fig. 4). However, we know from detailed geological survey mapping that about 500 m more to the SW, the Ufita River flows on the bedrock (fig. 3). Hence, we estimate that the thickness of the alluvial fan (laterally interfingered with the fluvial deposits of the Ufita River) cannot be much higher. The morphological

219

scarplet, that is one of the targets of this study (fig. 2a), is located about 100 m from the eastern end of the Isca *Ciampone* profile (fig. 4), and corresponds in the subsurface with the estimated contact between bedrock and recent sediments. However, these show a lenticular geometry and no thickening towards the scarp. In the *Piani* ERT (5) the alluvial fan shows a lenticular shape with the maximum thickness in the subsoil of about 30 m (fig. 4). The bedrock rises towards the southwestern end of the profile, in agreement with field geological observations (*e.g.* fig. 2d).

3.1.2. Renazzo I/II and Serritiella ERT

The *Renazzo I* and *II*, and *Serritiella* ERT (3, 2 and 4, respectively in figs. 1, 2 and 3) cross bedrock and alluvial deposits. The bedrock is composed of Lower Pliocene silty-marly clays and silty sands of the Baronia synthem (fig. 1).

In these ERT, the resistivity values lower than 10 Ωm («g» limit in fig. 5) were associated with the bedrock, while alluvial deposits are characterized by resisitivity values ranging between 10 and 20 Ωm («r» limit in fig. 5). However, from geological data we can associate outcrops of the bedrock also with resisitivity values ranging between 10 and 20 Ωm (green colours in the left-hand sides of these three profiles of fig. 5). Thus, also in this case there is an overlap of the two resistivity ranges, and we indicate the lower limit of the alluvial deposits with the uncertainty represented with the diagonal pattern. Moreover, all the ERT show an increase of the resistivity values upwards in the bedrock.

Finally, also in these three ERT, we did not observe thickening of the recent alluvial deposits towards the morphological scarp.

3.2. *Deep ERT*

A 3560 m long deep ERT (179 electrodes) across the Ufita Valley was carried out to delineate the geometry of the deeper sector of the basin (figs. 1 and 2c). The deep ERT was ob-

tained joining an 11 roll-along multielectrode acquisition (48 channels) system, using the Wenner array. The roll-allong technique allowed us to extend horizontally the area covered by survey, using a multielectrode acquisition system, characterized by a limited number of channels, with a minimum electrode spacing of 20 m and a maximum of 100 m. After completing the sequence of measurements, the first part of the cable (12 unit electrode spacing) was moved to the end of the acquired profile. Therefore, an investigation depth of about 170 m was reached. The tomographic section crossed the deeper part of the intramountain depression and about 5000 resistivity data were acquired. The analysis of the electrical model showed a variability of the resistivity values from 3 to more than 90 Ωm (fig. 6).

The RMS error is about 12% after one iteration. The choice of the first iteration electrical resistivity model is due to the unchanged value of RMS error in the following iterations. Moreover, the electrical image coming from the first iteration is in agreement with the geological data.

 In this area, a geological section was constructed based on stratigraphical data obtained from hydro wells (Basso *et al*., 1996), showing the existence of a 150-m-thick sedimentary sequence (D-D' profile in figs. 1 and 6). To interpret the deep ERT, we associated with the bedrock the same range of resistivity values obtained in the shallow ERT.

Conversely, the resistivity range of the Quaternary deposits reaches higher values (>70 Ωm) than in the shallow ERT. We interpret this difference as due to the presence of gravelly fluvial sediments filling the Ufita River channel. In our interpretation, the resistivity values lower than 10 Ωm («g» limit in fig. 6) are related only to the bedrock, while the resistivity values higher than 20 Ωm («r» limit in fig. 6) are associated only with the fluvial Quaternary deposits. Again, the resistivity values ranging between 10 and 20 Ωm are pertaining to both rock types. NE of the Ufita River course, the g-r resistivity zone is very wide, while SW of the river, the g-r resistivity zone is thinner, constraining better the shape of the Quaternary deposits. Moreover, even considering the occurrence of

the g-r resistivity zone, an asymmetric shape of the top of the conductive horizon, with the northeastern side steeper than the southwestern one, was observed. The bottom of the sedimentary infilling of this small basin is localized at a depth from 150 to more than 170 m, close to the maximum investigation depth. Finally, a good agreement between the result of the deep ERT and the geological cross-section carried out by Basso *et al.* (1996) was found in terms both of thickness and geometry of the sedimentary body, especially where the geological cross-section was constrained by the boreholes data.

4. Discussion and conclusions

The geological and geoelectrical results allow us to verify the efficiency of the ERT to locate the boundary between different geological bodies characterized by moderate resistivity contrasts. Several ERT were carried out in Ufita Valley. Resistivity ranges were associated to the bedrock (3-20 Ωm), fine grained alluvium (10-20 Ωm) and alluvial fan composed of gravel and sand in silty matrix (15-70 Ωm). A resistivity range of uncertainty (10-20 Ωm) was compatible with all the considered rock types. It could correspond either with the bedrock with a minor clay content and/or to a lower water content, or to the alluvial fan with a finer grain dimension and/or with a higher water content (see *e.g.* Schon, 2004).

Satisfactory results were obtained for *Piani* and *Isca Ciampone* sites presenting sedimentary bodies well discriminated in the resistivity section (alluvial fan superposed to the bedrock). The latest results highlighted a maximum thickness of the alluvial fan in the order of 30-40 m quickly diminishing in the two opposite directions. This observation is also constrained by surface geological data, indicating that the Ufita River flows on the pre-Quaternary bedrock close to the southwestern end of the ERT. Thus, our data confirm that the sector A-B of the Ufita River Valley (fig. 1) is characterized by a shallow bedrock covered by a thin Quaternary alluvial/colluvial sequence.

Conversely, *Serritiella*, *Renazzo I* and *Renazzo II* sites present bedrock outcrops (known

from geological survey) having resistivity values compatible with the alluvial deposits. The silty-marly clays and silty sands of the Baronia bedrock could have, locally, a minor clay content. The geological contact between alluvial deposits, superposed to the bedrock, is not well defined.

The association between each main resistivity range and the geological units was used for the interpretation of the deep geoelectrical investigation. The subsurface geometry, shown in the deep ERT, highlights a complex evolution of this small basin. The obtained resistivity model across the Ufita Valley put in evidence a thickening of the Quaternary deposits, more than 150 m below the ground surface, toward the valley axial area. The southwestern bedrock horizon appears smoother than in the northeastern part. Moreover, the deep ERT shows a thick fluvio-lacustrine deposit slightly asymmetric towards NE (fig. 6). The interpretation of the resistivity model has significant similarity with a geological section performed by Basso *et al*. (1996) along D-D' profile of fig. 1, based on some water-wells and surface geological data.

The interpretation of the shallow ERT allowed us to speculate on the origin of the triangular facets and of the scarplet. These features were interpreted as the surface expression of an active, SW-dipping, 22 km-long normal fault. From a geological point of view, a 22 km long normal fault would produce a pair of subsiding and uplifting areas of length comparable to the length of the fault itself. Moreover, using the average height of the triangular facets (about 100 m) as a proxy for the footwall vertical uplift, the related total subsidence should be in the order of about 3/400 m and the area that records at least 100 m of subsidence should be about 8 km wide. Following these observations, a deep depositional basin filled with lacustrine and fluvial sediments in the hanging-wall of the normal fault, and a wedge of recent deposits opening towards the fault itself were expected to be found.

None of these subsurface geometries were observed in the shallow ERT (figs. 4, 5). Moreover, the geological results of the deep ERT show that the dimension of the associated basin (4 km wide and 5 km long) is not scaled to the

A. Giocoli, C. Magrì, P. Vannoli, S. Piscitelli, E. Rizzo, A. Siniscalchi, P. Burrato, C. Basso and S. Di Nocera

size of the hypothesized fault (fig. 1).

Following these observations, we speculate that the triangular facets and the scarplet at their foot may be geomorphic features generated by the linear erosion process of the longitudinal Ufita River and of its right tributaries. However, we can not exclude that at the beginning this 11 km long reach of the valley may has been controlled by a structural discontinuity.

Finally, the results of this work could also be safely used as a good background for any future geohazard and environmental investigations in the study area. Knowing the electrical properties of the subsurface from surficial geoelectrical measurements, the hydraulic parameters could be estimated in areas where there are few hydrogeological direct data (Niwas and De Lima, 2003; Soupios *et al*., 2007a). Moreover, the knowledge of the depth to the bedrock through the application of the ERT method proved that it is crucial to obtain a detailed estimation of the seismic site response analysis and earthquake mitigation (Mucciarelli and Gallipoli, 2001; Parolai *et a*l., 2002; Soupios *et al*., 2007b). Finally, the identification of the tectonic regime of the area could be used to prevent the site from other correlated environmental problems, such as the movement of contaminants along the active fractures and pollution of the water table.

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