A deep geoelectrical survey in the Southern Central Alps

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Abstract
A deep geoelectrical survey was carried out on the Southern Central Alps, to the north of Bergamo, by means of the «continuous polar dipole-dipole» electrode array. Among the 6 profiles executed, 4 revealed the existence of a substratum with very high resistivity values (15 000-40 000 ohm.m) and a flat not very deep upper boundary; its thickness exceeds the maximum exploration depths of the soundings (1 to 6 km). On the grounds of general considerations and resistivity field data set, it is possible to infer that the high values should be ascribed to endogenous rather than to sedimentary rocks. A problem arises since these geophysical results are not in agreement with some geological models.

Key words *geophysics – geoelectric – Central Alps*

1. Introduction

This survey, the first of this type carried out in the Italian Alpine Region, includes 34 «continuous polar dipole-dipole» geoelectric soundings, (E.S.), 14 of which were carried out in the frame of the Deep Crust Project (CROP), with higher exploration depths (up to 6 km). The remainder, performed by students at the Milan University, with exploration depths of about 1 km, were helpful for the delineation of the more superficial structures. Those students, now graduates, are co-authors of this paper.

Figure 1 shows a map of the surveyed area; the total length of the 6 geoelectrical profiles reached about 74 km. Profile n. 1 is located in the Brembana Valley, where the seismic and gravity CROP surveys were also performed. The same figure represents in a broad outline a geological map. The area is divided into two principal regions: northwards, the Southalpine Crystalline Basement and its own covers outcrop, all Permian aged; southwards, a Mesozoic cover appears at the surface.

The problems concerning the thickness of this cover, as well as the basement's upper boundary shape, have been studied on the grounds of surface geological data, from which some structural models have been derived. These hypotheses go beyond the bounds of the present paper, where only the geoelectrical survey is shown, and its interpretation. Some data deriving from a magnetotelluric survey (Zaja, 1993) are also taken into account.

It is known that geoelectrical methods describe the underlying structures in terms of resistivity values. This parameter does not present values typical for each geological unit, but only ranges of values, into which different formations may be included. It follows that the interpretation in terms of lithology may offer some problems. On the other hand, contrary to other geophysical parameters, resistivity is characterized by a noticeable ratio between the highest (more than 50 000 ohm) and the lowest values (few ohm.m), which may be found in

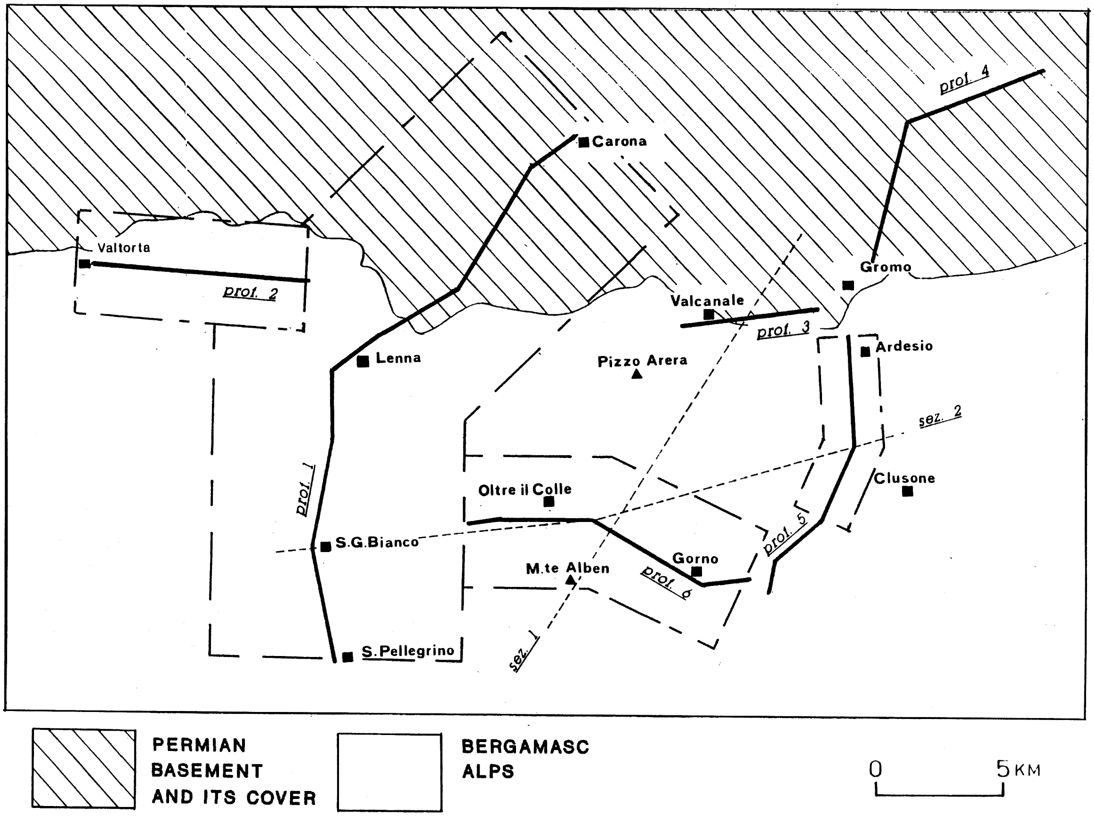


Fig. 1. Map of the surveyed profiles, and of the substratum.

the Earth's crust; this property may be helpful in the lithological interpretation.

2. The geoelectrical method used

The «dipole-dipole» electrode array for vertical soundings, (E.S), has been developed in recent decades mainly by Soviet Geophysicists (Al'pin,1950), (Al'pin *et al.*, 1966); the aim was a greater exploration depth than the Schlumberger array. The dipole-dipole array includes many variants (Orellana, 1982), among which the most popular are the azimuthal, perpendicular, parallel, and polar. All these arrangements present a drawback, since the apparent resistivity diagrams may be seriously affected by the local inhomogeneities in the electrical properties; this fact often makes it difficult to interpret field data in terms of resistivity variations with depth. The only possibility of avoiding this problem is based on a mathematical transformation from the dipole-dipole field data into half-Shlumberger values regarding the same structures. Generally speaking, this is possible only if plane-parallel structures occur. Nevertheless it may be shown that the said transformation is always possible, for arbitrary structural conditions, only if a polar dipole-dipole array has been used in the field (Alfano, 1980).

A further improvement of data quality may be obtained by means of the «continuous polar dipole-dipole» array, which is a particular type

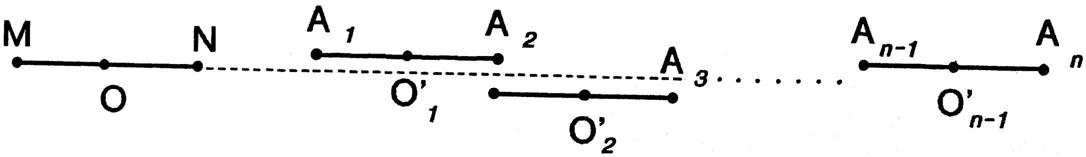


Fig. 2. The «continuos polar dipole-dipole array».

of the said polar arrangement (fig. 2) (Alfano, 1974, 1993; Patella, 1974, 1980; Zerilli and Bisdorf, 1990). In case the current dipoles $A_{i-1}\,A_i$ with centers in O'_{i-1} ($i = 2, 3, 4, \ldots, n$), present a continuity, namely the ends of the energizing dipoles are coincident; as usual, the potential dipole MN with its center O stay in a fixed position. In such a way the apparent resistivity diagram contains all possible information which may be obtained along the line covered by the electrode array; an important property whenever strong lateral variations occur. As usual for the vertical soundings, the successive electrode positions along the said line must be distributed uniformely on a logarithmic scale.

Since the signal to noise ratio becomes very low when the distances between the two dipoles reach some kilometres, the potential measurements require special apparatus based on digital recording of the data. It is necessary to inject commutated and rigorously periodic currents into the ground if the resulting potential (signal) must be distinguished from the essentially aperiodic noises. The inductive effects can be avoided if this period is sufficiently long. The minimum value of the period to be used is inversely proportional to the resistivity and directly proportional to the square of the distance between the two dipoles. The measurement lies in a digital recording of the said potentials during a sufficiently long time corresponding to a minimum number N of periods, where N is proportional to the square of the noise to signal ratio. A proper mathematical processing of the recorded data, carried out by means of a portable computer, allows signal calculation in real time, so that the geophysical operator can choose the number of periods to be recorded for a good result.

3. Locations of the surveyed profiles

Because of the rough topographic surface, typical of this Alpine Region, the field operations have been limited to the valleys, which offer a smoother ground surface, and the roads, useful for the displacements. Profile n. 1, about 26 km long, was carried out in the Brembana Valley from Carona to S. Pellegrino Terme. Its northern part lies where the crystalline Permian Basement and its own cover (Collio and Verrucano Lombardo Units) outcrop; the remaining part of the profile runs to the South of the Valtorta-Valcanale line, on the area covered by mesozoic formations.

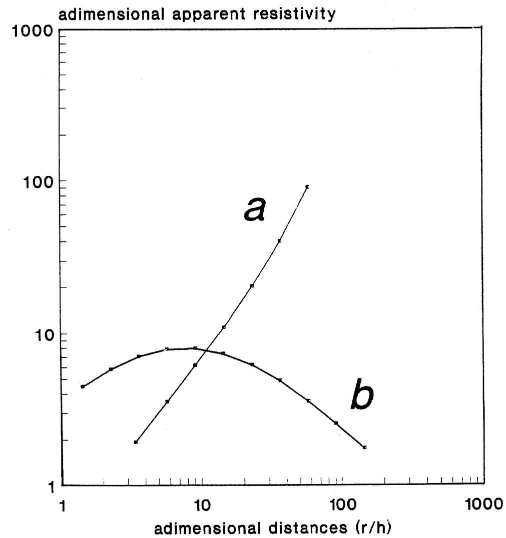
Profile n. 2 and n. 3 are shorter, since their lengths were limited respectively by the dimensions of the Valtorta and Valcanale valleys.

Profiles n. 4 and n. 5 (fig. 1) lie in the Seriana Valley. The first one, carried out northwards (Valbondione), is important since it was possible to measure the resistivity of the Permian Basement, here outcropping in a large area. The second one, 10 km long, is located southwards, between Ardesio and the confluence with the Del Riso Valley. Profile n. 6 connects profiles n. 1 and n. 5 with a length of about 12 km.

4. The apparent resistivity diagrams

Figures 5 to 10 and 12, 14, 16, 17, 18, 20, 22 show the apparent resistivity diagrams corresponding to the E.S. with higher exploration depths. Each electric sounding is represented by 3 diagrams: the dipole-dipole one, measured on the field, and two transformed half-Schlumberger, which derive from two different integration constants (Alfano, 1974, 1993). An interpretation is valid if it is common to both these last diagrams; the concordance occurs to a given depth, which must be assumed as the maximum exploration depth. The distances between the dipoles and the apparent resistivity values appear respectively on the abscissa and on the ordinate axes with the usual bilogarithmic scale. For the dipole-dipole values the distances are OO', (between the dipole centers), while for the half-Schlumberger ones the distances are the OA_j (between the center O and the J-nth current electrode (fig. 2)). It may be observed that the transformed diagrams are smoother than the field ones, because, as already said, they are less affected by local inhomogeneities.

It may be useful to make the following remarks about the interpretation of the diagrams. Since the dipole-dipole is a non symmetric array, it is suitable to know how the diagram shapes may appear when underlying structures present lateral changes. To this aim let us look at the theoretical example of fig. 3, which is particularly interesting for the interpretation of our survey. A structure formed by a plane highly resistant bed, dipping with an angle of about 2 degrees is shown in the lower part of the figure, together with the symbols of two conjugate half-Schlumberger E.S. Both these soundings are carried out along the direction of the bed's maximum slope. Two conjugate arrays are represented by horizontal arrows, as in the field sections shown in the next paragraph; the vertical segment represents, for each E.S., the fixed position of the potential dipole. The two arrays regard about the same tract of profile, but the current electrodes have been displaced in opposite ways, indicated by the arrows (conjugate E.S.). The upper part of fig. 3 shows the two corresponding theoretical apparent resistivity diagrams where the abscissae represent the ratios between the electrode distances r and the resistant bed depth h existing in correspondence of the potential dipole position (adimensional distances). As is usual for theoretical diagrams, the upper layer resistivity is assumed equal to unity (adimensional resistivities).



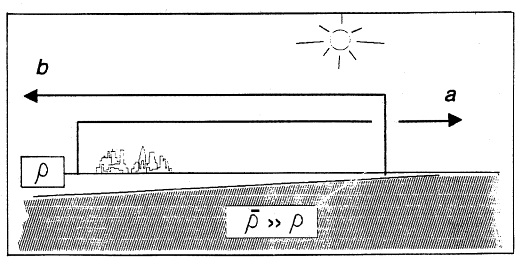


Fig. 3. Theoretical conjugate dipole soundings on a highly resistant and dipping bed (slope = 2 degrees).

The following remarks may be pointed out:

1) diagram a present a positive slope, higher than 45°, exceeding the maximum value compatible with a plane parallel structure: this is a symptom of a very resistant and dipping bed;

2) diagram b presents lower slopes and values; for large distances the values decrease, with negative slopes, towards a low asymptote;

3) the interpretation of diagram a is alone sufficient to ascertain the existence of the re-

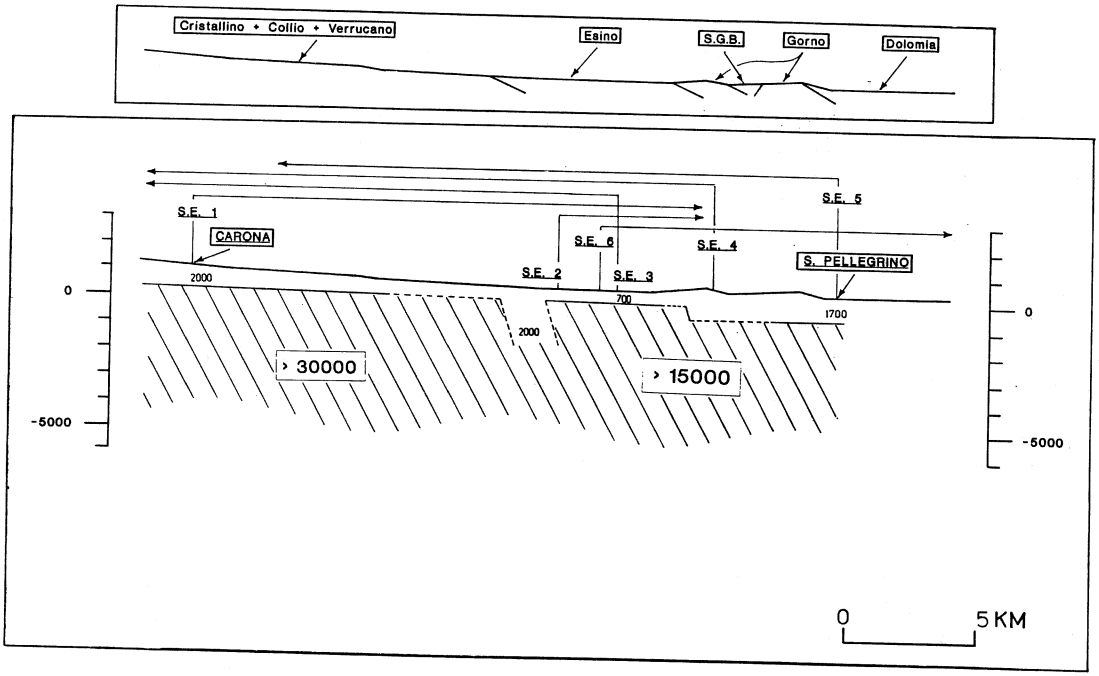


Fig. 4. Interpretation of profile n. 1 (Brembana Valley).

sistant dipping bed and also to evaluate its resistivity. On the contrary, diagram *b* cannot be interpreted alone, since it would give rise to a wrong interpretation;

4) diagram *b* must be interpreted together with *a*, and it may be helpful in the identification of the bed's slope. Therefore only apparently it is not in agreement with E.S. of type *a.*

5) it follows also that the execution of soundings with opposite displacement directions is a good rule.

5. Interpretative sections of the profiles

The profile interpretation is shown in form of vertical sections (figs. 4, 11, 13, 15, 19 and 21). Above the ground surface line we have shown the topographic data of all the E.S., including those with low exploration depth. As in the previous theoretical example, each E.S. is identified by means of the following data: serial number; position of the potential dipole (vertical segment); distance between the potential dipole and the farthest current electrode (horizontal segment); displacement path of the current electrodes (arrow).

Under the surface line, boundaries between regions with different resistivities are drawn, according to the data interpretation. These boundaries have been drawn dashed or dotted, respectively if they are approximate or hypothetical. In all profiles the deeper stratum (substratum) has been hatched down to the estimated maximum exploration depth.

Profile n. 1 (fig. 4), includes 6 E.S. with maximal electrodic distances ranging between 6 and 21 km. The main result is the presence, on the whole profile, of a substratum with an exceptionally high resistivity value, and a thickness of 6 km at least. The substratum resistivity values indicated in the figure (> 30 000 and > 15 000), are prudential, namely the minimum consistent with the data. In effect, in the diagram of E.S. 1 (fig. 5), the apparent resistivity value reaches about 40 000 ohm.m, with a dipole separation of 18 km; namely the distance between Carona (potential dipole) and S. Giovanni Bianco (current dipole).

It may be shown that the existence of the resistant substratum could be proved on the grounds of this sounding alone, independently of the other five E.S. carried out on the profile, (see the theoretical example of fig. 3). According to some mathematical models, the substratum must be present at least on a sufficiently wide rectangular area defined in fig. 1 by means of dashed lines.

Along this profile the top of the resistant substratum appears to be continuous across the Valtorta-Valcanale line, where only a short break appears, revealed by E.S. 2. This fact, concerning the underlying structures, is in contrast with the lateral variations in the surface geology occurring across the said line.

The E.S. n. 4 and E.S. n. 5 of profile n. 1 confirm the presence of the resistant substratum by means of the positive slope in the diagrams, even if the effects of conducting superficial layers (the formations Gorno and S. Giovanni Bianco), lower all resistivity values (figs. 8 and 9) in comparison with E.S. n. 1. The diagrams of E.S. 3 and E.S. 6 (figs. 7 and 10), do not present high values and positive slopes, contrary to their respective conjugate soundings (E.S. 1 and E.S. 5). This fact only apparently implies a discrepancy, according to the theoretical example already discussed and shown in fig. 3.

The resistant substratum was also found in profiles n. 2, n. 5 and n. 6; here the minimal thicknesses are smaller than in profile n. 1, because the distances reached between the dipoles are shorter. It may be interesting to remark the presence in Val Biandino, near the west end of profile n. 2, of a dioritic outcrop with very high resistivity values.

The deepest resistivity in profile n. 3 (fig. 13), does not exceed 5000 ohm.m. According to some geological evidence, it may be inter-

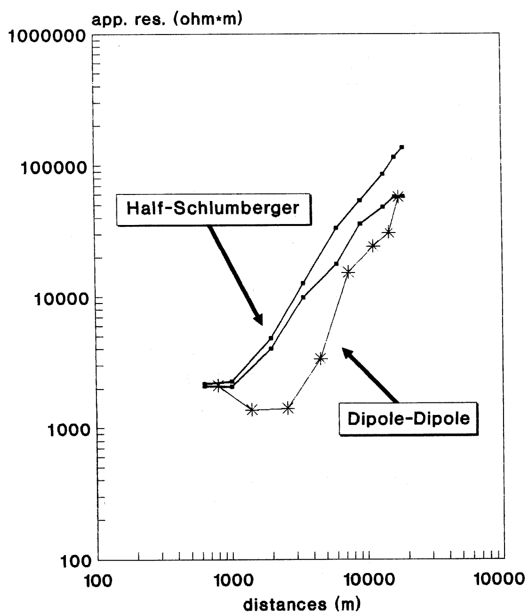


Fig. 5. Apparent resistivity diagrams. Profile n. 1, sounding n. 1 (Brembana Valley).

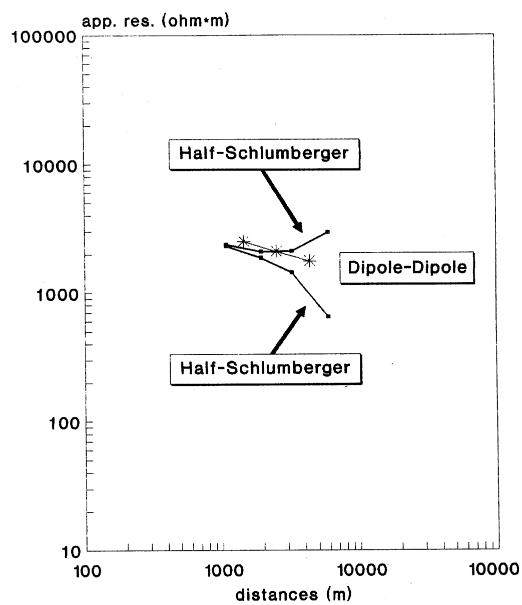


Fig. 6. Apparent resistivity diagrams. Profile n. 1, sounding n. 2 (Brembana Valley).

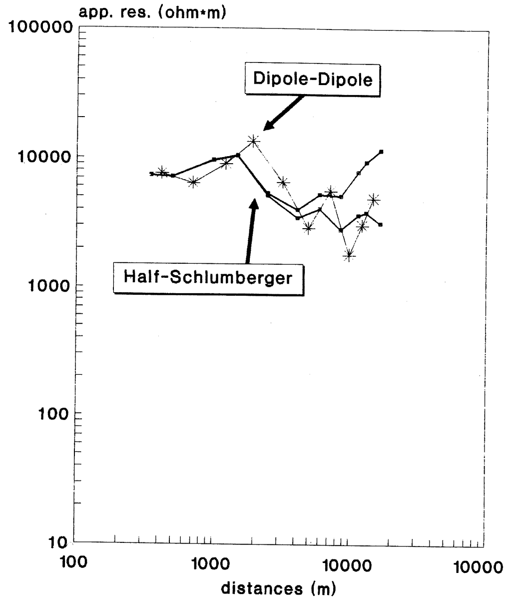


Fig. 7. Apparent resistivity diagrams. Profile n. 1, sounding n. 3 (Brembana Valley).

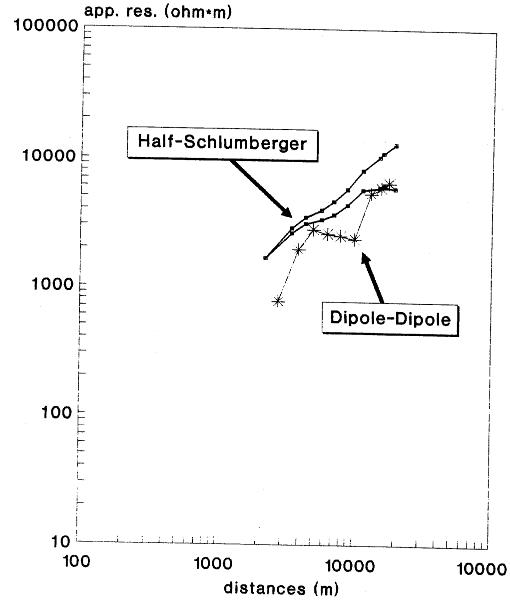


Fig. 8. Apparent resistivity diagrams. Profile n. 1, sounding n. 4 (Brembana Valley).

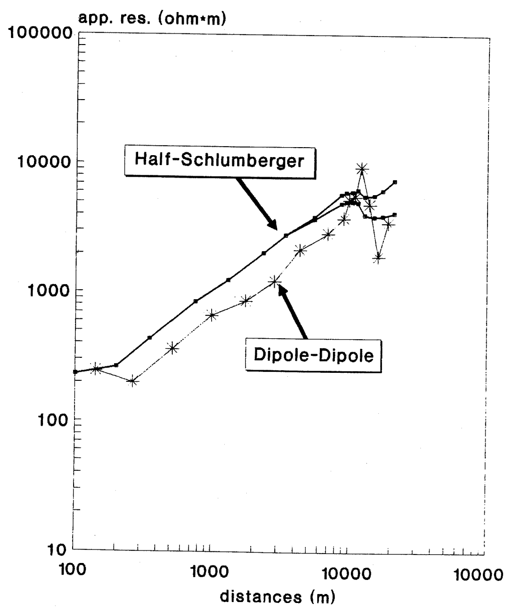


Fig. 9. Apparent resistivity diagrams. Profile n. 1, sounding n. 5 (Brembana Valley).

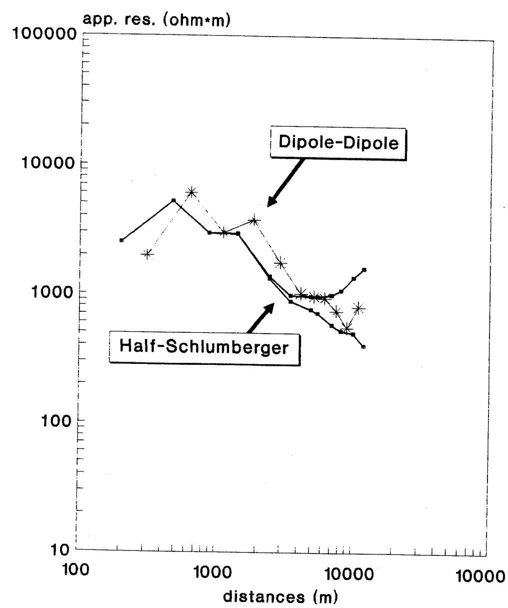


Fig. 10. Apparent resistivity diagrams. Profile n. 1, sounding n. 6 (Brembana Valley).

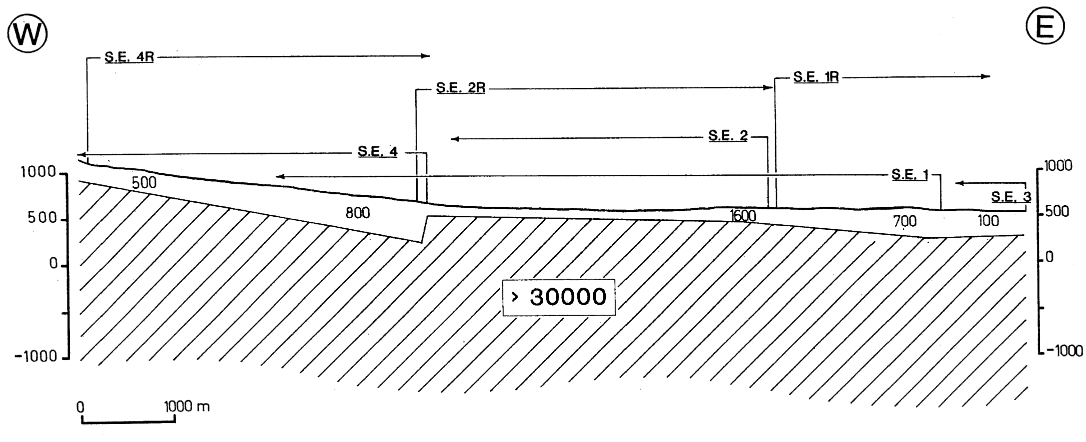


Fig. 11. Interpretation of profile n. 2 (Valtorta Valley).

preted as the Collio formation. Two vertical sections appear in this figure, relating respectively to the high exploration depth E.S. 4, and to the other soundings which were carried out on a partially different topographic profile.

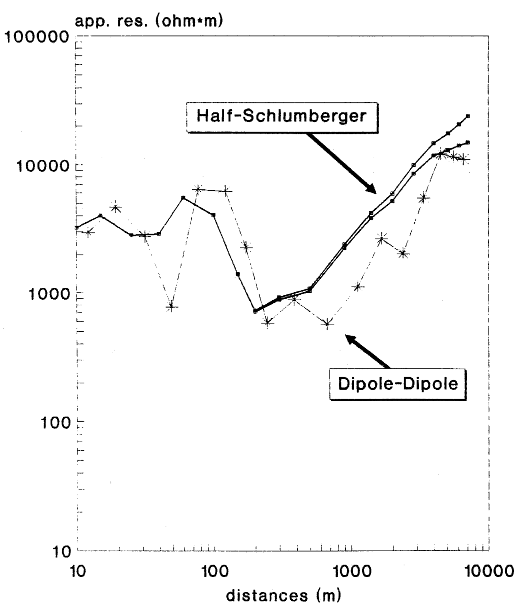


Fig. 12. Apparent resistivity diagrams. Profile n. 2, sounding n. 1 (Valtorta Valley).

Profile n. 4 (fig. 15), lies on the northern part of the Seriana Valley where the Permian Basement outcrops. Consequently the resistivity of this geological formation was measured directly. Until the maximum exploration depth (about 4 km), the resistivity values are surprisingly low for a metamorphic rock (from 30 to 1400 ohm.m). At first, this fact was underestimated and considered only a consequence of a particular situation of this area. But the magnetotelluric survey (Zaja, 1993) carried out in the frame of the CROP project to the north of the Orobic Line, where the same formation outcrops extensively, also revealed low values. A consequence of all these data is that the resistant substratum found on profiles n. 1, 2, 5, 6 are difficult to consider constituted by the Permian Crystalline Basement.

6. Lateral extension and lithological interpretation of the substratum

As already said, it may be shown that the geoelectrical methods can reveal resistive beds only if sufficiently wide. So in the map of fig. 1, and particularly along profiles n. 1, 2, 5 and 6, the minimal horizontal extensions of the substratum are shown. Dashed lines define these estimated widths: about 10 km for profile n. 1,

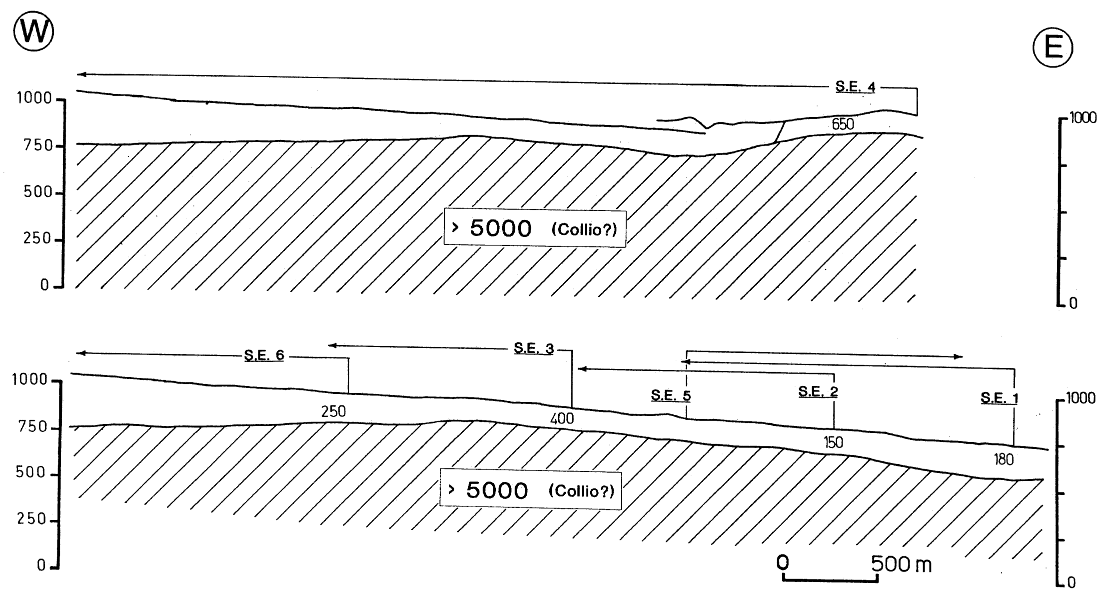


Fig. 13. Interpretation of profile n. 3 (Valcanale Valley).

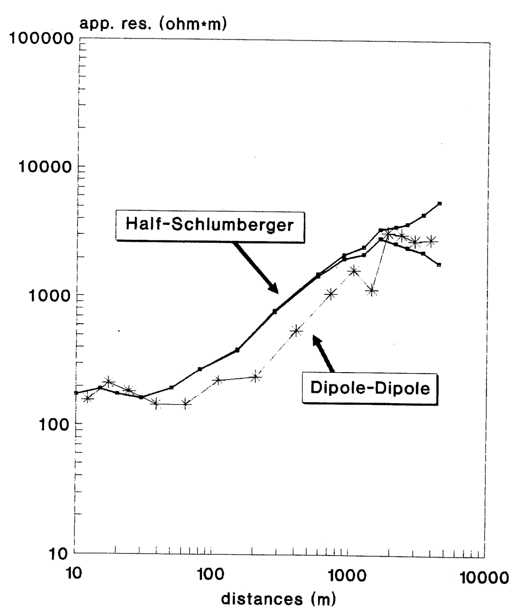


Fig. 14. Apparent resistivity diagrams. Profile n. 3, sounding n. 4 (Valcanale Valley).

4 km for profile n. 2, 2 km for profile n. 5, and 5 km for profile n. 6.

The same lateral dimensions have also been shown on the interpolated vertical sections of figs. 23 and 24, whose planimetric positions are indicated in fig. 1. The substratum top surface appears to be sufficiently regular; its elevation is about constant. Consequently it represents a flat lower boundary for all geological formations appearing on the surface. This fact, consistent with the geophysical data, does not seem to be in agreement with the downward extrapolation of some features of the surface geology; it gives rise to a problem, independently of the lithological interpretation of the substratum.

This last lithological matter may be discussed in two ways: the first is based on general considerations, and the second on the grounds of resistivity values measured on the outcropping formations. According to the first, we can say that the very high resistivity values found for the substratum occur in volcanic rocks or, less frequently, in strongly metamor-

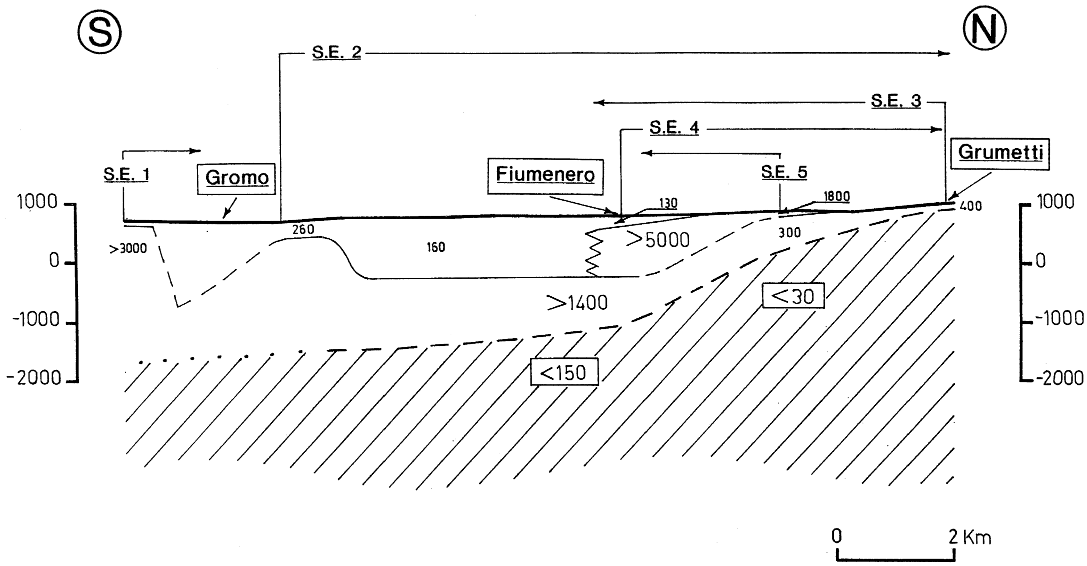


Fig. 15. Interpretation of profile n. 4 (Northern Seriana Valley).

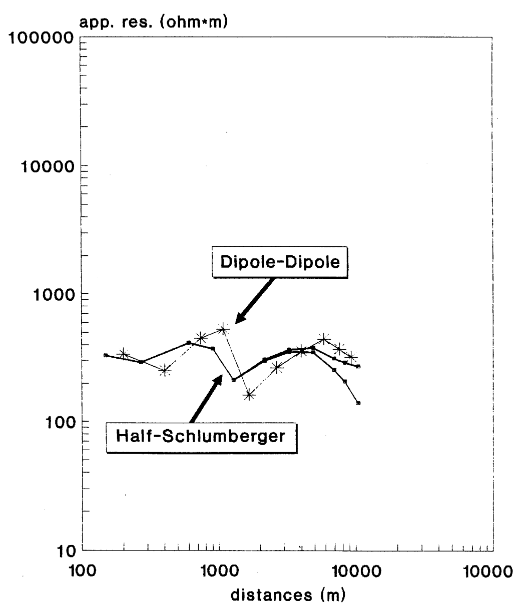


Fig. 16. Apparent resistivity diagrams. Profile n. 4, sounding n. 2 (Northern Seriana Valley).

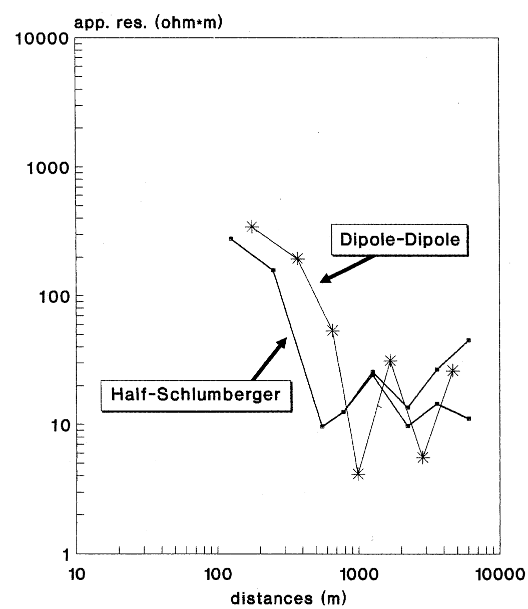


Fig. 17. Apparent resistivity diagrams. Profile n. 4, sounding n. 3 (Northern Seriana Valley).

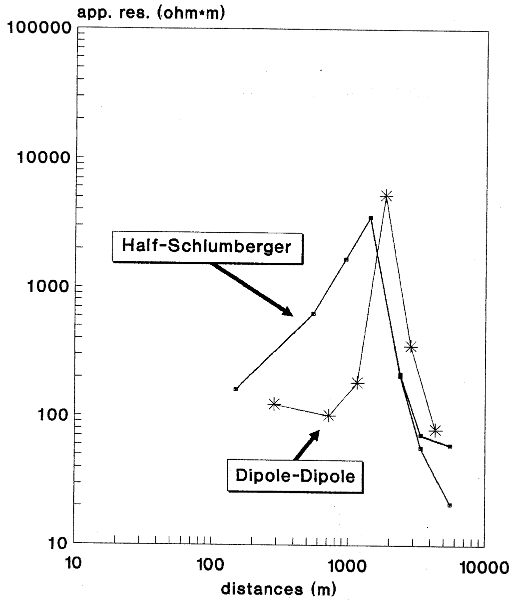


Fig. 18. Apparent resistivity diagrams. Profile n. 4, sounding n. 4 (Northern Seriana Valley).

phosed formations (in the Brembana Valley the measured, and not only interpreted values reach 40 000 ohm.m). It is difficult to ascribe similar values to large masses of sedimentary rocks, in the physical conditions occurring at depth.

According to the second approach let us consider the actual values of the outcropping formations. The following upper limits for the resistivities derive from some complete electrical soundings carried out on the surveyed area; consequently they regard large rocks volumes, and not only the first superficial levels.

North of Valtorta-Valcanale line:

Verrucano Lombardo	2000	ohm.m
Collio	5000	ohm.m
Crystalline Permian Basement	150-1400	ohm.m
Diorite in Val Biandino	> 40 000	ohm.m

South of Valtorta-Valcanale line:

Esino limestones	5000	ohm.m
Gorno	200	ohm.m
S. Giovanni Bianco	200	ohm.m
Dolomitic limestones	5000	ohm.m

The last four units form a geological series, and consequently they should be found together in the subsoil. Now, as is easily computed, the equivalent resistivity of a pile constituted by these formations, according the respective thickness observed at the surface, do not reach 1000 ohm.m. But even in the hypothesis of underground strata constituted only by limestone, resistivity values should be smaller than 5000 ohm.m. It derives that the presence of these sedimentary formations in the underground regions where very high resistivity values have been found is not likely, at least from a geophysical point of view. Moreover this last conclusion may be further supported if one

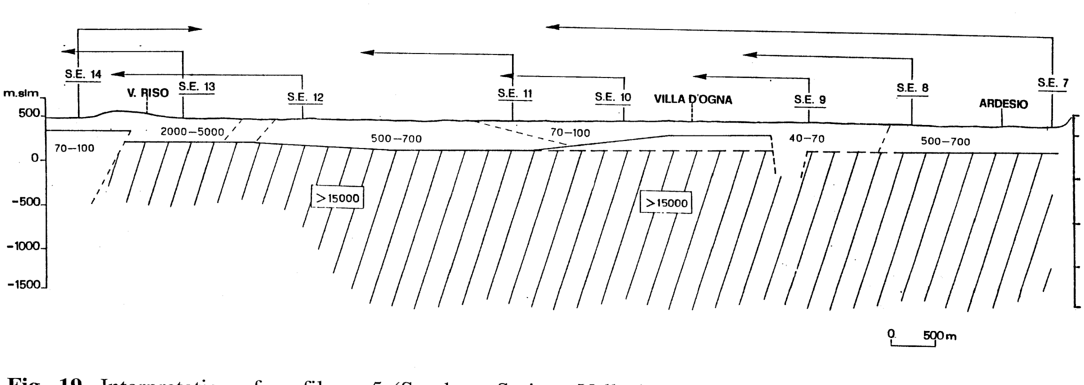


Fig. 19. Interpretation of profile n. 5 (Southern Seriana Valley).

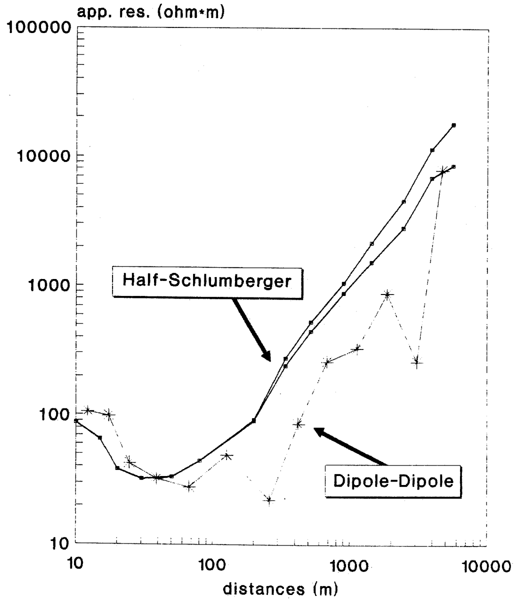


Fig. 20. Apparent resistivity diagrams. Profile n. 5, sounding n. 7 (Southern Seriana Valley).

take into account the temperature rise with depth, namely a downward increase up to 120 °C about in the first 4 km. It is known that this is one reason why, particularly for the sedimentary rocks, the resistivity at depth may be one half or less than the values at the surface. For this purpose it may be remembered that the resistivity of an electrolyte or a saturated rock decreases for increasing temperatures according to the following formula:

$$\rho_t = \frac{\rho_{18°}}{1 + \alpha(t - 18°)} \tag{6.1}$$

where t is the actual temperature at depth; ρ_t and $\rho_{18°}$ are the resistivity values respectively for temperatures t and 18° (centigrades degrees); $\alpha = 0.025$.

7. Conclusions

A deep geoelectrical survey was carried out on the Southern Central Alps, north of Bergamo, along 74 km of profiles. The method used was the «continuous polar dipole-dipole», and the soundings (E.S.) were 34, among which 14 carried out in the frame of the CROP project, with higher penetration depth (up to 6 km).

From a geologic point of view the explored area can be divided into two regions: in the north the Southalpine Crystalline Basement outcrops together with its own covers (Collio

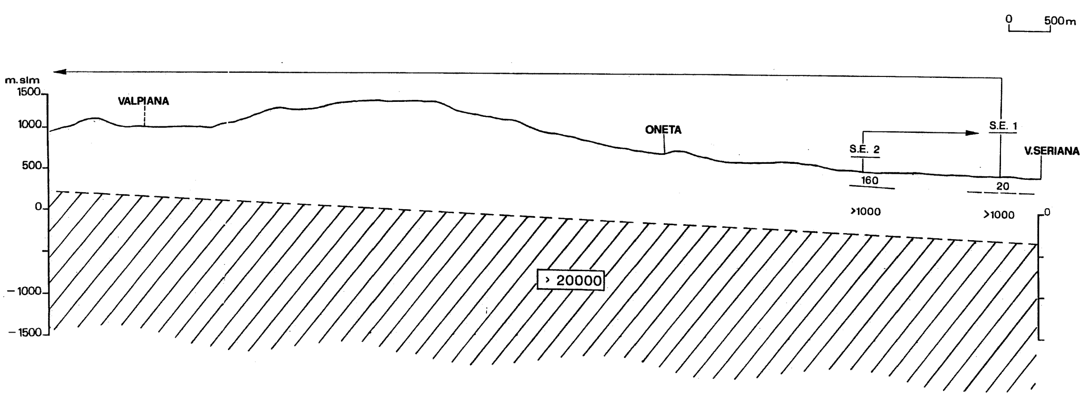


Fig. 21. Interpretation of profile n. 6 (Val Del Riso).

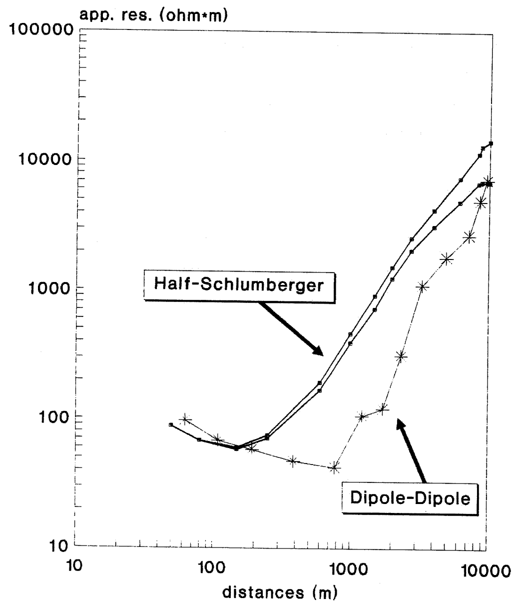


Fig. 22. Apparent resistivity diagrams. Profile n. 6, sounding n. 1 (Val Del Riso).

and Verrucano Lombardo), all Permian aged; southwards the remaining part is occupied at the surface by younger geological units, members of a mesozoic sedimentary cover.

The main result of the survey derives from 4 of the 6 profiles executed, where a substratum was found, with an exceptionally high resistivity, (15 000-40 000 ohm.m), and with a not too deep upper boundary. The thickness was not determined since it appears to be greater than the exploration depths of the geoelectrical soundings.

Along profile n. 1, in the Brembana Valley, where gravity and seismic surveys were also carried out in the frame of the CROP project, the top of the substratum appears to be practically continuous, from Carona to S. Pellegrino Terme, in spite of important variations in the surface geology across the Valtorta-Valcanale line. Along this profile the minimum thickness of the substratum may be evaluated at 6 km. In correspondence of the other three profiles this minimum value appears to be smaller because of the shorter exploration depths of the E.S.

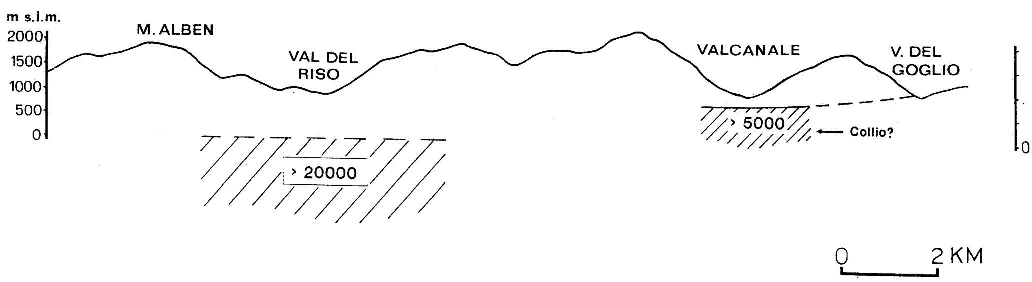


Fig. 23. Vertical section n. 1: minimum horizontal extension and minimum thickness of the resistant substratum.

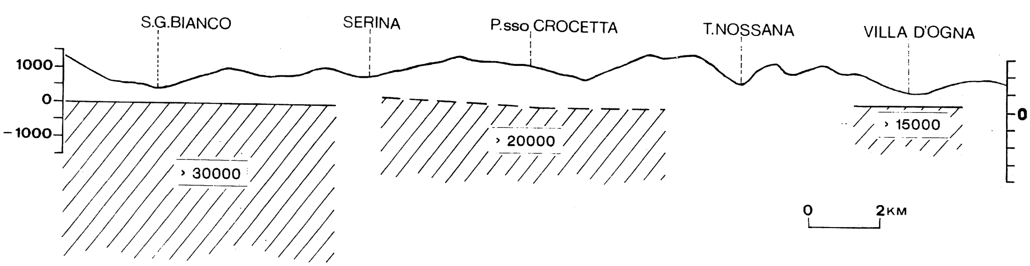


Fig. 24. Vertical section n. 2: minimum horizontal extension and minimum thickness of the resistant substratum.

According to the geoelectrical method properties the existence of a resistive substratum cannot be limited to narrow strips along the profiles, but must extend laterally with a minimum horizontal width. These widths are shown in the map of fig. 1, by means of rectangular areas defined by dashed lines. The vertical sections of figs. 23 and 24 connect the surveyed profiles.

The soundings carried out along profile n. 4, in the northern part of the Seriana Valley, made it possible to measure directly the Permian Basement resistivities, which appear to be surprisingly low for a metamorphic formation. This result, which was also confirmed by a magnetotelluric survey carried out to the north of the Orobic Line (Zaja, 1993), suggests that the highly resistant substratum cannot be constituted by the Permian Basement. On the grounds of general knowledge on rock electrical properties and field resistivity data, the high substratum values cannot be ascribed to the mesozoic formations outcropping to the south of the Valtorta-Valcanale line, particularly if one takes into account the high temperatures existing at depth. On the contrary, these values are frequent in igneous bodies. A clear example of this fact is given by the Diorites outcropping in the Biandino Valley, near the western end of profile n. 2. Here the measured resistivity exceeded 40 000 ohm.m. At least from a geometric point of view it should be possible to connect this dioritic outcrop with the resistant bed found at small depths on profile n. 2.

All these conclusions do not agree with the hypothesis, generally sustained in the geological literature, about the existence at depth, south of the Valtorta Valcanale Line, of a thick sedimentary rock pile, laying on the Permian Basement. This hypothesis should be consistent with the lack of important igneous outcrops in this region; nevertheless, the presence of many lodes, particularly at S. Pellegrino Terme and in the Seriana Valley, already suggested to some geologists the possible presence of sub-volcanic bodies at depth.

Independently of the lithologic problems, the resistive substratum presents a practically flat upper boundary, which is a not too deep lower boundary for all geological formations outcropping in this area. This feature does not seem to be in good agreement with the simple downward extrapolation of some surface geological data.

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