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Electrical imaging and self-potential surveys to study the geological setting of the Quaternary slope deposits in the Agri high valley (Southern Italy)

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Abstract
We present the results of a geophysical survey carried out to outline the structural modelling of Quaternary slope deposits in the northern part of the Agri high valley (Basilicata, Southern Italy). Quaternary folding and brittle deformations of the subaerial slope deposits have been studied combining electrical imaging and self-potential surveys with geological structural analysis. This integrated approach indicates that the area underwent both transpressional and transtensional tectonics during Pleistocene times as testified by the existence of a push up structure in the basement buried by deformed Quaternary breccias. On this basis, the valley appears to be a more complex structure than a simple extensional graben, as traditionally assumed in the literature.

Key words *electrical imaging – self potential – structural geology – slope deposits – strike-slip fault*

1. Introduction

The intermontane basin of the Agri high valley represents one of the higher seismic and environmental hazard areas of the Southern Apennines. In historic and recent years this area has been hit by many seismic events, sometimes destructive, like that which occurred on December 1857 (*I* = XI MCS) (Mallet, 1862; Boschi *et al.*, 1994). Additionally, for the endemic inadequacy of the anthropic buildings, the presence of important hydraulic engineering structures (Pertusillo and Marsico Nuovo Dams) and the intense exploitation of oil and natural gas, operated since 1980, it is particularly exposed to strong seismic events (Amato and Selvaggi, 1993).

In this area many research groups have focused their attention on the geological and structural analyses (Giano *et al.*, 1997; Schiattarella *et al.*, 1998), the monitoring of geophysical and geochemical parameters possibly correlated with local tectonic activity (Di Bello *et al.*, 1998) and the estimates of site seismic hazard and site amplification for several towns and villages located in this area (Gallipoli *et al.*, 1998).

In this framework, self-potential and electrical imaging surveys, combined with a deep geological structural analysis, were performed to better define the structural modelling of Quaternary slope deposits in the northern part of the valley and, consequently, to contribute to a more

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complete picture of the tectonic evolution of the valley.

The preliminary geological and hydrogeological prospecting allowed us to identify rock formation characterised by a wide contrast of resistivity values and the presence of intense underground fluid flow. For this reason, a geophysical survey based on resistivity and self-potential measurements was considered a powerful tool to better delineate the complex geological environment.

The paper is so organised: Section 2 summarizes the geological setting of the investigated area; Section 3 discusses the results obtained from self-potential survey; the resistivity tomographies are analysed in Section 4 and, finally, Section 5 proposes a conclusive structural model of the investigated area, based on the results coming from the geophysical campaign and the geological analysis.

2. Geological and structural outline

The investigated area is located on the Southern Apennines that are an Adriatic-verging fold-and-thrust belt mainly derived from the deformation of the African-Apulian passive margin (fig. 1). The chain was built on from late Oligocene to Pleistocene and is composed of Mesozoic-Cenozoic sedimentary cover from different paleogeographic domains and of the Neogene-Pleistocene piggyback basin and foredeep deposits of the active margin. The average trend of the chain axis is about N150°, corresponding to the strike of the main thrusts and coaxial normal faults. The belt is also affected by Plio-Quaternary strike-slip faults mainly oriented according to N120° ± 10° and N50°-60° trends (Schiattarella, 1998).

The high valley of the Agri River is a NW-SE trending intermontane basin located in the

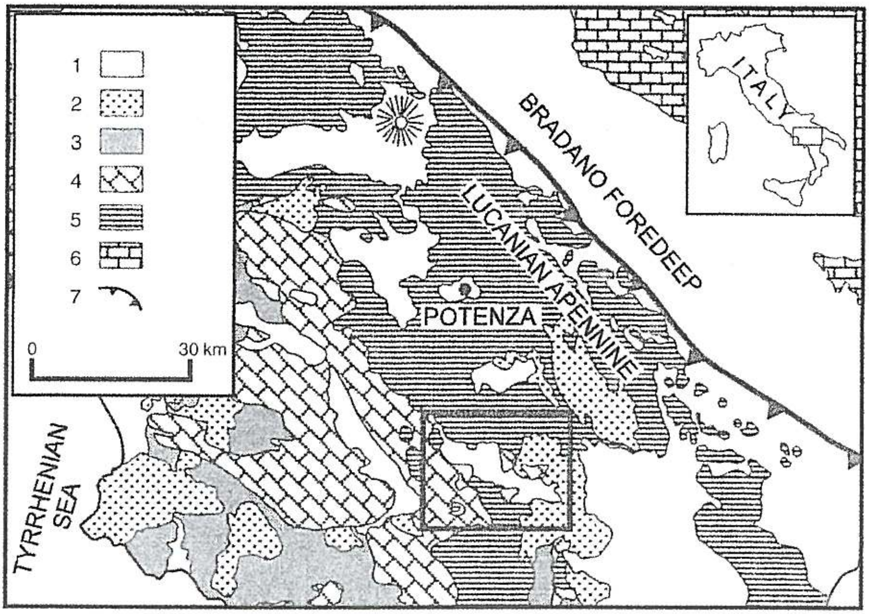

Fig. 1. Geological sketch map of Southern Apennines. 1 = Plio-Quaternary clastics and Quaternary volcanics; 2 = Miocene syntectonic deposits; 3 = Cretaceous to Oligocene ophiolite-bearing internal units (Ligurian Units); 4 = Meso-Cenozoic shallow-water carbonates of the Apenninic platform; 5 = Lower-middle Triassic to upper Miocene shallow-water and deep-sea successions of the Lagonegro basin; 6 = Meso-Cenozoic shallow-water carbonates of the Apulian platform; 7 = Thrust front of the chain. In the frame: the high valley of the Agri River.

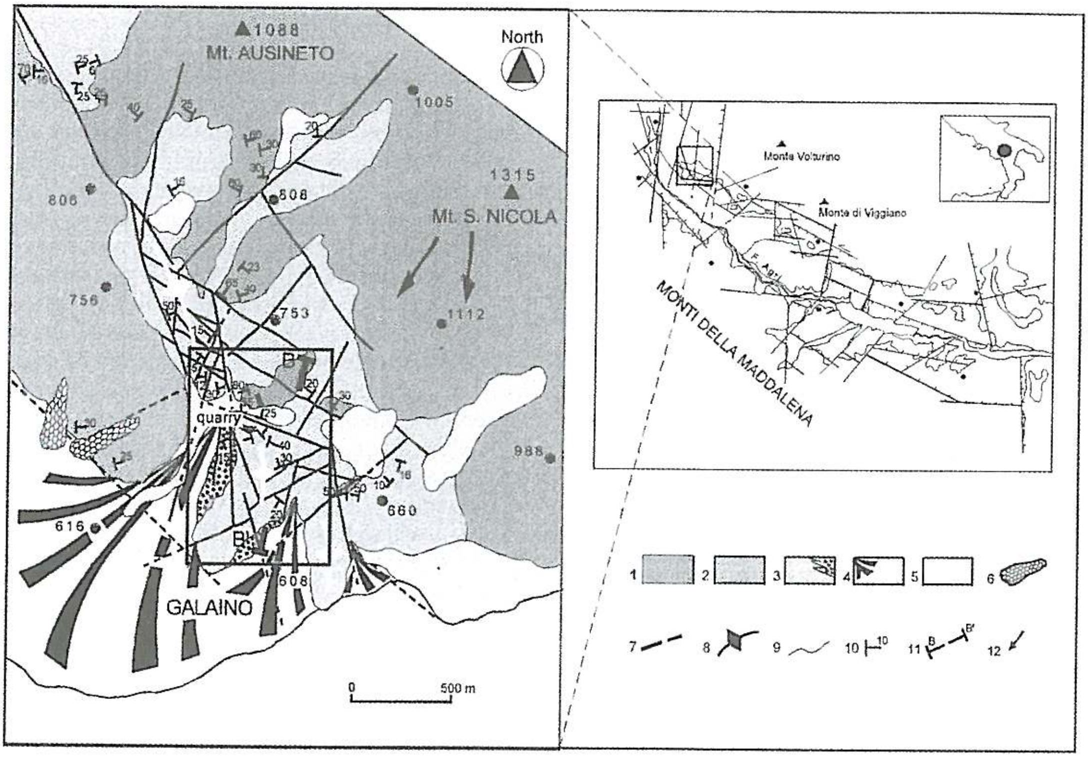

Fig. 2. Geological map of the Galaino area. 1 = Calcari con Selce Formation (upper Triassic); 2 = Galestri Formation (lower-middle Cretaceous); 3 = Ancient slope breccias (lower-middle Pleistocene); 4 = Alluvial deposits of the valley floor (middle-upper Pleistocene); 5 = Recent debris slope deposits and colluvium (Holocene); 6 = Landslide deposits; 7 = Fault; 8 = Anticline axis; 9 = Stratigraphic boundary; 10 = Attitude of the beds; 11 = Trace of electrical image BB′; 12 = Direction of groundwater outflow. In the frame: the investigated area. The right sketch shows the structural framework of the Agri high valley.

Lucanian Apennine. The basin formed during Quaternary times along the axial zone of the chain and is filled by middle Pleistocene alluvial deposits. The pre-Quaternary bedrock is constituted by Mesozoic-Cenozoic shallow-water and slope carbonates, mainly outcropping along the western side of the basin, thrust on coeval pelagic successions which crop out mainly along the eastern flank of the valley (Scandone, 1972). Toward east and south-east the bedrock is formed by Tertiary siliciclastic sediments which occupy the southern part of the high valley.

Brittle tectonics has strongly controlled both morphological and sedimentary evolution of the basin up to the present, as proved by seismicity and by the occurrence of recent paleosoils involved in faulting (Giano *et al.*, 1998). Early Pleistocene displacement along the boundary faults is evidenced by slope deposits that are tilted and uplifted at various elevations along the basin flanks. Extensional tectonics is commonly envisaged as responsible for the basin evolution, but recent structural studies (Giano *et al.*, 1997; Schiattarella *et al.*, 1998) suggest that the valley is a structure more complex than an extensional graben. Map-scale folds, in fact, affect Quaternary subaerial slope deposits of the eastern flank of the basin, near Galaino village (fig. 2). Fault kinematics and cross-cutting relationships indicate that the fold structures in the slope deposits are induced by strike-slip tectonics and predate normal faulting (Di Niro and Giano, 1995) (fig. 3).

As regards the local hydrogeological system, D'Ecclesiis *et al.* (1995) pointed out that the springs existing in the area, probably, represent outflows of a deep reservoir. The feeding basin involves the entire carbonatic aquifers of Mt. Volturino and Mt. S. Nicola. Figure 2 shows the main directions (black arrows) of the groundwater outflow toward the valley. A fraction of groundwater outflows, under the Quaternary cover, into the fractured basement of the valley. To depths of approximately –170 m, at the bottom of the slope, in fact, hydrologic wells have identified a confined groundwater, uprising until approximately –20 m from ground level, characterised by a pressure of 15 atm (D'Ecclesiis *et al.*, 1995).

3. Self-potential survey

The Self-Potential (SP) method consists of measuring at the earth surface the natural electrotelluric field developed in the subsurface by several mechanisms: electrokinetic coupling (streaming potential), thermoelectric coupling, electrochemical effects, cultural activity etc. (Nourbehecht, 1963; Corwin and Hoover, 1979).

In past and recent years the SP method has been applied in a wide class of geological problems: in mineral prospecting (Sato and Mooney, 1960), in the detection and delineation of thermal sources in geothermal and volcanic areas (Corwin and Hoover, 1979; Zlotnicki *et al.*, 1994; Di Maio *et al.*, 1997) and in hydrogeological studies for local and regional groundwater investigations (Ogilvy *et al.*, 1969; Coppola *et al.*, 1994; Loddo *et al.*, 1996). In the latter investigations, SP anomalies are mainly due to elec-

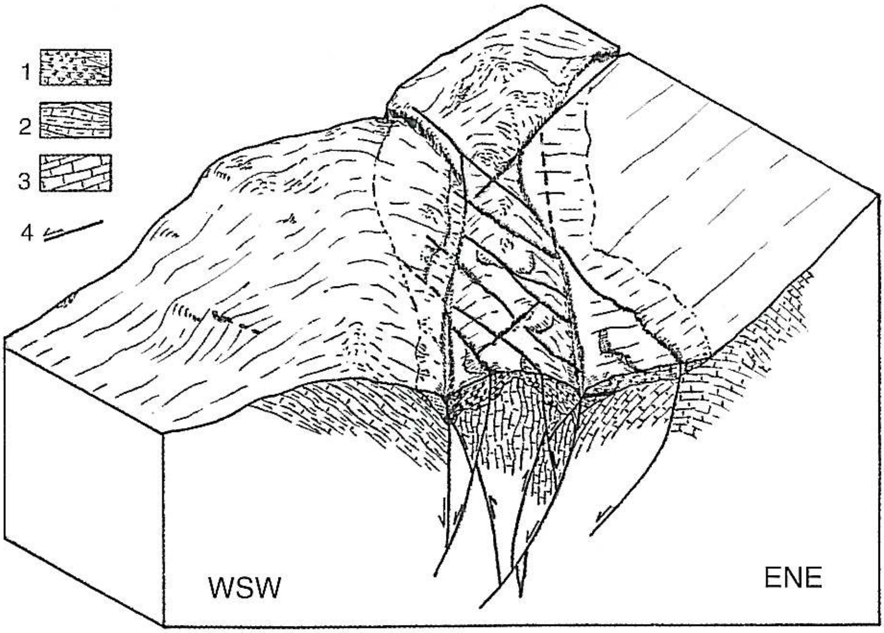

Fig. 3. Interpretative block-diagram of the studied area. 1 = Continental slope deposits; 2 = Galestri Formation; 3 = Calcari con Selce Formation; 4 = Faults and respective dip-slip components. Fault scarps in the ancient breccias are N120° striking and show extensional kinematics. The architecture of the syntectonic deposits forming N-S trending ridges shows a deformation older than the extensional faults, which is linked to a stepover of the N120° trending left-lateral strike-slip fault.

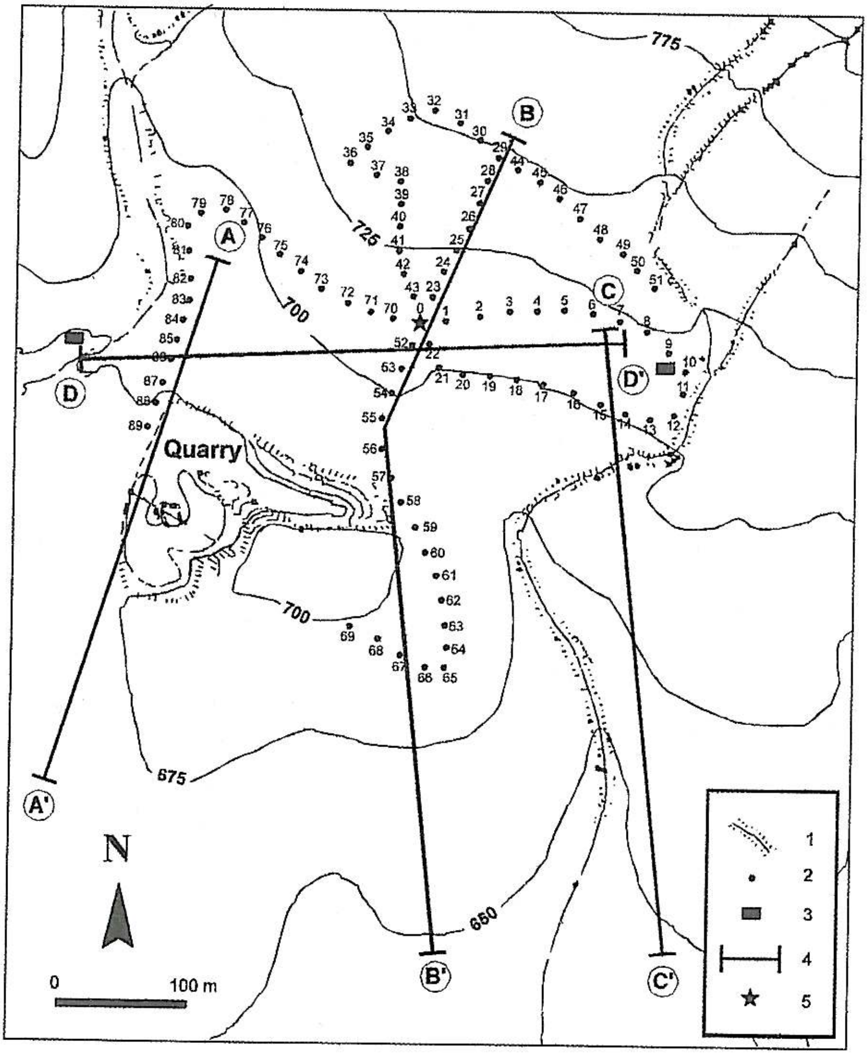

Fig. 4. Location map of the geophysical surveys. 1 = Surface drainage lines; 2 = SP areal survey circuits; 3 = Spring; 4 = Trace of the electrical tomography profiles; 5 = Zero SP reference station.

trokinetic effects (Schiavone and Quarto, 1984; Ernstson and Scherer, 1986) produced by the movement of underground electrolytic waters in porous media.

In this work a reconnaissance survey of the SP field was performed with the aim of finding indications on the structural discontinuities that affect the area and on the local hydrogeological system. Moreover, it may also furnish useful constrains for the interpretation of the electric tomographies.

Figure 4 shows the topographic map of the investigated area which reports the SP observation points and the electrical tomography profiles. The equipment for SP measurements consisted of a pair of copper rod electrodes, spaced 20 m apart, connected via screened cables to a high-impedance millivoltmeter.

Potential horizontal gradients were measured along closed loops and linked traverses, alternating the leading and following electrodes (leapfrog technique) to reduce cumulative errors due to electrode polarisation. The SP values in the measuring net were obtained adding individual readings after attributing an SP arbitrary zero value to a reference point in the area (black star in fig. 4). Moreover, SP measurements were corrected to compensate for accumulative errors distributing linearly the closure errors along each circuit. Finally, for a better visualization of the SP anomalies, we subtracted from the potential obtained in each point of the net the average value of the whole set of SP data. The contour map showing the distribution of the SP field is given in fig. 5 with a contour interval of 50 mV.

As concerns the quantitative interpretation of SP data, in recent years innovative methods able to describe the spatial distribution of charge accumulation phenomena in subsoil have been proposed (*e.g.*, Patella, 1997). However, in this work a qualitative description of SP anomaly field was carried out, the main objective of the SP survey being devoted to characterising only the main features of the circulation network of the underground waters and supporting the resistivity prospecting.

The SP contour map reveals a rather simple pattern showing an evident long wavelength NE-SW oriented dipolar SP field. In particular, the relatively «negative» anomalous zone develops over the mountain slope, reaching around -350 mV in magnitude, while the «positive» SP values are superimposed on the slope deposits to the foot of the ridge. This negative correlation between SP and the topographic elevation, known as «topographic effect», is often observed in mountainous areas (Corwin and Hoover, 1979; Hashimoto and Tanaka, 1993; Zlotnicki *et al.*, 1994) and is explained as due to a streaming potential effect produced by steady-state fluid flow caused by spatial variations in the elevation of the water table or to the percolation of waterfall through the massif. Our measurements show that the gradient of the SP *versus* topographic elevation is around -1 to -10 mV/m, according to that reported by the above authors.

Small negative and positive anomalies, relatively to the surrounding potential values, are superimposed locally on the major anomalies, probably caused by local electrokinetic phenomena, geological noise, reading errors and so on.

Moreover, we can see a sharp transition from negative to positive SP values along a NW-SE oriented belt in close correspondence with the orientation of the regional Plio-Quaternary strike-slip fault system N 120° affecting the area. Such steep gradients could be associated with an enhanced electrokinetic activity in correspondence of a deep highly permeable fault, as recognized in surface by the geological survey and in depth by the analysis of the electrical images discussed in the following section.

Another important feature is the presence of a circular positive SP anomaly inside the area with negative SP values. The anomaly approximately shows a concentric pattern centred on the spring located in the right hand of the investigated area. This evidence indicates that the anomaly probably is related to electrokinetic effects due to the discharge of groundwater. Generally, under the conditions of an ordinary ground water, positive charges are carried with fluid flow and concentrated in the region where the water flow ascends, producing a positive SP anomaly at the surface.

4. Electrical imaging survey

The electrical imaging or electrical resistivity tomography is a geoelectrical method, widely applied, to obtain a high-resolution image of the subsoil in areas of complex geology (Griffiths and Barker, 1993; Dahlin, 1996; Cosentino and Luzio, 1997). It has been shown to be useful in a wide class of problems: in the delineation of the structural setting in volcanic areas (Di Maio *et al.*, 1998), in investigating coastal aquifer pollution (Frohlich *et al.*, 1994), in outlining hydrologic systems (Coppola *et al.*, 1994) etc.

In this work we applied the electrical imaging technique to depict the local geological structures in the investigated area. A georesistivimeter system was used to obtain four resistivity tomographies using a dipole-dipole array configuration with electrode spacing of 20 m. Three profiles were oriented with directions perpen-

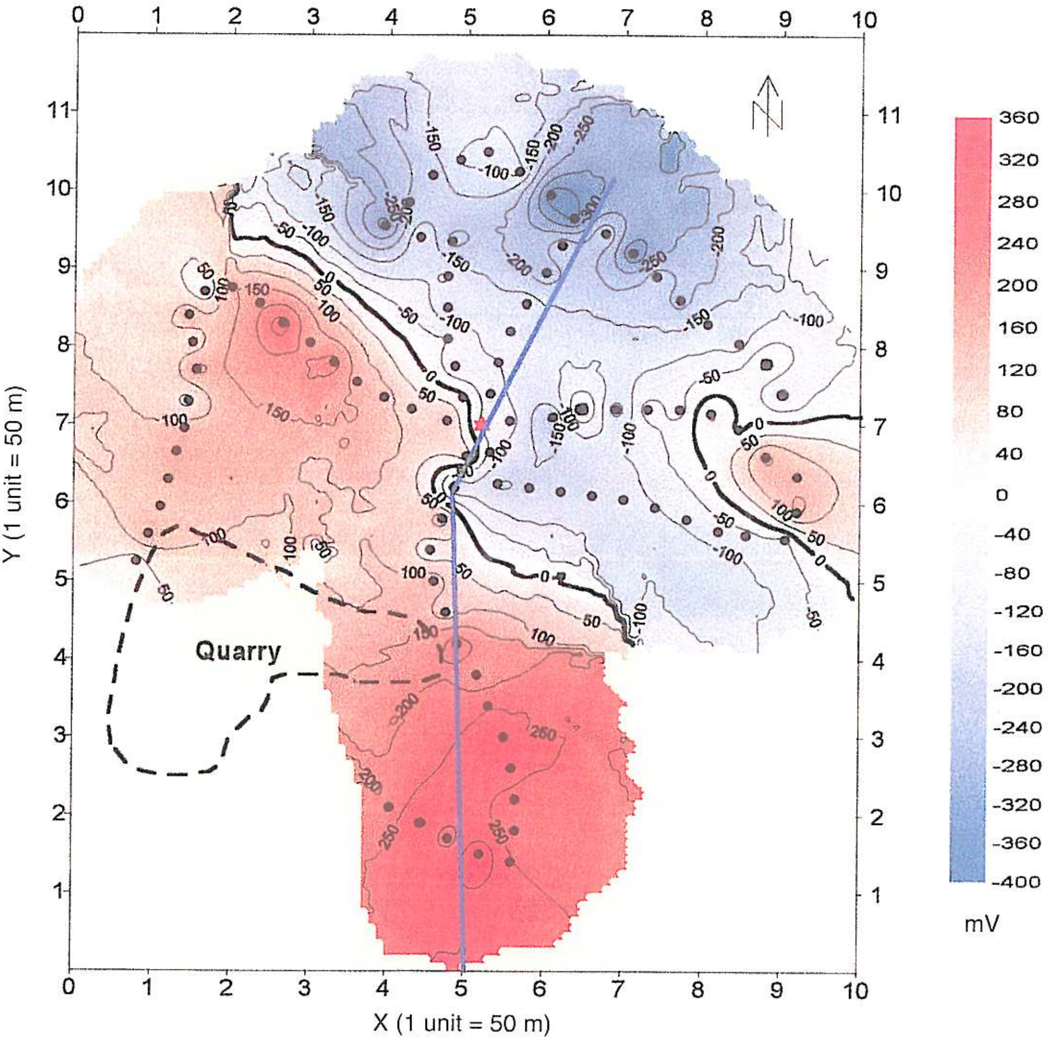

Fig. 5. SP anomaly map in the Galaino area. The blue line indicates the trace of the SP profile reported in fig. 7.

dicular (AA′, BB′ and CC′) and one parallel (DD′) to the slope (fig. 4).

The resistivity tomographies were obtained applying the algorithm proposed by Loke and Barker (1996), for the automatic 2D inversion of apparent resistivity data. The inversion routine is based on the smoothness constrained least-squares inversion (Sasaki, 1992) implemented by a quasi-Newton optimisation technique. The optimisation method adjusts the 2D resistivity model trying to reduce iteratively the difference between the calculated and measured apparent resistivity values. The Root-Mean-Squared (RMS) error gives a measure of this difference.

Figure 6 reports the inverse model resistivity section related to the electrical tomography carried out along the AA′, CC′, DD′ profiles, while fig. 7 shows the tomography BB′ with the SP profile, extracted from the SP map along the

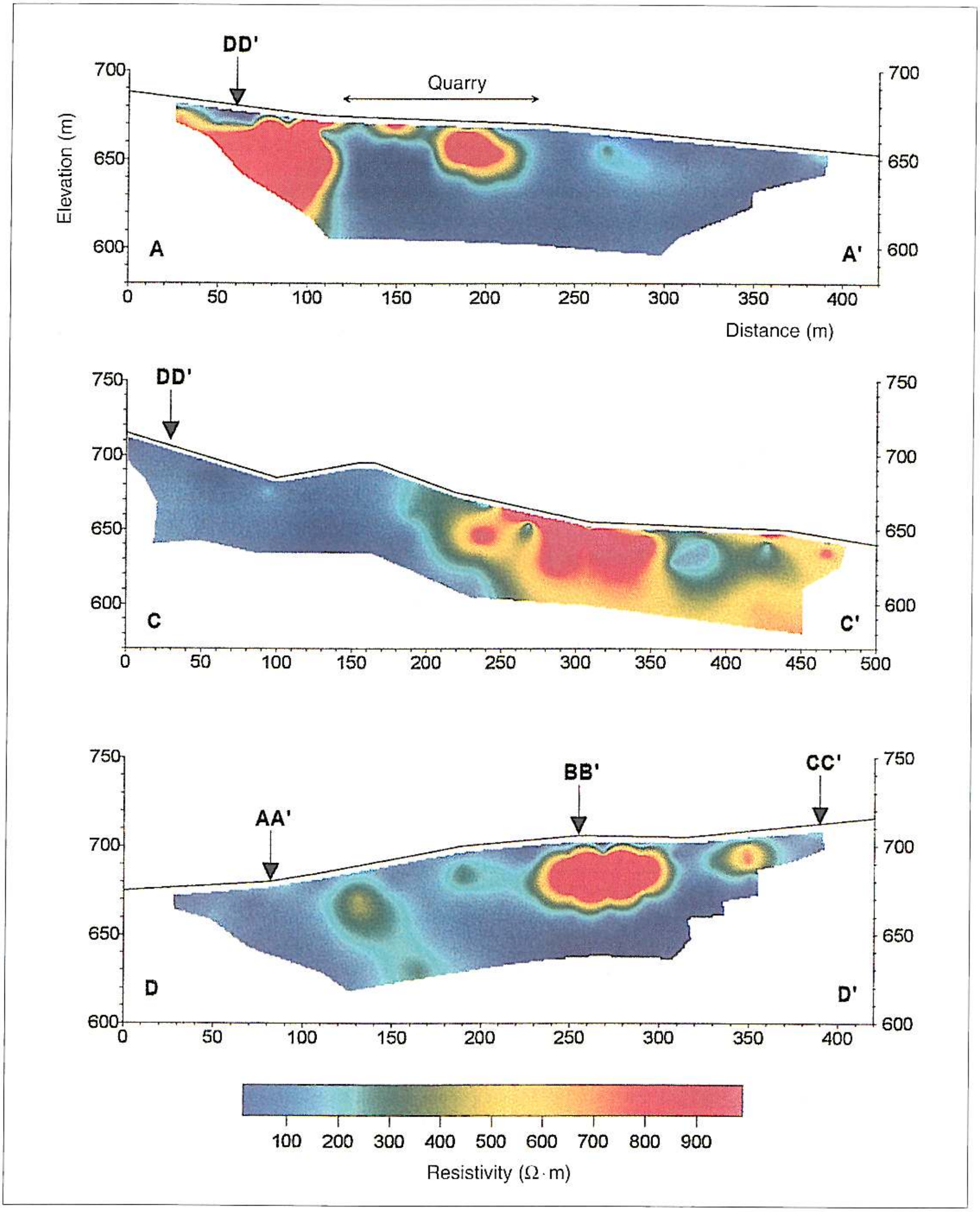

Fig. 6. Electrical tomographies of profiles AA′, CC′ and DD′. Vertical arrows indicate the crossover points with the transverse profiles.

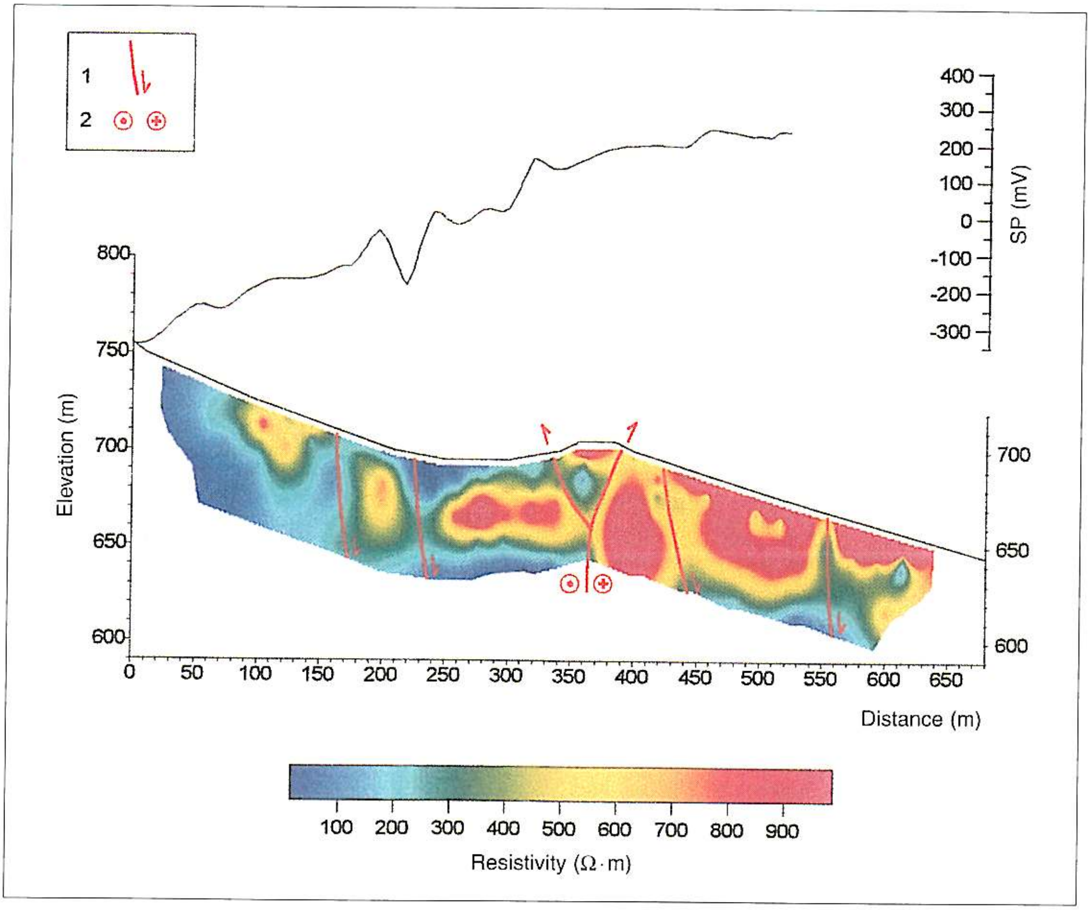

Fig. 7. Interpretative electric cross-section along the BB′ profile and SP profile extracted along the blue line reported in the SP anomaly map (fig. 4). 1 = Normal fault; 2 = Left-lateral strike-slip fault.

blue line of fig. 5. In all cases the number of iterations was set to 5 with a RMS error less then 15%.

All the electrical images show a remarkable resistivity contrast between relatively high resistivity zones (above 400-500 Ω·m) and relatively low resistivity sectors (below 200-300 Ω·m). The first could be associated to the compact slope deposits with low permeability and low content of water, while the second could be related to the pre-Quaternary carbonatic basement highly fractured and permeable with high saturation degree, according to hydrologic studies. The estimated thickness of the slope deposits is extremely variable being controlled by the fluctuation of the intensively fractured bedrock. In any case, we note a thickening of the slope deposits, even more than 50 m below the ground surface, towards the valley as expected from the geological analysis.

Moreover, we observe narrow vertical low resistivity belts, in particular in image BB′, affecting both rock formations that are interpreted as structural lineaments along which explicated the complex tectonic phases occurred in this area. Spatial variation of the SP field along the profile BB′, extracted from the SP anomaly map, exhibits anomalies of short wavelength as well as a high potential gradient in close correspondence with a low resistivity belt in the electrical image. The SP profile shows a consistent increase of nearly 200 mV in less than 50 m. The increase of the SP amplitude may relate to the upward flow of groundwater along a preferential flowpath created by a deep highly permeable fault.

It is worth noting that, close to the quarry, the electrical image DD′ shows an uprising of the bedrock, with estimated resistivities going well below 50 $\Omega \cdot$m, that reaches the surface identifying a push-up structure, as observed directly in the quarry, and giving evidence of a transpressional tectonic phase. Finally, combining the results of the geoelectrical survey with geological evidence, we propose an interpretative section in fig. 7 in which the presence of several faults and the existence of the push-up structure is highlighted.

5. Comparative data analysis and conclusions

The integrated interpretation of geological and geophysical data revealed the existence of a strongly deformed pre-Quaternary bedrock and of faulted and folded Quaternary deposits. The intense fracturing of the bedrock is highlighted by the presence of several low resistivity belts observed in the electrical resistivity tomographies and by specific patterns on the SP contour map that strongly resemble the near surface water flow.

Geological and geophysical data allowed us to define the existence of a left-lateral strike-slip brittle shear zone that determined the folding of the Pleistocene breccias and generated a positive push-up structure in the pre-Quaternary bedrock (fig. 7). The area was subsequently involved in the Quaternary extensional tectonics that acted along the same faults. In this way, the Quaternary coarse sediments and associated palaeosoils were faulted and tilted mountainward. The N120°-stricking faults represent regional tectonic elements and were responsible also for the Agri high valley structural setting, being active with different kinematics during several deformational stages.

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