ANNALI DI GEOFISICA, VOL. 41, N. 3, August 1998

Applicability of the dipole-dipole method for structural studies: examples from the Northern Apennines

Mauro Giudici and Luigi Alfano
Dipartimento di Scienze della Terra, Sezione di Geofisica, Università di Milano, Italy

Abstract
We present some results of a geoelectrical investigation program conducted in the Northern Apennines, namely in the Val d'Aveto and Bobbio window and surrounding areas. Field activity included the execution of more than 50 vertical electrical soundings with continuous polar dipole-dipole spread. We image the geometries of some deep geological structures; in particular we found a resistive background, whose resistivity is different along the geoelectrical profiles. In our interpretation the resistive background consists of subligurid and tuscan units underlying the alloctone Ligurid units in the area surrounding the Val d'Aveto and Bobbio window. The resistive background was not found, at least at the same depths, toward north-east. Therefore, the geoelectrical survey revealed the position of the front of the subligurid and Tuscan nappes toward the plain for a depth of about one kilometer.

Key words *geoelectrical prospecting – dipole-dipole DC soundings – crustal exploration – Northern Apennines*

1. Introduction

Electrical and electromagnetic techniques have been applied successfully to image the structure of the Earth's interior in several regions. Electrical DC methods are widely used for shallow studies, mainly for hydrogeological or engineering problems; they can give important information about deep structures in geothermal or volcanic areas. Electrical DC methods can also be applied to collect data useful for the determination of the structural setting of complex regions.

Mailing address: Dr. Mauro Giudici, Dipartimento di Scienze della Terra, Sezione di Geofisica, Università di Milano, Via Cicognara 7, 20129 Milano, Italy; e-mail: Mauro.Giudici@unimi.it

For structural studies, which often require great exploration depth, the use of dipole-dipole spreads is convenient. In particular, we use continuous polar dipole-dipole spreads where the potentiometric dipole (MN) remains fixed and the current dipole (AB) is progressively moved far away from MN: MN and AB are aligned along a straight line (polar spread) and there is no gap between two successive current dipoles (continuous spread) (Alfano, 1974, 1980).

In this paper we present some of the results obtained with dipole-dipole prospecting in the Ligurian-Emilian Apennines. This region is characterised by a complex tectonic evolution, which finally produced the present situation represented in fig. 1, which is based on the «Carta Strutturale dell'Appennino Settentrionale» (Boccaletti and Coli, 1980). The alloctone Ligurid and subligurid units overlay Tuscan units, which outcrop in the Bobbio window and more extensively toward south-east and constitute the dominant outcropping units in the Emilian-Tuscan Apennines. The displacement of Ligurid and subligurid units from their original position has produced a number of nappes, whose geometry is complex and whose relative position has changed during the tectonic evolution.

In these conditions seismic prospecting has not proved as powerful as in other regions, for instance in the Po plain, where the seismic stratigraphic sequence is more regular and can be mapped with great precision. In such complex areas as the Northern Apennines scattering phenomena due to folding, intrinsic attenuation and the effects of thin layering limit the applicability of the seismic techniques, as recognised by Cassinis and Mazzotti (1993).

More than 300 electrical soundings with continuous polar dipole-dipole spreads have been realised since 1980 in a region extending from Val Versa to Val d'Arda over a surface of about 1600 km^2. The field work was coordinated by the authors and achieved with the collaboration of more than 20 students from the Universities of Milan and Pavia. The length of each spread varies from a minimum of 500 m to a maximum of 15 000 m. The corresponding exploration depth varies from 200 m up to 3 km. Generation of the electric field is obtained with an AC portable generator connected to an AC/DC converter. Silt and clay are the principal components of the near-surface rocks in this area, so that a good contact between electrodes and terrain was possible and currents flowing in the Earth were sometimes greater than 2A. The potential difference at the potentiometric dipole was measured with analog devices for distances between the two dipoles up to a couple of kilometers, whereas a digital acquisition system was used for greater distances. In this case signal amplitude was evaluated by stacking or statistical procedures (Alfano, 1993). The electrical soundings were realised along lines, called geoelectrical profiles.

In the following Section 2 we present results from the Val d'Aveto and Bobbio window and from surrounding areas, marked with a rectangle in fig. 1. In Section 3 the geologi-

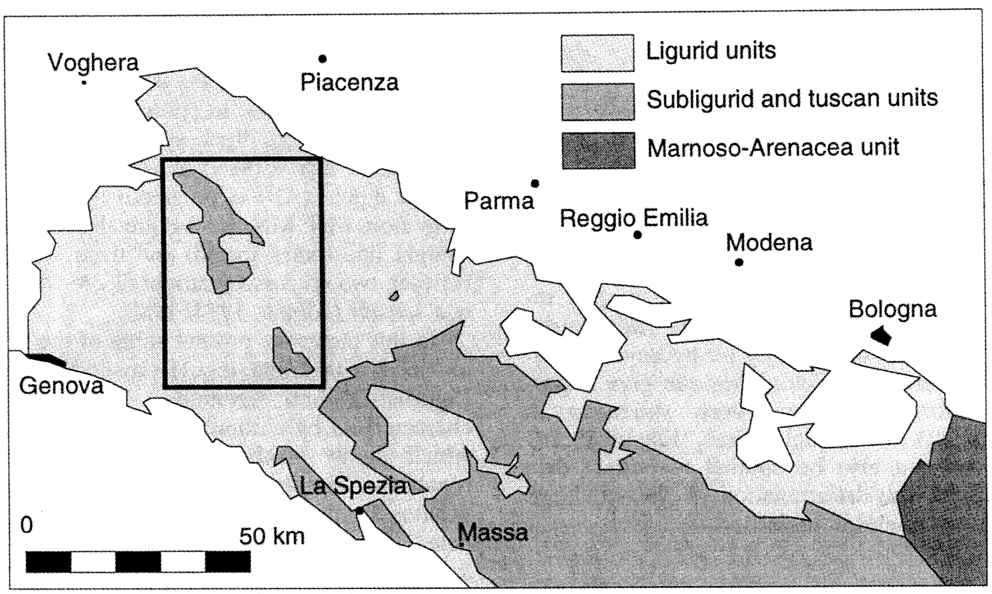

Fig. 1. Geological schematic map of the Ligurian-Emilian Apennines, elaborated from «Carta Strutturale dell'Appennino Settentrionale» (Boccaletti and Coli, 1980). Rectangle shows the region of Val d'Aveto and Bobbio window.

cal problems posed by the geophysical interpretation are discussed and finally we recall the main conclusions.

2. Geoelectrical results for the «Val d'Aveto and Bobbio window» and surrounding areas

The area which is considered in this paper is the region enclosed in the rectangle of fig. 1 and is represented in more detail in fig. 2: solid lines show the geoelectrical profiles that we shall consider. The geoelectrical profile from Perino to Coli is parallel to the river Trebbia and is partly located inside the Bobbio window. The geoelectrical profile from Marsaglia to Cabanne via Boschi runs along the Val D'Aveto, where subligurid units outcrop extensively. The geoelectrical profile starting south of Bettola and arriving at Ferriere runs along the Val Nure, whereas the geoelectrical profile from Bardi toward M. Ragola connects the Valley of T. Ceno and Val Nure. Shorter geoelectrical profiles were realised on the Tuscan units (Trebbia unit) of the Bobbio window and around Santo Stefano d'Aveto, moving toward the main ophiolitic massif of M. Maggiorasca. Along these profiles we executed more than 50 soundings with continuous polar dipole-dipole spread; along each of the four main geoelectrical profiles more than 10 soundings were executed.

The interpretation of each sounding is performed by comparison of the field resistivity curves with master curves for plane parallel layering and three-dimensional models (see, *e.g.*, Giudici and Alfano, 1996). This preliminary interpretation of all the soundings performed along a geoelectrical profile is revised, in order to merge the information obtained from the single soundings. The final results are geoelectrical sections, where the geophysical interpretation is sketched; such a geophysical interpretation has often been very useful to distinguish geological units, because they have different resistivities. As an example we present the schematic section along Val d'Aveto in fig. 3. We have chosen this profile because

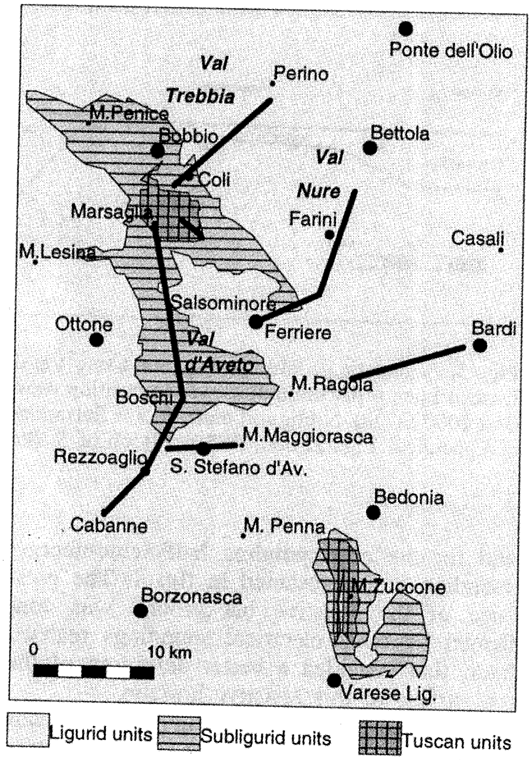

Fig. 2. Schematic geological map of the Val d'Aveto and Bobbio window, corresponding to the rectangle in fig. 1. Lines show the position of geoelectrical profiles analysed in this paper.

it is the longest profile and it is very significant; in fact it crosses outcrops of several geological formations of Northern Apennines and it shows how geoelectrical soundings can distinguish between these units and to map their burden contacts. We can separate the different subligurid outcropping units; in particular the Salsominore unit has the lowest resistivity (50-100 $\Omega \cdot$ m), whereas the Aveto unit has the highest resistivity (500 $\Omega \cdot$ m). Note the presence of a resistive background below subligurid units in the northern part of the section. This resistive background was put in evidence by a 12 km-long electrical sounding from Marsaglia to Boschi: the diagrams of apparent resistivity for the dipole-dipole field sounding

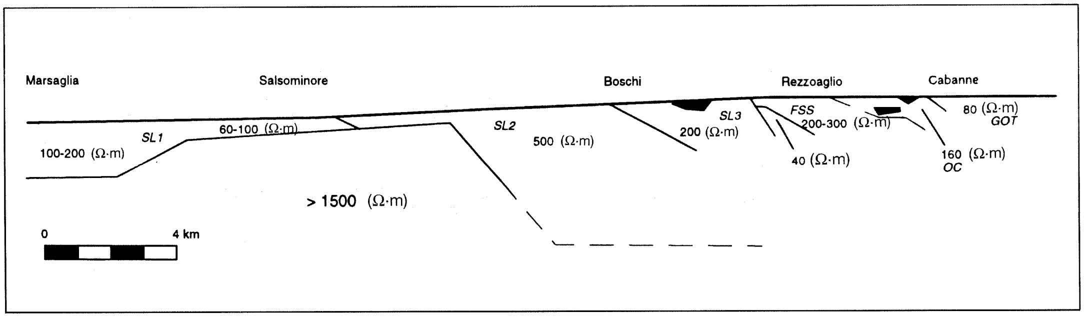

Fig. 3. Schematic geoelectrical section along Val d'Aveto. Continuous lines: well determined discontinuities. Dashed lines = discontinuities whose position cannot be determined exactly; black spots = ophiolitic bodies ($\rho \cong 1000\ \Omega \cdot$ m). Subligurid units: SL1 = Salsominore unit; SL2 = Aveto unit; SL3 = Penice unit «Complesso di Canetolo». Ligurid unit: FSS = Flysch of S. Stefano; OC = Ottone-Casanova unit; GOT = Gottero unit.

and for the corresponding half-Schlumberger sounding are represented in fig. 4. The presence of the resistive background was confirmed by other electrical soundings realised later, that provided a better definition of the top surface of this resistive horizon.

The basis of the outcropping formations was imaged not only in Val d'Aveto, but also along other geoelectrical profiles. In fact some other electrical soundings found a resistive background. In fig. 5 we sketched the position of this background; the lateral extension shown with the dashed lines was estimated taking into

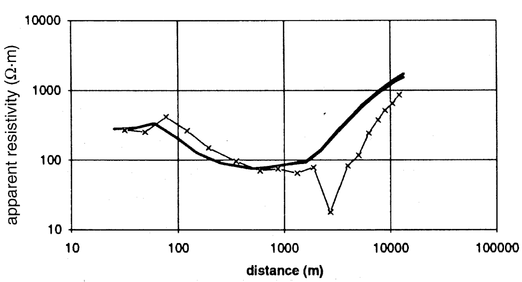

Fig. 4. Diagrams of apparent resistivity for a sounding (spread extension from Marsaglia to Boschi, see figs. 2 and 3) showing the presence of the resistive background in Val d'Aveto. Crosses and thin line = field dipole-dipole diagram; thick lines = half-Schlumberger transformed diagrams.

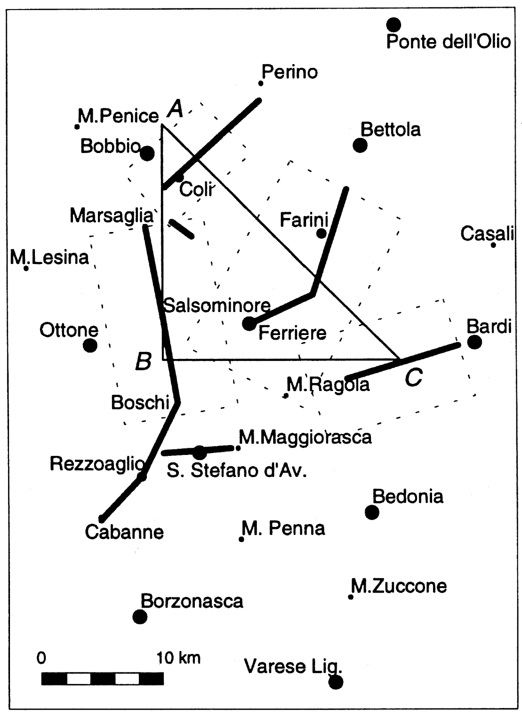

Fig. 5. Schematic representation of the resistive background found from geoelectrical soundings. Dashed lines denote the approximate minimum lateral extension of this resistive background. Lines and lettering indicate the sections represented in fig. 6.

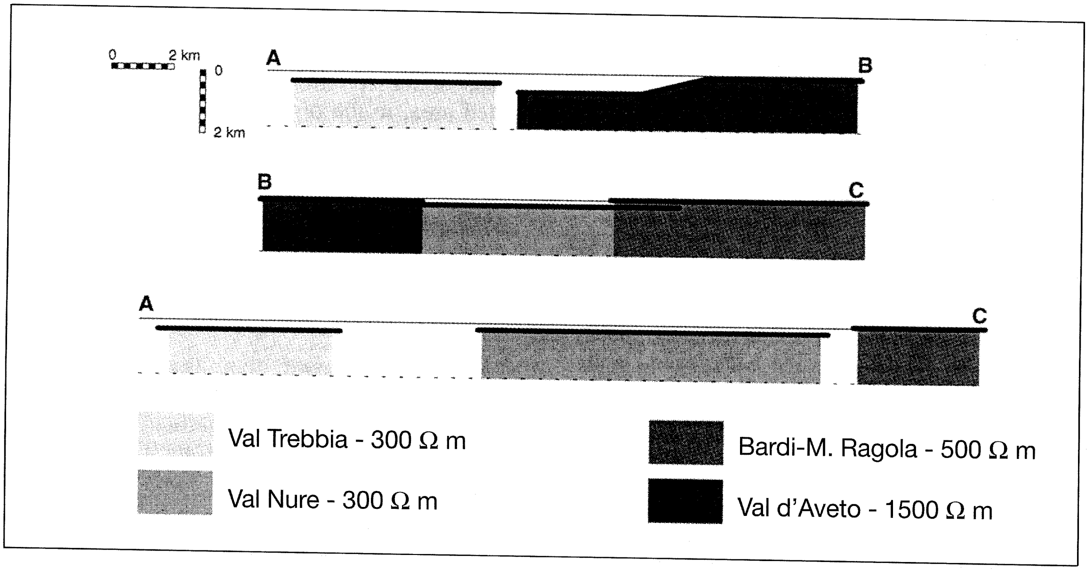

Fig. 6. Schematic geoelectrical sections. The position of each geoelectrical section is represented in fig. 5. Solid line = mean sea level; thick line = approximate position of the top of the resistive background; dashed line = approximate maximum exploration depth.

account the results of mathematical models (Giudici and Alfano, 1996). The results from different zones show variations of the values of resistivity of this background. This is shown with the synthetic geoelectrical sections drawn in fig. 6, where different shadings correspond to different resistivities; this schematic representation shows that the height of the top surface of the resistive horizon does not vary very much and this horizon appears quite continuous over the investigated area.

3. Problems for the geological interpretation

The geological interpretation of the results obtained from the geoelectrical survey in this area is interesting and still open to debate. One of the key problems is the interpretation of the resistive structures underlying the outcropping formations. We shall consider this separately for each of the longest geoelectrical profiles.

3.1. *Val Trebbia and Val Nure* ($\rho > 300\ \Omega \cdot \mathrm{m}$)

In this case we can confidently assume that the resistive background is given by Tuscan units and, more precisely, by the Trebbia unit. This conclusion is supported from several pieces of evidence. First of all, the value of resistivity is the same as that obtained from a sounding executed on the Trebbia unit (see the short geoelectrical profile south of Coli in fig. 2). Furthermore, the discontinuity is dipping and if we extrapolate it linearly from the geoelectrical section, it encounters the limit of the Bobbio window with a good precision. Also surface geological data are consistent with the dip found from the electrical soundings.

The interpretation of wide angle seismic profiles executed along Val Trebbia and Val Nure during 1988-1989 (Cassinis *et al.*, 1990) at small distances from the geoelectrical profile proposed the existence of a shallow high velocity (6 km/s) body. From a geological point of view this was considered to be the signature of an outcropping ophiolitic body, whose bottom should be located at a depth of about 5 km.

3.2. *Bardi-M. Ragola* ($\rho > 500\ \Omega \cdot \mathrm{m}$)

Taking into account the value of resistivity of the background in this region, we could suggest the presence of subligurid units, namely the Aveto unit. However it is difficult to justify the thickness of the resistive background without invoking complex, and unlikely, repetitions of the stratigraphic sequence that composes this formation.

It is again possible to suggest that the resistive background is composed of Tuscan units as for Val Trebbia, although we have fewer arguments to confirm this hypothesis.

If the Aveto unit were a relatively thin layer interposed between the shallow Ligurid units and deeper Tuscan units with high resistivity it would not be possible to reveal its presence with geoelectrical methods.

3.3. *Val d'Aveto* ($\rho > 1500\ \Omega \cdot \mathrm{m}$)

The value of resistivity found in this region is the highest that we have ever measured in the Northern Apennines. The only rocks that showed such high values of resistivity are the ophiolites. However the hypothesis of a ophiolitic background has to be discharged, since ophiolitic bodies are included within Ligurid units, mainly in the Ottone-Casanova unit, and cannot be found below subligurid units.

We recall that resistivity as high as 500 $\Omega \cdot \mathrm{m}$ was obtained on the Aveto unit; these sandstones could eventually increase their resistivity if they are more compact and dry at depth. However the same objections mentioned for the Bardi-M. Ragola profile are still valid.

Once again, we suggest the hypothesis that the resistive background corresponds to Tuscan units, but it is difficult to admit that they are given by the Trebbia unit as for the Val Trebbia and Val Nure profiles, because the value of resistivity found here is higher. However, Tuscan formations like «Macigno», which outcrops about 20 km south east of the investigated area, in the region of M. Zuccone, could have such high values of resistivity. Unfortunately we cannot trace definite conclusions on this, since we did not measure the resistivity of «Macigno» directly.

4. Conclusions

We have shown that the dipole-dipole method can be applied with success in geologically complex areas. In particular we have been able to image the geometries of some

Fig. 7. Representation of the resistive background. The shaded zone is interpreted as the advancing front of the Tuscan and subligurid units toward the Po plain for a depth of about 1 km.

deep geological structures, notwithstanding the relatively low density of soundings.

We stress that it was very important to execute soundings with long spreads. In fact, from the diagrams of apparent resistivity of fig. 4, it is easy to convince oneself that if the spread had been limited to 6 km, it would not have been possible to reveal the presence of the resistive background. The result of fig. 4 motivated some further investigations in the area that led to the results of this paper. The importance of using very long spreads to obtain confident information on deep structures is more evident for dipole-dipole soundings. In fact, the diagrams of apparent resistivity of fig. 4 for the half-Schlumberger spread show an increase in apparent resistivity starting at about 2 km distance between the current pole and the potentiometric dipole, whereas the increase in apparent resistivity for the dipole-dipole spread starts about 4 km later.

As far as the geological interpretation is concerned, we have reconstructed the top surface of subligurid and Tuscan units below the alloctone Ligurid units in the area surrounding the Val d'Aveto and Bobbio window. This discontinuity corresponds to the top of the resistive background put in evidence in the area.

This resistive background was not found toward north-east, at least at the same depths. Therefore, according to our interpretation, we can claim that the geoelectrical survey revealed the position of the front of the subligurid and Tuscan nappes toward the plain for the first kilometer of depth. Such a position is represented by the shaded area of fig. 7.

Acknowledgements

This work was funded by MURST (ex 40%) - LEMI project.

Most of the field data considered for this work were collected by the following students during the preparation of their degree thesis: R. Canobio, A. Cristina, L. Paravelli, F. Pastonesi, C. Sala, J. Sommaruga, N. Turolla and M. Volpones.

We thank the reviewers for some valuable suggestions.

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