ANNALI DI GEOFISICA, VOL. XXXVII, SUPPL. N. 5, 1994

Application of unconventional geoelectrical methods to the hydrogeological examination of the Mt. S. Croce rock formations (Umbria, Italy) involved in a railway tunnel project

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Abstract
The project of doubling and developing of the railway line Orte-Falconara, committed by the Italian State Railway Company to the COMAVI Consortium (Rome, Italy), envisaged building the Mt. S. Croce tunnel, about 3200 m long between the stations of Narni and Nera Montoro (Umbria, Italy). During the last phase of the feasibility project, a geophysical research based on geoelectrical prospecting methods was carried out to complement other geognostic investigations with the following goals: a) to outline the complex geotectonic model of the rock system, which will be affected by the new railway layout; b) to gain information on the hydrogeologic features of the survey area, in relation to the existing geologic situation and the consequent effects on the digging conditions of the tunnel and on the operation conditions of the railway layout. The geophysical work was thus organized according to the following scheme: a) execution of dipole electrical sounding profiles, to depict a series of significant tomographic pseudosections, both across and along the new railway layout; b) execution of self-potential measurements, to draw an anomaly map over the whole hydrogeological network system in the survey area. The research provided information which has helped to improve the geological-structural model of the area and disclosed the hydrogelogic network, conforming to the classified field surface manifestations. At present, further detailed field investigations are being carried out, which confirm all the results obtained by the geoelectrical survey.

Key words *geoelectrics – self-potential – engineering geophysics*

1. Introduction

A geophysical study, based on the application of unconventional geoelectric methods, was performed in the territory of Narni (Umbria, Italy) in relation to the railway tunnel project between the stations of Nera Montoro and Narni Scalo along the new layout of the Orte-Falconara line. The tunnel will be about 3200 m long at an average elevation of 90 m a.s.l., under a rock mass cover of more than 300 m of thickness along its central sector (fig. 1). The COMAVI Consortium (Rome, Italy) was entrusted with the realization of the project by the Italian State Railway Company (Ferrovie dello Stato S.p.A., Rome, Italy).

The aim of the study was twofold. First, it aimed to identify the pattern of the local geo-

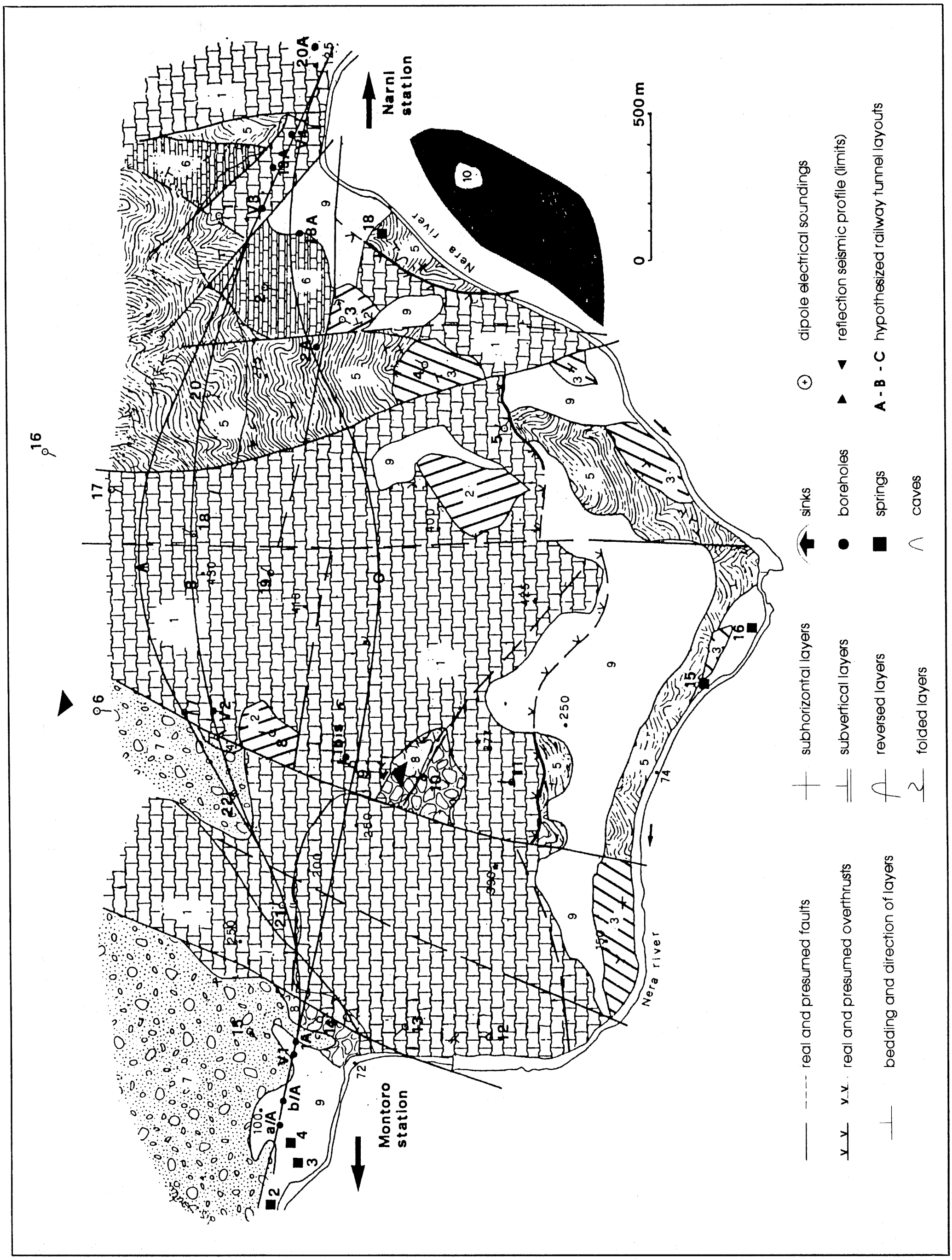

Fig. 1. Geologic sketch map of the survey area. 1 = Massive Limestone (Lias); 2 = Cornel (Dogger); 3 = Flinty Limestones and Jaspers (Malm); 4 = Fucoid Schists (Lower Creta); 5 = Red Shales (Upper Creta, Eocene); 6 = Grey Shales (Upper Eocene); 7 = Sands, Conglomerates and Pelites (Calabrian); 8 = Breccias and Conglomerates (Pleistocene); 9 = Nappe Debris and Alluvium (Olocene); 10 = Urban area.

logic structures, which are constituted by rocks of different geological nature and with variable degrees of fracturization and permeability, in some places also subject to complex karst phenomena. Second, the study delineated the circulation network of the underground waters, which are locally characterized by strongly inhomogeneous chemical compositions.

The survey was programmed to give a substantial contribution to the choice of the optimal tracing of the railway tunnel across the Mt. S. Croce composite rock massif.

The geoelectric survey was based on the fact that, among the many geophysical prospecting methods, it is the only approach capable of assuring, in principle, a proper solution to the problem under study, particularly as it concerns both shallow and deep hydrogeologic circulations and the effects of water-rock interaction.

Given the peculiarity of the problem and in consideration of the local heavy field difficulties, in particular the rough topography and the poor accessibility in the survey sites, we decided to use dipole electric sounding (DES) profiling and the selfpotential (SP) mapping methods.

In the following sections, we shall give an outline of the local geology and then describe the procedure and results of the geoelectric surveys in detail. Finally, we shall depict a geo-hydrologic interpretative model of the studied area, which combines the geophysical data with the previous and subsequent geological and borehole information.

2. Geological outline

Mt. S. Croce, which is the object of the present study, belongs to the complex of the Amelia Mountains, which form a ridge with a NW-SE Apenninic trend. The Amelia Mountains are bounded westwards by the Tiber river graben and eastwards by the Terni plain across which the Nera river flows. In the neighbourhood of Narni the Nera river cuts the Amelia ridge transversely before joining the Tiber river, of which it is a left-hand tributary.

The local geologic setting has been examined by many authors (Decandia, 1982; Decandia and Giannini, 1977a,b,c; Chiocchini *et al.*, 1987). This section summarizes the main elements derived from the synthesis by Chiocchini *et al.* (1987) and from a set of new data collected during our more recent detailed geological surveys (see fig. 1).

From the geological point of view the Amelia Mountains ridge is characterized by a folded structure with both asymmetrical anticlinals and groups of reverse or north-eastwards overthrust anticlinals, almost always sharply cut by normal faults showing remarkable throws. Most of the outcropping rocks belong to the Jurassic-Eocene sedimentary cover of the southernmost margins of the Umbrian-Marchesian pelagic series. The part of this series which outcrops in the Mt. S. Croce area is not complete because of the intense synsedimentary and orogenic tectonic activity which affected the area.

The following terms have been recognized:

Trias – micrites and marls of the «Rhaetavicula Contorta» formation. Such a lithofacies does not outcrop in the survey area, but it was found in borehole 1A (see fig. 1) below rocks of Calabrian facies. The permeability is very low;

Lower Lias – a massive limestone formation («Calcare Massiccio») with local maximum thickness of about 250 m. The average permeability is high;

Jurassic-Cretaceous – series of formations («Cornel», «Ammonitic Red», marls and limestones of Mt. Serrone, «Majolica» and others), observed in the study area in reduced and discontinuous form with total thickness not exceeding 100-120 m;

Upper Cretaceous – «Red Shale» with a local maximum thickness of about 250 m. The permeability is high;

Eocene-Oligocene – «Grey Shale», with local maximum thickness of about 100 m. The permeability is low;

Pleistocene – sandy-conglomeratic deposits and breccias. Middle-to-low permeability.

The tectonics in the area is characterized by the overthrust of the massive limestone on the Red Shale formation and by a subsequent large throw intense faulting.

The morphology in the survey area is distinguished by a very rough topography, showing deep cuttings and scarps in correspondence with the structural strike lines of the rock massif, as well as by moderate surface karst manifestations. It is worth mentioning the existence of some sinks in the central part of the massif and along the right steep slopes of the Nera river, just opposite to the Narni historic centre.

The local hydrogeological system appears to be characterized by a rather complex network. All along the Nera river between the small towns of Narni and Nera Montoro, there are numerous springs with a global flow rate of the order of 15 000 l/s (Chiocchini *et al.*, 1987), of which at least 3000 l/s must be ascribed to seven springs placed at the foot of Mt. S. Croce. These springs represent the most important hydrogeologic evidence in the study area. They probably represent outflows of deep reservoirs, the feeding basin of which seems to be extensive as it involves the whole Terni plain and the mountains following to the east, from Spoleto to the south of Rieti (Messina, 1977).

Chemical analyses, performed on water samples from the above mentioned springs (Chiocchini *et al.*, 1987), have distinguished three different groups, according to the distinctive mineral compositions (see fig. 1):

a) carbonatic-sulphatic-sodic-calcic outflows (2, 3 and 4);

b) carbonatic-chloridic-calcic-sodic outflows (15 and 16);

c) carbonatic-chloridic-calcic outflow (18).

Such strong mineralizations of the spring waters support the previously cited hypothesis of a very extended feeding basin with deep water circulation, in contact with prevailing carbonatic and evaporitic rocks. A different classification of the waters, based on salt concentration distinguishes a high salinity class including groups (a) and (b), from a low salinity one constituted by group (c). Since the water outflows are located along the same slope as Mt. S. Croce, the last classification also suggests the existence of a geological element of hydraulic separation inside the rock massif.

3. Dipole-sounding profiling

The DES profiling method consists in the determination of the apparent resistivity distribution along the vertical axis through a set of reference stations distributed on the ground surface along a profile.

DES measurements are carried out by means of two dipoles, of which one is used to send an electric current into the soil and the other to detect a surface component of the electric field associated to the current flow and distorted by the underground resistivity structure. In performing the axial sounding, one of the two dipoles is held fixed and constitutes the base station, while the other, in line with the fixed dipole, is moved along the sounding expansion axis, in order to explore deeper and deeper underground volumes. Due to local field difficulties, the expansion axis of a few DES could not be taken to coincide with the profiling axis.

Basically, DES surface data are influenced by both vertical and horizontal resistivity variations. The profiling technique is thus devoted to highlighting such variations, by allowing mutual correlations between adjacent DES apparent resistivity data.

Conventionally speaking, the definition of a buried geologic structure in terms of sharp resistivity contrasts may be achieved by a modeling procedure of the measured surface data by a forward or inverse scheme. However, in many situations of complex geology this is a very hard task, as it requires not only the capacity of solving 2D or 3D modelling, but also many constraints or a priori information necessary to reduce critical ambiguities due to equivalence of solutions. When these facilities are not available, as is usually the case, any even upgraded modelling approach can actually prove largely ineffective or poorly conforming to the real structure. Moreover, particular tectonic, mineralogical, petrological and hydrological complex situations, which can cause widespread inhomogeneous physical statuses, can hardly be modelled by a set of sharp resistivity contrasts across the boundaries between forcedly homogeneous rock volumes.

To overcome these difficulties, one may resort to an analytically less problematic, but, to some extent, more impressive and less subjective approach. It consists in drawing a pseudo-section of the DES data sets, which provides a self-explanatory sketch of the anomalous resistivity pattern along the profile. To make this operation, the apparent resistivity data of each DES are reported along the vertical line through the centre of the fixed dipole at «effective depths» equal to half the spacings between the centres of the two dipoles (Alpin, 1950; Patella, 1974). By choosing geophysically significant apparent resistivity classes or variable contour intervals, one may consider the pseudo-section as a tomographic image of the subsurface structures (Worthington, 1984).

Of course, in the case in which abrupt resistivity contrasts between homogeneous rock volumes are justified, such a conformity would appear rather daring as no close similarity can actually be found between the contoured resistivity ranges of a tomographical pseudo-section and the expected cross-section of any step-like or block-wise actual resistivity distribution. Therefore, the proper definition of the buried geometries deserves much more care and a closer correlation between the geophysical qualitative subsurface imaging and surface geology and borehole information. However, if one admits, as outlined above, the existence of point resistivity variations, as those predicted by the conceptual model of distribution of α-harmonic resistivity centres (Stefanescu, 1970), this correspondence is straightforward and one can really consider the pseudo-section as a first order tomographic image of the underground resistivity setting. Moreover, a proper integral transformation of the pseudo-section data set, whose design is, however, outside the scope of the present text, would then lead to a second order cross-section tomography, which could better delineate the underground resistivity pattern. For the reader's sake, we recall that an α-centre is a resistivity pattern characterized by a conductive or resistive nucleus, from which resistivity radially increases or depletes as the distance from the nucleus increases. A spatial network of distributed α-centres can adequately represent any geophysical situation, in which radially damping cracking action, fluid permeation and salt concentration, as well as transitional boundaries are distinctive geological features. All these factors probably concur to determine gradual resistivity variations as those predicted by the α-centre theory.

In the study area, we carried out 22 DES with the centres of the fixed dipole arranged as in the map of fig. 2. The arrows show the directions of the sounding expansion axes. The centres of the DES were located in such a way as to realize the five profiles of fig. 2. In particular, profile AA′, including DES 1 through 5, about 1.2 km long, is a nearly N-S line running along the eastern slope of Mt. S. Croce close to the tunnel entrance from the side of Narni Scalo. Profile BB′, which includes DES 6 through 11, is a NNW-SSE alignment, of about 1.5 km of length, along the western border of the top part of Mt. S. Croce, at a mean altitude of 320 m a.s.l., which crosses borehole 1 bis, previously drilled near the original tracing C of the railway tunnel project (see fig. 1). Profile CC′, including DES 12 through 15, is a WNW-ESE alignment, of about 1 km of length, developing along the south-eastern edge of Mt. S. Croce, close to the tunnel entrance from the side of Nera Montoro. Profile DD′, of about 1 km of length, including DES 16 through 19, is about a N-S alignment running along the top of Mt. S. Croce at a mean height of 430 m a.s.l.. Finally, profile EE′ of about 3 km of length, including DES 20 through 22, DES 18 of profile DD′, and points a, b and c of intersection with profiles CC′, BB′ and AA′, respectively, was designed in order to realize an important pseudo-section along the alternative tracing B for comparison with the preliminary layout C (see fig. 1).

Figure 3 shows the DES «apparent resistivity-versus dipolar spacing» curves on a double versus dipolar logarithmic sheet. As one can observe, the apparent resistivity values along the entire spacing axis are spread over a very

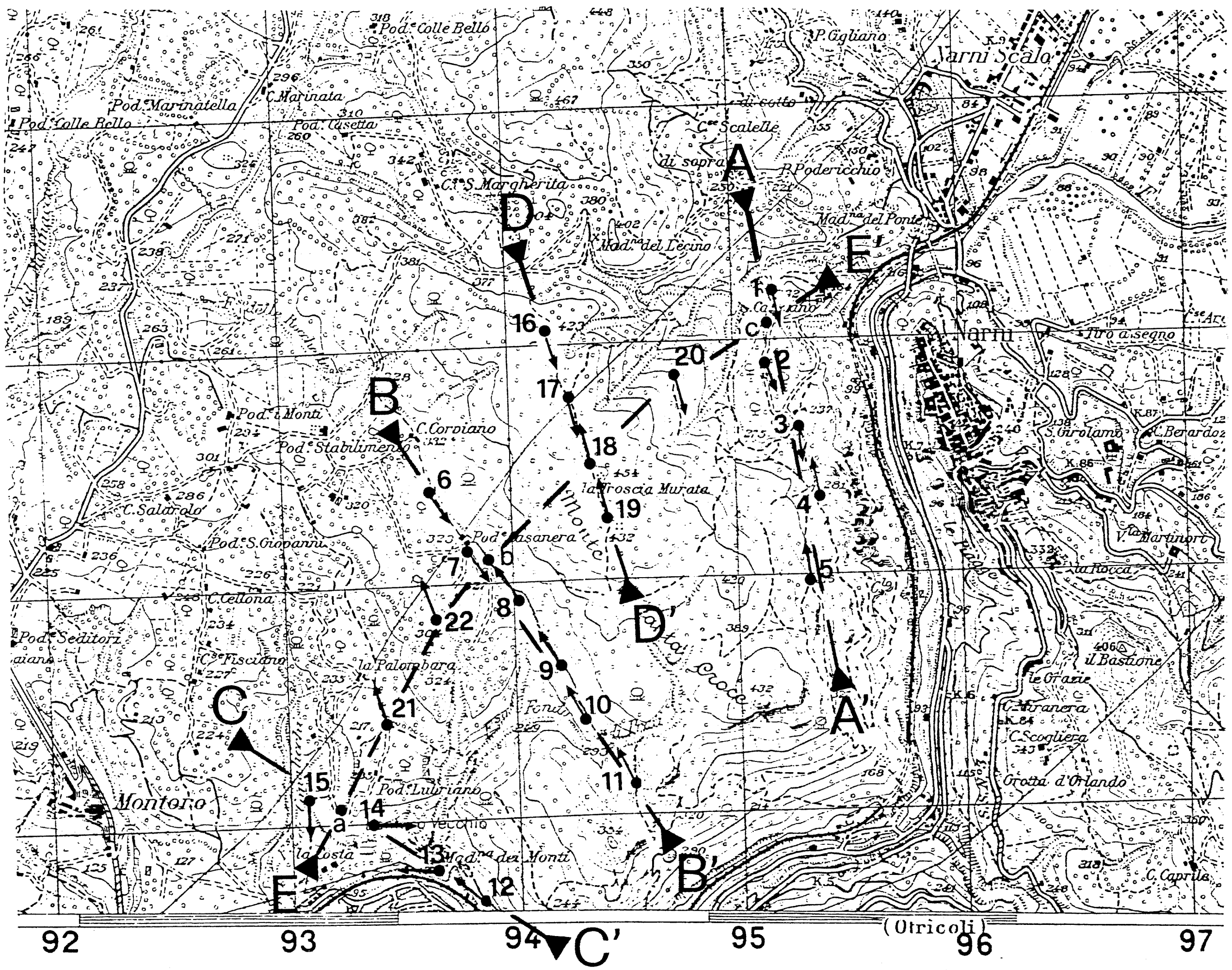

Fig. 2. Topographic map of the study area with indication of the centre (heavy circle), expansion direction (arrow), profiling axis and identification number of the dipole geoelectrical soundings (DES).

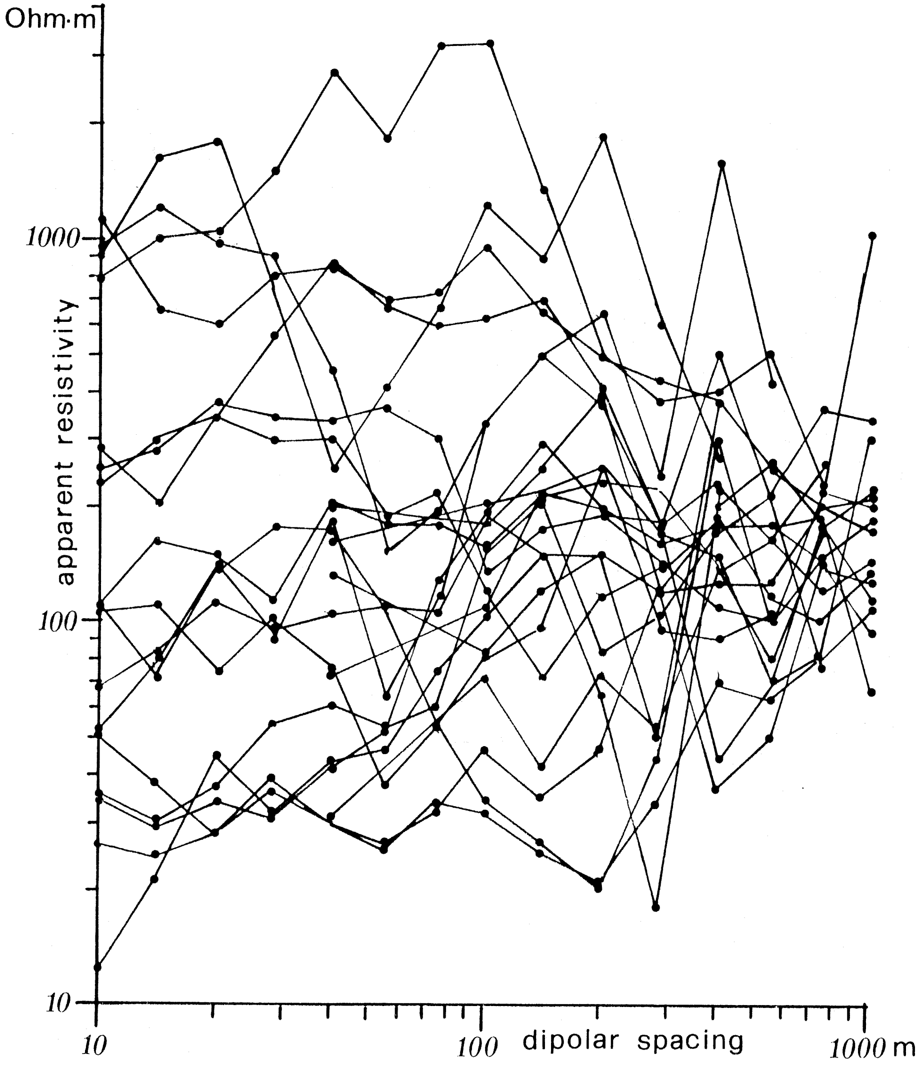

Fig. 3. Assembled DES apparent resistivity diagrams.

large resistivity range, say within a little more than 10 Ωm and a little less than 4000 Ωm. Moreover, each sounding curve is affected by a large scattering of the data again along the whole spacing axis. Both occurrences well outline the presence in the area of a high degree of lateral and vertical inhomogeneities, which can be better visualized by the tomographical representation. Therefore, the DES data have been utilized to depict the tomographical pseudo-sections of figs. 4 through 8. To this aim the following apparent resistivity ranges were established to conform to the expected geohydrologic local conditions:

a) < 50 Ωm; values of this class may be related to the presence of very conductive materials such as clay or loose sediments with a

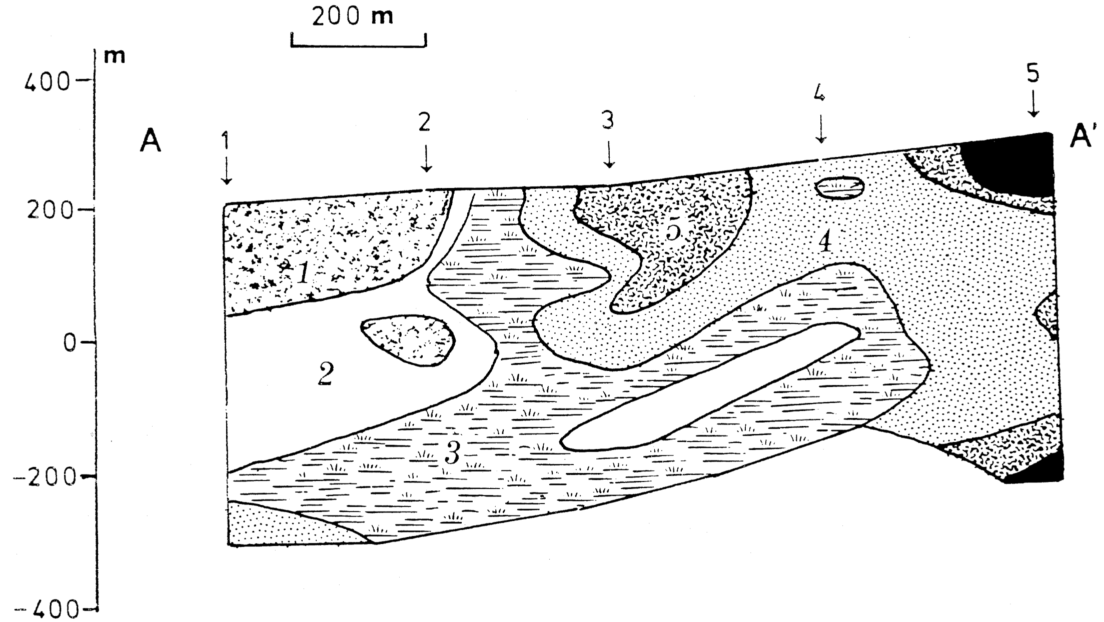

Fig. 4. Tomographical pseudo-section of DES profile AA′. DES station sites and execution order numbers along the profile are indicated by vertical arrows and above standing figures. Resistivity classes are identified as follows: 1 = <50 Ωm; 2 = 50-100 Ωm; 3 = 100-200 Ωm; 4 = 200-500 Ωm; 5 = 500-1000 Ωm; black = >1000 Ωm.

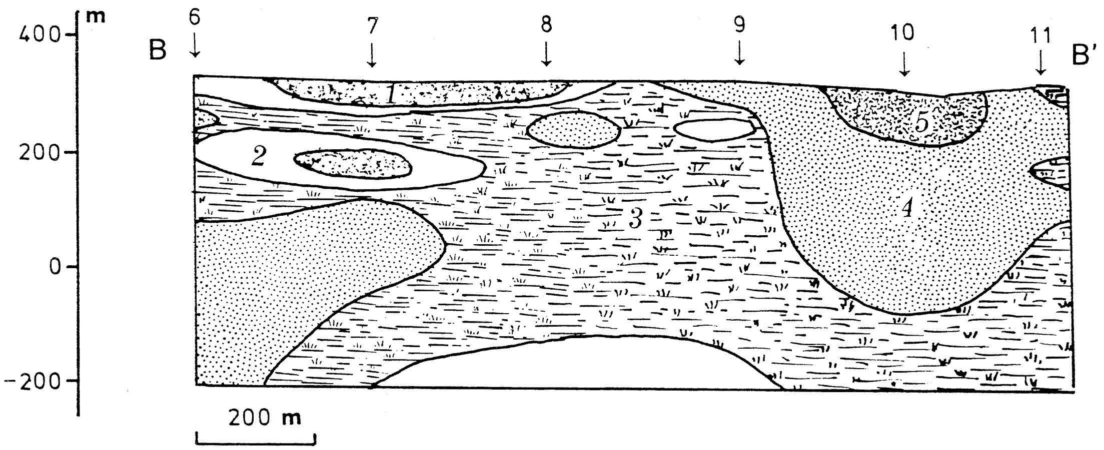

Fig. 5. Tomographical pseudo-section of DES profile BB′. DES station sites and execution order numbers along the profile are indicated by vertical arrows and above standing figures. Resistivity classes are identified as follows: 1 = <50 Ωm; 2 = 50-100 Ωm; 3 = 100-200 Ωm; 4 = 200-500 Ωm; 5 = 500-1000 Ωm.

very high percent of clay content. They must be considered totally impermeable.

b) 50-100 Ωm; values of this range may be determined by the presence of conductive material in an otherwise resistive matrix. Lithoid rocks with a high clay content, like marls or marly limestones, could be responsible for this low-intermediate resistivity class. They can be also considered globally impermeable.

c) 100-200 Ωm; this class may be associated with the presence of weakly resistive bodies, such as largely fractured stone rocks saturated with highly mineralized waters. These bodies can be considered as highly permeable rocks.

d) 200-500 Ωm; this range may be determined by the presence of resistive materials of the same type as those belonging to the previous class, but less fractured and/or filled with less mineralized waters. The permeability of these bodies can be lower than in the previous case.

e) 500-1000 Ωm; this range may again be ascribed to the existence of materials of the same type as those characterizing the two previous classes, but with a negligible fracturization degree and water content. The permeability of these rocks should be vanishing.

f) > 1000 Ωm; values of this last class should be determined by the presence of very compact and dry materials possibly of the same type as those of the three previous classes. They can be considered globally impermeable.

Looking at figs. 4 through 6, we note that along the pseudosections AA′, BB′ and CC′ there is a remarkably different resistivity pattern between the south-eastern sectors, towards the Nera river, and the opposite north-western ones. In the former sectors we observed the massive presence of the resistive materials of classes (d), (e) and (f), of which the most resistive terms practically constitute the nuclei of the entire geo-structure, which develops from surface down to great depth. In the latter sectors, terrains of classes (a) and (b) are predominant. In particular, across the two profiles AA′ and CC′, the conductive materials seem to have a very large thickness in contrast with the evident thinning of the same bodies in profile BB′.

Of great importance for the solution of the problem is the extent of the materials belonging to the resistivity class (c), which is very likely to be characterized by an intense water

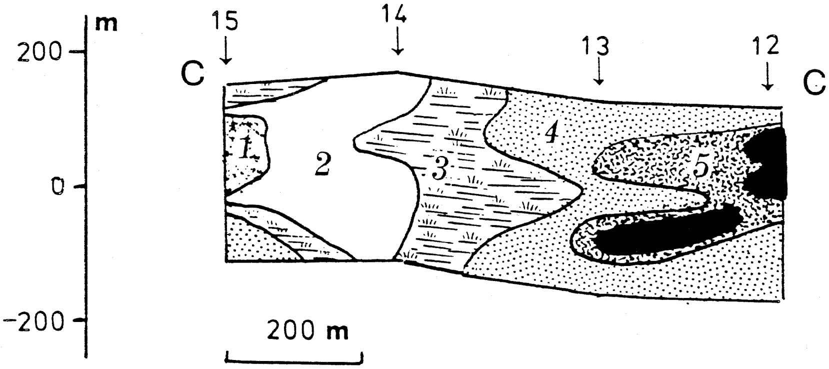

Fig. 6. Tomographical pseudo-section of DES profile CC′. DES station sites and execution order numbers along the profile are indicated by vertical arrows and above standing figures. Resistivity classes are identified as follows: 1 = <50 Ωm; 2 = 50-100 Ωm; 3 = 100-200 Ωm; 4 = 200-500 Ωm; 5 = 500-1000 Ωm; black = >1000 Ωm.

circulation. Such bodies appear largely extended both laterally and vertically mainly in pseudo-section BB′, while in cross-section CC′ they are drastically reduced.

It is worth mentioning that profiling DD′ was designed after having examined the results from the three previous geotraverses AA′, BB′ and CC′. From the relative pseudosections we had observed that the preliminary railway tunnel tracing, running at an average altitude of 90 m a.s.l., would have almost totally crossed volumes identified by the resistivity class (c), to which high permeability water-bearing formations are very likely to be associated. The same pseudo-sections also outlined in their north-western sectors the presence of conductive bodies, very probably impermeable, belonging to the resistivity classes (a) and (b). This experimental evidence led us to explore some uphill variants for the optimal design of the railway tunnel tracing. To facilitate this approach, profile DD′ was at first attempted. However, the results depicted in the relative pseudo-section (see fig. 7) revealed throughout the section at the depths of interest an almost uniform presence of bodies belonging to resistivity class (c), apart from a lenticular structure, located in the height range 150-200 m a.s.l. and laterally extended for about 500 m between the station sites of the DES 17 and 19, which very likely includes impermeable materials of resistivity class (b). In order to derive all the necessary information on the uphill geologic situation, profile EE′ was then concluded, hypothesizing that a railway tunnel layout could be realized there, corresponding to layout B of fig. 1. The relative tomographic pseudo-section of fig. 7 shows that the railway tunnel tracing B, also placed at a mean altitude of about 90 m a.s.l., would very probably encounter less difficulties, since only about one third of the whole layout would now be affected by permeable materials of resistivity class (c).

On the basis of this information, which was obtained at the highest possible confidence limit on account of the mentioned heavy field

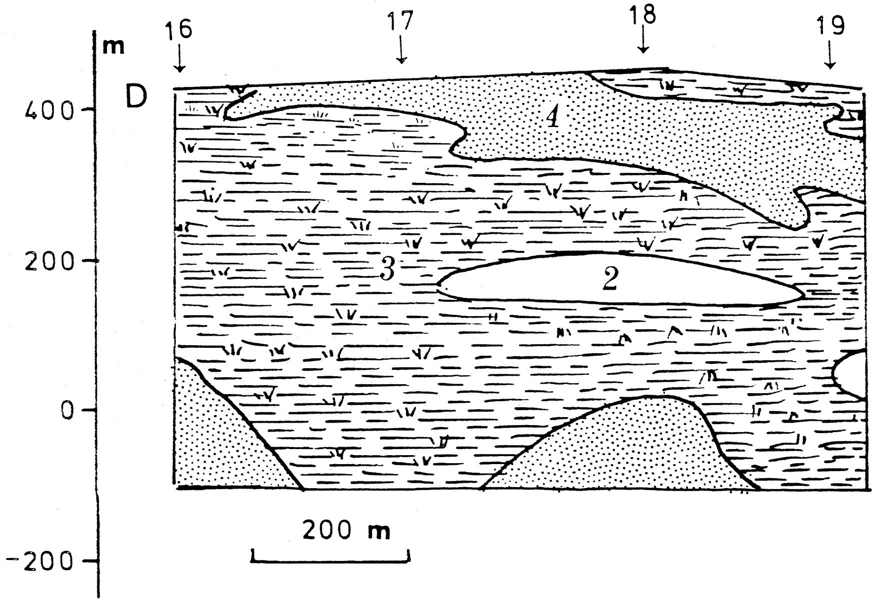

Fig. 7. Tomographical pseudo-section of DES profile DD′. DES station sites and execution order numbers along the profile are indicated by vertical arrows and above standing figures. Resistivity classes are identified as follows: 2 = 50-100 Ωm; 3 = 100-200 Ωm; 4 = 200-500 Ωm.

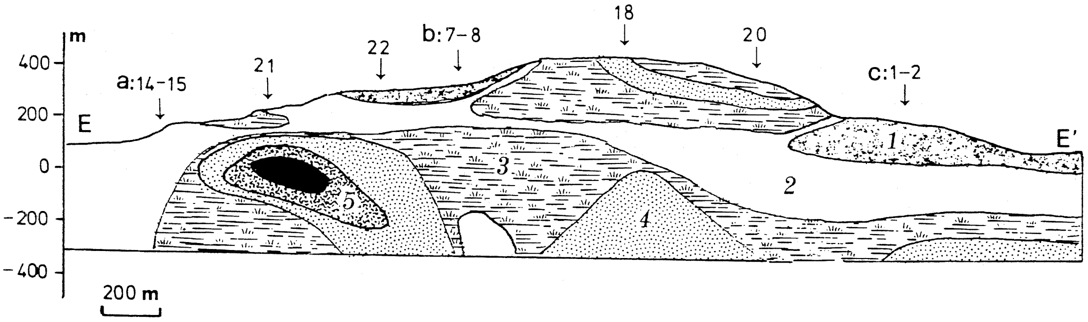

Fig. 8. Tomographical pseudo-section of DES profile EE′. DES station sites and execution order numbers along the profile are indicated by vertical arrows and above standing figures. The crossover points with the transverse profiles AA′, BB′ and CC′ are indicated by the letters (a), (b) and (c), respectively. Resistivity classes are identified as follows: 1 = <50 Ωm; 2 = 50-100 Ωm; 3 = 100-200 Ωm; 4 = 200-500 Ωm; 5 = 500-1000 Ωm; black = >1000 Ωm.

difficulties, we consider tunnel tracing solution B a reliable alternative to the preliminary layout C, which on the other hand seems compromised by the presence of an almost continuous sequence of permeable materials of resisitivity class (c).

A possible further alternative solution could be layout A of fig. 1, which has to be considered the upper tracing limit, as any further upward displacement would introduce such a high curvature in the middle portion of the railway layout to be incompatible with the required operating train velocity. In fact, layout A would presumably be affected by a minor portion of water bearing materials, around the intersection zone with profile BB′, where a major extension of the rock bodies belonging to resistivity class (d) is evident at the tunnel project depth (see fig. 5).

4. Self-potential mapping

The phenomenon which originated the self-potential (SP) anomalous field of interest in the present hydrogeologic study, is known as electrofiltration. Basically, it consists of the generation of an electric field due to movement of underground electrolytic waters in a porous permeable system.

When an electrolytic solution moves across a porous membrane a potential difference is generated between the opposite sides of the membrane. The rocks can be considered membranes, when they have porosity in the form of a dense network of capillaries, which the underground waters can permeate. The walls of the pores have the power of adsorbing only one type of ions, which in turn attract all around them mobile ions of opposite signs thus forming a stable electric double layer. The adsorbed ions remain fixed to the walls of the crystalline matrix, whereas the mobile ions can be easily transported by the water molecules if they are mobilized by a pressure gradient, for instance. The flow of water thus produces a net separation of charges which is seen in the form of an anomalous SP field.

The electrofiltration phenomenon can be originated in almost all water bearing rock materials, but the corresponding SP fields are generally weak, excluding some particular situations in which their intensity can reach high values, well beyond the background noise, because of the presence of densely fractured and/or karstified rocks or in areas with intense flow of strongly mineralized waters.

During the SP survey over the territory of Mt. S. Croce the SP measurements were performed along closed circuits including about eighty stations regularly distributed at the constant step of 200 m, as shown in fig. 9.

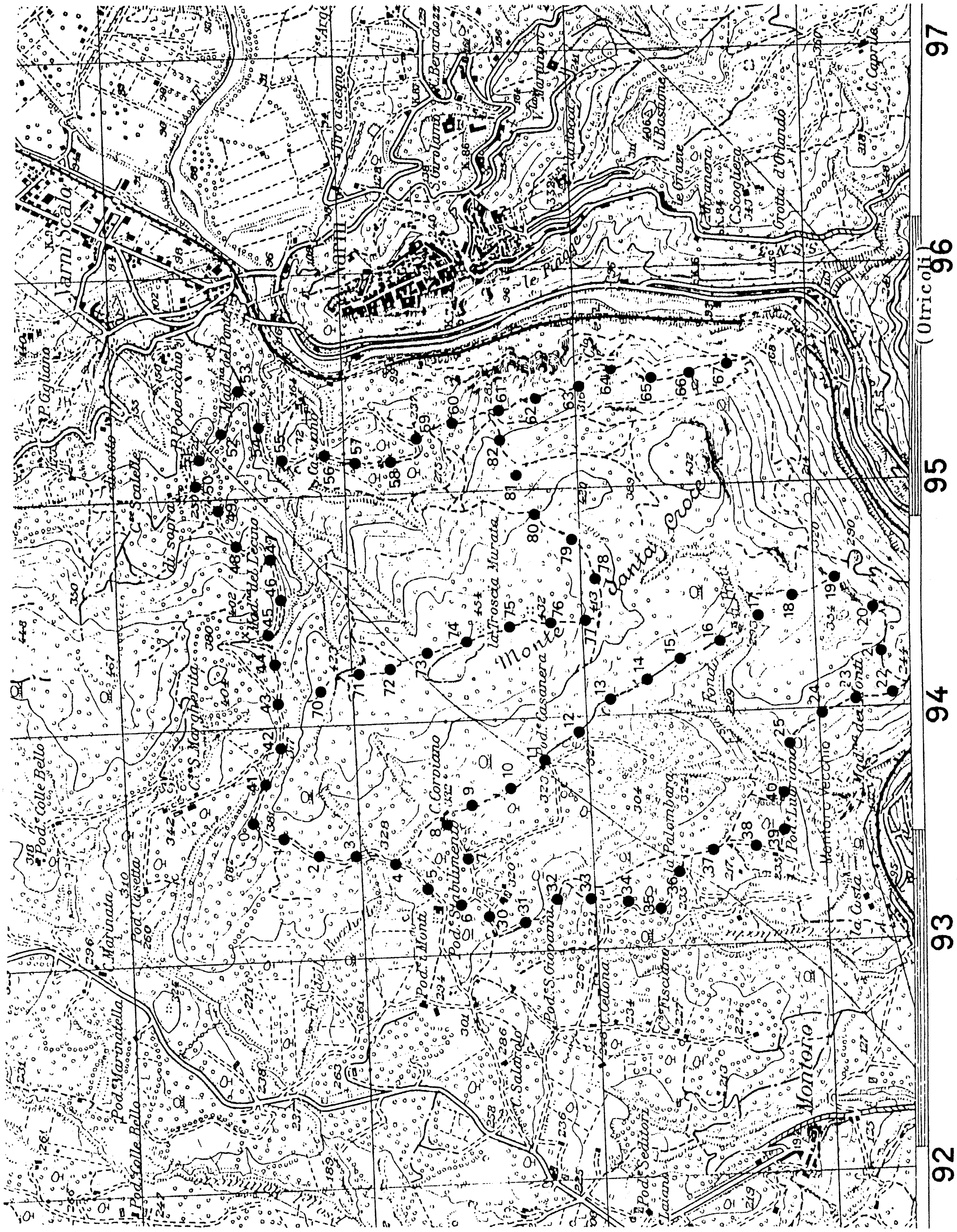

Fig. 9. Topographic map of the study area with indication of the station sites (dots) and numbers along the circuits of the self-potential (SP) areal survey.

The SP measurements consisted of the detection of the potential drop across passive bipoles 200 m long, using copper rods as electrodes. A digital multimeter connected to a microcomputer with data control and elaboration capabilities, both fed by rechargeable Ni-Cd batteries with an autonomy of about twelve hours, was utilized. Every SP determination represents the mean value of twenty consecutive measurements, sampled every 3 s.

All SP data were corrected to eliminate the mis-tie error in each circuit as well as the spurious signals due to the electrode polarization. The first correction was carried out by summing all SP drops along a closed circuit, dividing the sum by the number of bipoles composing the whole circuit and subtracting the resulting ratio from each measured SP drop. The second correction was realized by a special field procedure consisting of using a set of three electrodes cyclically, in same sequential order. By summing the potential drops every three consecutive bipoles starting from the first position in the map, which was given the station number «0» (see fig. 9) and a zero SP value, all SP values at the initial points of all consecutive triads were free from the electrode polarization error. As the computed SP values in all polarization free stations are essentially undetermined, because of the arbitrary zero value assigned to station site «0», a further step consisted of the translation of all SP values by a constant quantity given by their mean value. This shifting of the zero has only the purpose of better differentiating the negative and positive parts of the SP surface field, which is a useful piece of information contributing to solve the problems of the water flow direction and the ion adsorption property of the rock matrix.

The resulting SP values were then contoured to draw an SP anomaly map over the survey area with a contour interval of 50 mV (see fig. 10). The pattern of the isolines discloses the presence of some anomalies, which are now discussed. Before doing this, we note that, by an empirical calculation very similar to the one currently done in gravity analysis, based on the examination in each anomalous zone of the ratio between the maximum excursion of the SP field and its maximum horizontal gradient, an estimate of about 500 m b.g.l. is obtained for the maximum depths of burial of the SP field sources.

In fig. 10 we observe the presence of an uphill north-western SP positive nucleus and of two downhill negative nuclei, close to the Nera river. There appears a good correspondence of the south-eastern negative nucleus with the water springs of group (b) and of the south-south-western negative nucleus with the water springs of group (a) (see the introductory section and fig. 1 for the definition of the spring groups and their locations). In particular, one may hypothesize the presence of two distinct, prevailingly horizontal flow systems, with which the two different mineralized waters of the above quoted spring groups (a) and (b) very likely correspond.

In fact, the first flow system, which feeds springs 2, 3 and 4, seems locally concentrated south-westward from a watershed line localized exactly in correspondence with DES profile BB′ (see fig. 2), along which borehole 1 bis was drilled. The geological map of fig. 1 shows in correspondence with the DES profile BB′ and the evidenced watershed line the strike of a fault plane. Hence, one may suppose that the waters feeding this hydric system are of deep origin and that the fault area, in the zones where it is permeable, favours a vertical hydric flow per ascensum feeding the south-western acquifer. In support of this hypothesis, we may observe that the cited watershed line (the double pointed line in the SP map of fig. 10) indicates the locus of maximum spreading of a set of wedge-shaped SP isolines separating the negative nuclei. Of course, this pattern may not correspond with a strong horizontal component of the electrical field and hence of the electrokinetic flow. Conversely, a relevant vertical component of the same field and hence of the electrolytic flow may very likely conform to the pattern under analysis, as hypothesized above. In all sites where the SP isolines tend to crowd together a reverse flow pattern can be hypothesized, *i.e.* the electric field horizontal component becomes stronger, while the vertical component may even vanish. The arrows drawn in the SP map of fig. 10 out-

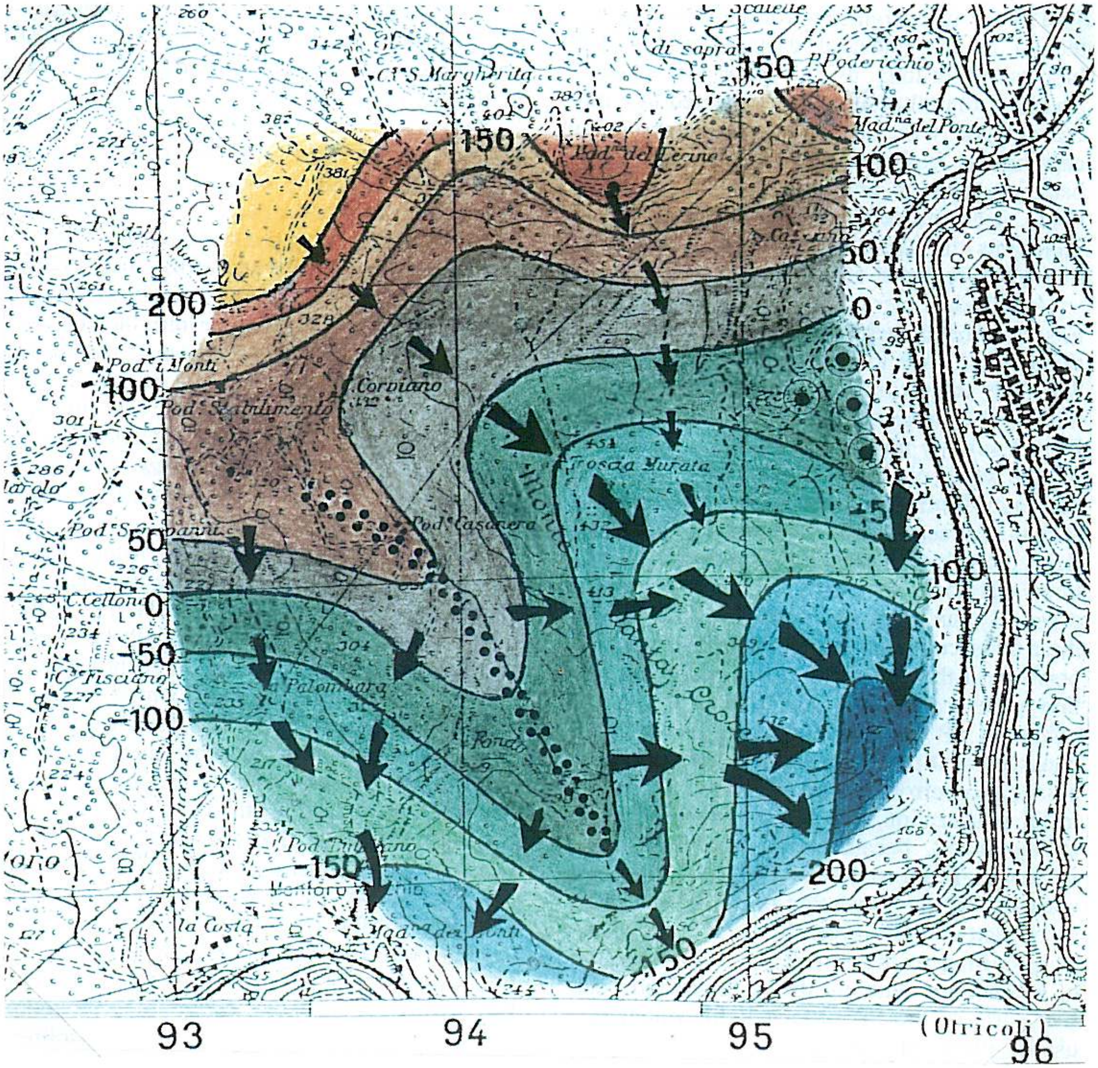

Fig. 10. Colour sketch map of the SP anomaly surface field.

line this occurrence, as they schematize the main horizontal flows along paths of relative maximum of the SP horizontal gradient.

Similar considerations can be pointed out for the flow pattern on the other side of the above cited watershed line. The system of paths which branch off from it seems to supply that part of the acquifer feeding springs 15 and 16. These springs appear also fed by conspicuous water flows, which can be substantially identified by the following two directrices. The first one directly links the uphill positive nucleus with the south-eastern downhill nucleus along the belt of maximum SP superficial gradient. It is of particular importance for the problem under examination, as it crosses transversally from NW to SE the whole sector across which the DES profilings BB′ and DD′ had pointed out the net prevalence of the highly permeable rocks of resistivity class (c). The second directrix, which is only partially outlined, runs parallel to the Nera river.

It is now worth spending a few words on a slight anomaly which appears in the eastern side of the map just opposite to the Narni historic centre. The two isolines 0 and −50 mV start to diverge eastward opening a very localized sector of weak horizontal flow, to which a not negligible vertical flow could very probably correspond. Spring 18 belonging to group (c) is located in this area (see fig. 1).

In conclusion, a general view of the SP map of fig. 10 shows that the study area may be qualitatively interpreted as composed of two adjacent sectors, physically separated by a NE-SW trend straight diagonal, ideally connecting the two localities of Narni Scalo and Nera Montoro, across the Mt. S. Croce top part. The downhill sector seems to be affected by hydric flows uniformly distributed over it. Hence, the preliminary railway tunnel tracing C must be considered inadequate, as it is completely designed in this sector. Conversely, in the uphill half-space only a few preferential transverse flow directrices are manifested, of which the central one seems to be the most significant. The new railway tunnel tracing B, suggested after an analysis of all DES profilings, crosses this second sector and, on account of the above considerations, it appears the optimal solution to the problem under examination, essentially because of its minor hydrogeologic impending risk.

5. Comparative data analysis, testing investigations and conclusions

The geoelectric investigations performed in the survey sites have provided the expected cognitive elements, which are still subject to careful evaluation. On the whole, the elaboration of the DES and SP measurements has disclosed the following guidelines, which can help delineate both the geostructural setting in the study area and the water circulation network underground:

a) presence of geological structures, with prevailing subhorizontal bedding, characterized by low-to-medium resistivity values and overlying more or less isolated and remarkably resistive deep nuclei;

b) presence of rock volumes, characterized by a high mean conductivity which is typical of water-bearing bodies, localized all around the average elevation a.s.l. of the planned tunnel tracing and with variable lateral extension from place to place;

c) presence of a two-modal SP surface field, which denotes the existence of a double underground water flux directed towards the two main spring groups (2,3,4 and 15,16 of fig. 1), located along the right-hand side of the Nera river. Presence of a wedge-shaped band of the SP field, which points out the probable existence of a barrier separating the two hydric flows.

These elements conform very well to a structural model based on the occurrence of overthrusting events and of a system of more or less extended faults, which divide and dislocate the deeper geological formations. In particular, the discontinuous more resistive deep nuclei could be indicative of the existence of dislocated formations, delineating a system of localized trenches and pillars, which could affect the base Triassic rocks. Conversely, the masses characterized by a middle-to-low resistivity, which is typical of water-bearing rocks, could be correlated with the «Red Shale» formation. Moreover, the distribution of the SP field surface isolines better defines the peculiarity of the hydrogeological model in the survey area, by pointing out the existence underground of a hydraulic separation diaphragm and also the two main flow directrices toward the most important groups of springs along the right-hand side of the Nera river.

As validity tests of the proposed modeling elements, some boreholes were drilled and a reflection seismic profile performed along a transversal line crossing the hypothesized railway tunnel layouts (see fig. 2). All tests con-

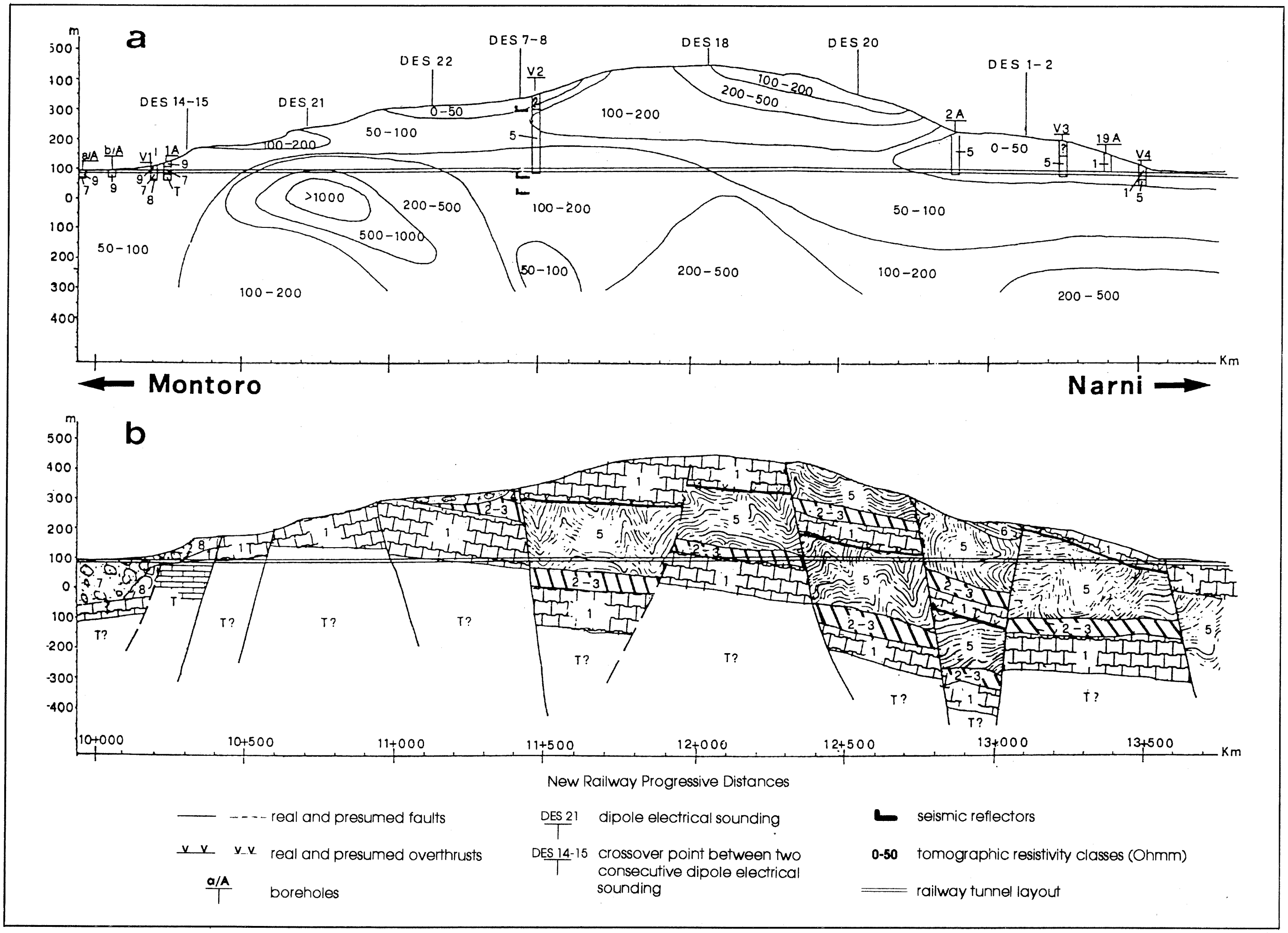

Fig. 11a,b. Panel (a): tomographical pseudo-section of DES profile EE′, with indications of borehole and seismic reflection data. Panel (b): interpreted geological cross-section. The legenda for lithotypes is: 1 = Massive Limestones (Lias); 2 and 3 = Cornel (Dogger), Flinty Limestones and Jaspers (Malm); 4 = Fucoid Schists (Lower Cretaceous); 5 = Red Shale (Upper Cretaceous-Eocene); 6 = Grey Shale (Upper Eocene); 7 = Sands, Conglomerates and Pelites (Calabrian); 8 = Breccias and Conglomerates (Pleistocene); 9 = Nappe Debris and Alluvium (Olocene); T = «Rhaetavicula Contorta» formation (Upper Trias).

firmed the modeling elements deduced from the geoelectric DES and SP surveys. Figure 11a summarizes the results of the in situ test investigations.

On the basis of the whole set of information, the interpretive geologic cross-section of fig. 11b was finally traced. It constitutes the present state of knowledge on the hydrogeological structure of Mt. S. Croce. This interpretive section was constructed across the hypothesized tunnel tracing B, which, on account of the manifold aspects intervening in such a type of railway project, appears the most suitable for the realization of the tunnel layout.

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