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# Magnetotelluric investigations of the seismically active region of Northwest Bohemia: preliminary results

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**Abstract**
During 1997, within the framework of an Italian-funded scientific cooperation between Italy and the Czech Republic, a series of magnetotelluric (MT) soundings was carried out in the region of Northwest Bohemia (Czech Republic). This is one of the most seismically active areas in Central Europe, where micro-earthquake swarms frequently occur during the apparently quiescent intervals between large macro-seismic swarms. Fifteen MT stations were installed in an area of about 15 × 20 km$^2$ where 80% of the seismicity of the entire region has been recorded since 1986. The area showed a high electromagnetic noise, possibly of high cultural origin from the nearby industrial zone of the Sokolov basin, which affected both the electric and the magnetic signals. The final data, carefully selected, were modeled by 2D and 3D techniques. The results show an extensive conductive structure in the depth range from 0.5 to 3 km. This structure could be connected with the locally buried granitic massif in the inhomogeneous metamorphic basement, probably accompanied by fracturation, thermo-metamorphism or paleofluids. Moreover, the presence of a conductive anomaly in the northern part of the investigated region could be linked to a lithological change in the metamorphic rocks (prevalence of phyllites over mica schists), which would even increase the effect of the granite.

**Key words** *magnetotelluric – seismic area – Bohemia*

## 1. Introduction

The electromagnetic (EM) induction technique provides self-reliant information with respect to other geophysical investigation methods on the electrical conductivity distribution of the Earth's subsurface. In the framework of a joint Czech-Italian research project, a natural source-based EM investigation was carried out in the northwestern part of Bohemia (Czech Republic). This area is characterized by persistent tectonic activity, manifested by the occurrence of micro- and macro-earthquake swarms with occasional single events. Between 1986 and 1996, 80% of seismic activity was clustered along a narrow belt running from Novy Kostel to Kraslice (Horálek *et al.*, 1996). It is 24 km long and 1 km wide with a depth of 7-13 km that dips steeply to the west (fig. 1, lower part). The activity of the southern and northern parts of this belt displays different patterns. The southern part, where the last earthquake swarm also occurred (1985-1986), is characterized by the recurrence of micro-earthquake swarms, whereas single events are characteristically observed

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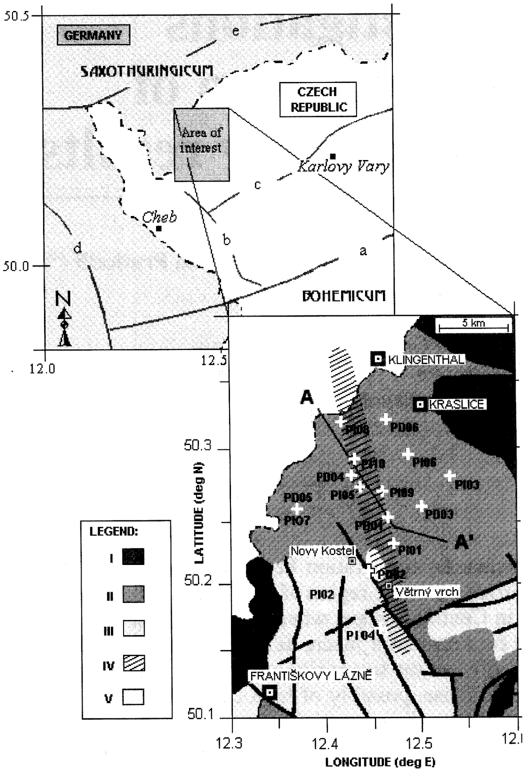

**Fig. 1.** *Upper part*: Tectonic sketch map of the Northwest Bohemia area, showing the Saxo-turingicum and Bohemicum structural units and the main faults. a = Litomerice deep fault; b = Marianske Lazne fault zone; c = Krusne Hory fault; d = Franconian fault zone; e = Central Saxonian lineament. *Lower part*: Geological sketch of the study area with the locations of the MT sites. I = Granites (Variscean); II = metamorphic basement (Ordovician – Cambrian – Algonkian); III = sedimentary basins (Oligocene – Miocene – Pliocene); IV = cluster of 1986-1996 epicentres; V = cluster of 1985-1986 epicenters. The broken line (A-A') represents the profile of the 2D inverse model (see fig. 5).

in the northern part. The investigated area is about 300 km$^2$ and 15 MT stations, distributed across the Czech portion of the belt, covered it.

In order to improve our knowledge of the geo-structural configuration of the region, the geoelectrical image of the target area through the EM inductive investigations was defined.

## 2. Tectonic configuration of the investigated area

The tectonic configuration of the study region is rather complex and not yet completely understood. The post-Cadomian large-scale structural-geological setting of Central Europe was determined by three great tectonic events:

– Paleozoic Variscean orogenesis, which defined the main strike direction (NE-SW) of the different units belonging to the present-day Bohemian Massif zone.

– Cretaceous-Tertiary Alpine orogenesis, which led to the uplift and the dislocation of blocks of the Variscean area.

– Tertiary-Quaternary subsidence phenomena of the Rhine and Eger grabens.

The western part of the Bohemian Massif consists of three different structural units: Saxothuringicum in the NW, Moldanubicum in the SE, and the Central Bohemicum (Tepla-Barrandian). The collision between the two parautochthonous units (Saxothuringicum and Moldanubicum) occurred in the lower-middle Carboniferous. Bohemicum is considered an allochthonous complex of the late stage of orogenesis. Post-orogenic granites intruded the zone about 320 million years ago. Within a complex pattern of tectonic lines it is possible to recognize (fig. 1, upper part):

– The deep ENE-WSW Litomerice and Krusne Hory fault systems, which are connected with the main orogenic events and determine the main geological strike of the region (Grunthal *et al.*, 1990).

– The West Bohemia NW-SE fault system, including the probably active Marianske Lazne tectonic line.

Volcanic activity is still visible in this region in the form of numerous mineral springs, rich in carbon dioxide.

The Moldanubicum and Bohemicum units are nearly aseismic and constitute the oldest and most rigid part of the Bohemian massif. A zone of tectonic stress extends into the Saxothuringicum, and especially into the well known Vogtland-West Bohemia seismic area. The Bohemian section of this zone is situated at the transition between the Krusne hory (Erzgebirge) mountain range and the Eger graben. In the south, it merges with the 400 m deep mid-Pliocene Cheb basin.

Behr *et al.* (1989) put forward the hypothesis of the West Bohemia fault zone being a section of a NW-SE transcurrent zone, possibly a remnant of an original transform fault of the subducting Bohemicum. This zone is supposed to have controlled the tectonic evolution of the adjacent regions over several tectonic cycles, and may control or affect it even today.

## 3. Experimental data

### 3.1. *Field measurements in the seismically active area*

In spite of the large number of geophysical studies on the Bohemian Massif, the geoelectrical properties of the region have only been sparely examined. Some interesting geological and geophysical information has, however, emerged from the German deep drilling project KTB (Emmermann and Lauterjung, 1997; Vrána and Štědrá, 1997). With regard to induction vectors, the deep, over-regional structure exhibits a quasi-2D character with structural strike in an approximately E-W direction. The huge blocks, with large anisotropy and striking NW-SE to NNW-SSE, observed in the close vicinity of the KTB borehole in Germany, as well as in West Bohemia south of the Cheb basin, seem to finish abruptly several kilometers SW of our target area.

Earlier Czech projects directed at improving the structural model of the region have included a series of geoelectrical induction soundings very near the study area. One of the objectives of these soundings was to define the influence of cultural noise on magnetotelluric data and the resistivity curves for several sites. These data are only marginally related to the data presented in this paper, but were useful for comparative purposes during data processing.

The results of test measurements in the spring of 1997 showed that telluric noise is generally present at most of the tested sites. This helped for selecting suitable sites for MT survey and for assessing the noise level within the target region. Noise became a prohibitive factor only on the eastern margin of the target area, near the open-cast coal mines and industry of the Sokolov basin.

The site locations were thus carefully selected in this area to avoid large disturbances.

In July 1997, an array of 15 broadband MT stations, with spacing of about 2 km, was set up in the Czech portion of the 1986-1996 earthquake focal zone (see Introduction). Three different measurement systems of the Italian partners were used, one from to the Department of Geology, Paleontology and Geophysics, University of Padua (DGDP), and the other two from to the International Institute for Geothermal Research (IIRG). The detailed layout of the MT sites is shown in fig. 1 (lower part) on a schematic geological map.

The sites were widely distributed across the focal zone for a better investigation of the shallow likely 3D conductivity structure of the area. Only three MT sites were located in the Cheb sedimentary basin where the highly conductive shallow units reduced the noise problem but did not allow deep penetration. Most of the recording sites were thus located above the crystalline units, north of the Cheb basin, where EM noise of cultural origin did not prevent the measurements. In order to compare the MT results from the two systems used, high frequency data were recorded simultaneously at the same site (PD05-PI07). They showed no significant discrepancy in the common frequency range (see fig. 2)

### 3.2. *Data acquisition and processing*

The MT soundings were performed using two Phoenix systems (by IIRG) and a medium-short period magnetotelluric system; hereafter called the MS system (by DGDP). Induction coil magnetometers were used to record the horizontal magnetic components. Pb-PbCl electrodes were used as sensors to detect the horizontal electric field. Dipole lengths varied between 50 m (in a few cases) and 100 m with the Phoenix V5 receivers; it was set to 50 m with the MS system.

The Phoenix V5 receiver can operate in three distinct bandwidths: 320-60 Hz, sampling rate 2560 Hz, 40-7.5 Hz, sampling rate 320 Hz and $6\text{-}55 \times 10^{-4}$ Hz, sampling rate 24 Hz. During acquisition, a low-pass filter (5-point digital fil-

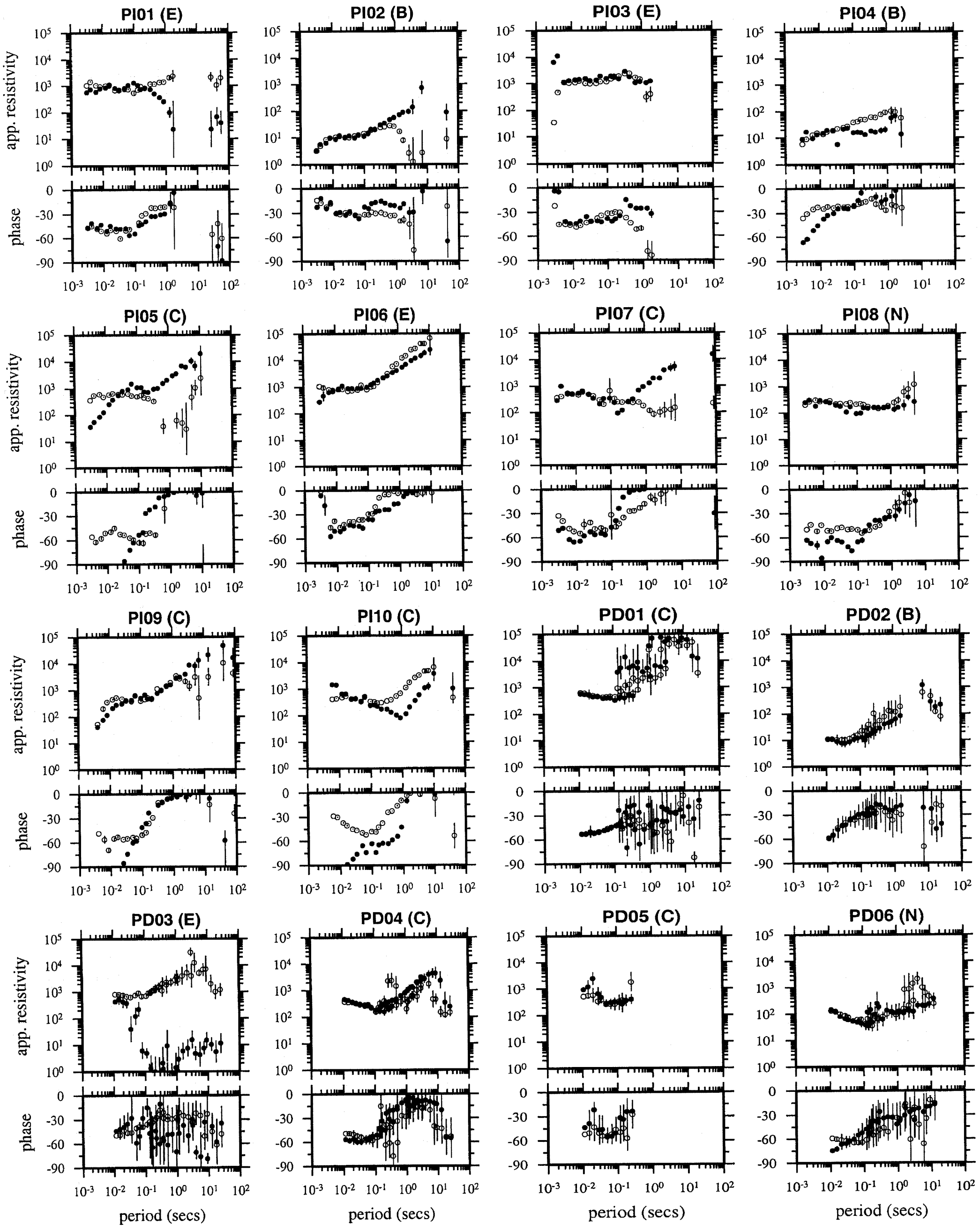

**Fig. 2.** MT apparent resistivity and phase values with error bars in the two polarization modes *xy* (filled circles) and *yx* (open circles) against periods for the 15 investigated sites. All data are rotated in a N-S direction. Letters (E), (B), (C) and (N) indicate eastern, basin, central and northern stations respectively.

ter) was applied to data by the cascade decimation technique (Wight and Bostick, 1981) to avoid aliasing and noisy contributions. The MS acquisition system can operate in the partially overlapping frequency bands: 100-1 Hz, sampling rate 400 Hz, 8-1/8 Hz, sampling rate 32 Hz, and 1-1/64 Hz, sampling rate 4 Hz. An appropriate analog filter was applied to the data to reduce the noise effect and to eliminate aliasing. All the data were discrete-Fourier transformed in the frequency domain and corrected for the system response function before the application of standard processing methods (Swift, 1967). MT impedance, apparent resistivity and phases were then estimated for each site. To assess the dimensions of the structures involved and possible influence of galvanic distortions, also basic MT parameters were computed: specifically the principal directions, skew and main decomposition parameters. They indicate a rather 3D character of the structure and, in general, do not meet conditions for the application of a simple local/regional composite model.

The 3D character of the area prevented a clear and general definition of a strike direction. However, a general N-S trend was found, which is coherent with the direction of the main fault systems, synclines and sedimentary basins of the area. For uniformity, the data were rotated toward the north and the corresponding apparent resistivity and phase values for each site and for the two polarization modes were plotted against period, where the $x$ axis is N-S (fig. 2). We generally did not consider data with periods greater than 10 s due to their high noise level.

The global response of the apparent resistivity is schematically shown in fig. 3 by means of apparent resistivity maps. The two polarization

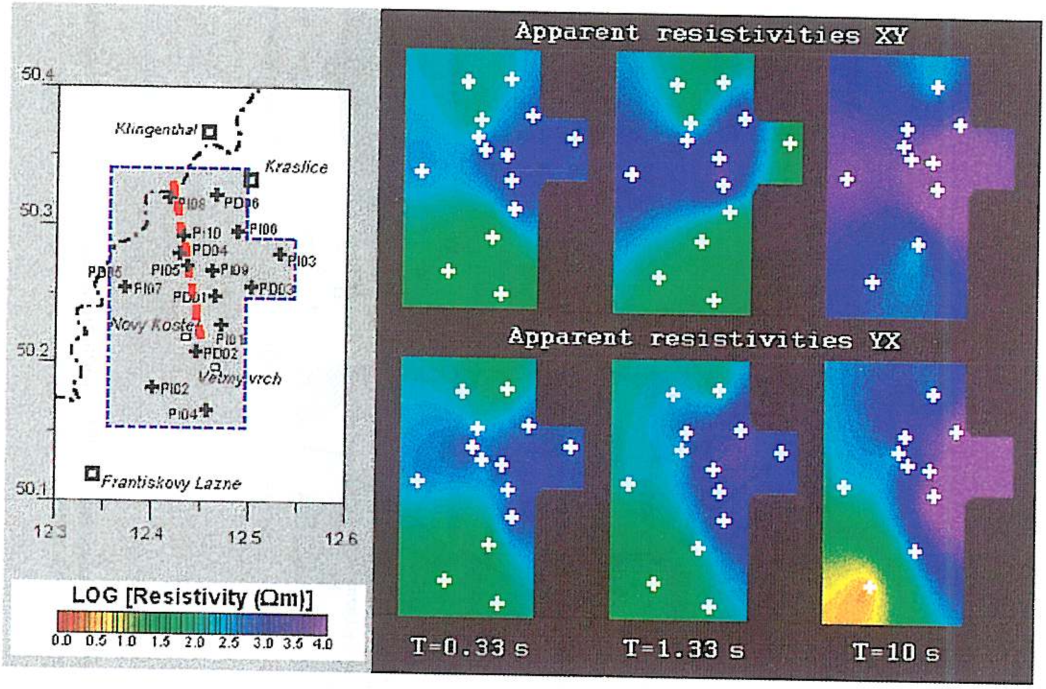

**Fig. 3.** Overall apparent resistivity maps for the study area. The three periods of 0.33, 1.3 and 10 s are shown for the two polarization modes. Thick dashed line in the left panel represents the location of the Czech portion of 1986-1996 seismic zone. Each plot shows the sites used for the contour; only sites having impedance data within 25% around the particular central period were used.

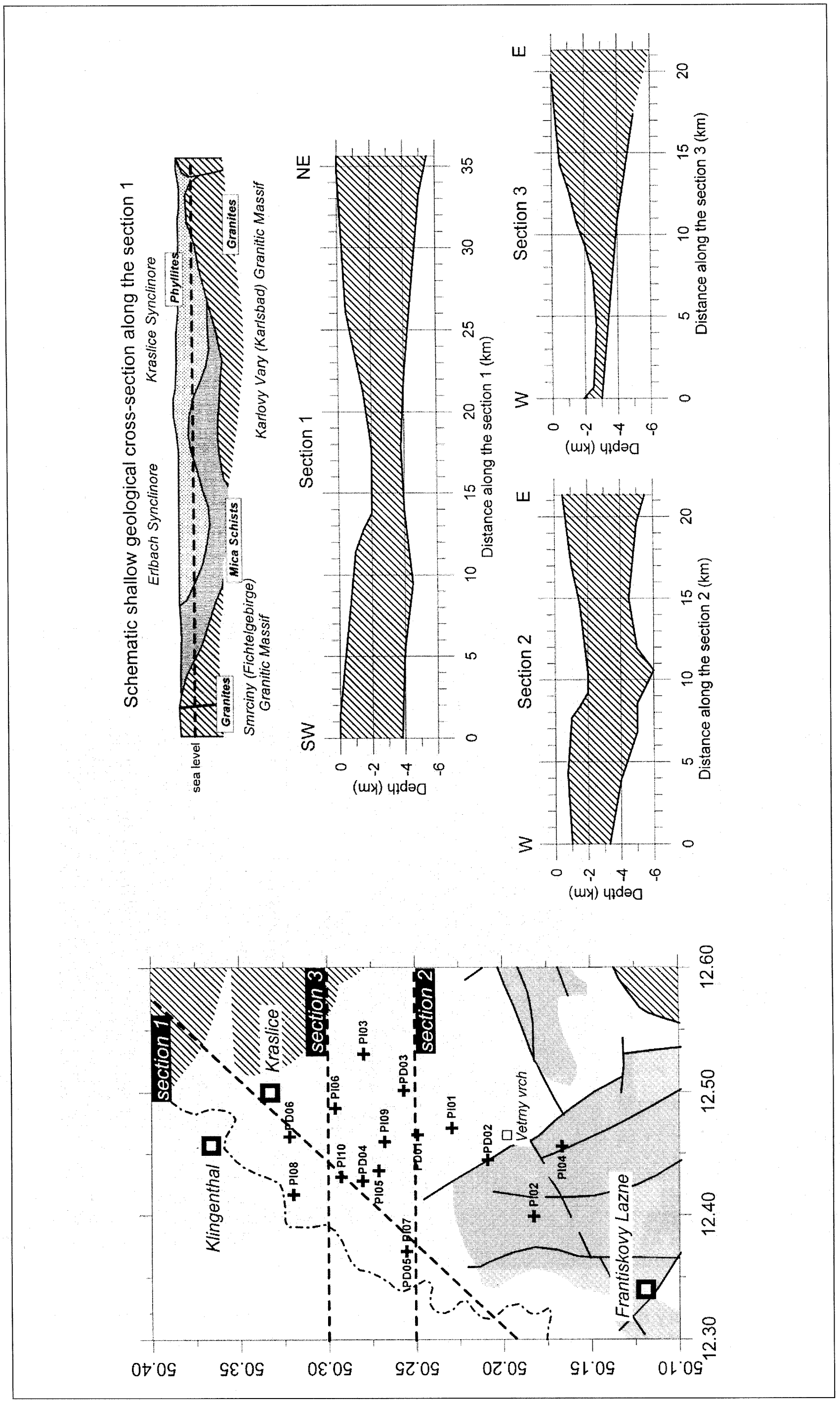

**Fig. 4.** Gravimetric reconstruction of the Northern Bohemia zone (from Behr *et al.*, 1989, redrawn): the supposed geometrical features of the buried granitic massif are shown along three profiles, as indicated in the left panel.

modes are shown for increasing periods (0.33, 1.33, 10 s) in order to give a first electrostratigraphic image of the investigated area. As expected, the sedimentary basin of Cheb contributes to the lowest values of resistivity.

The sites located on the metamorphic units can be divided into 3 groups whose resistivity characteristics can be summarized as follows (see also fig. 2):

– «Central sites» close to or west of the seismic line (PI07-PD05-PI10-PI05-PD04-PI09-PD01). They show a shallow resistivity of 700-800 $\Omega \cdot$ m and a moderate decrease of the resistivity for periods of 0.1 to 1 s; stations belonging to this group show the greatest difference in resistivity values between the two polarizations ($\rho_{xy}$ and $\rho_{yx}$).

– «Northern sites» (PI08, PD06) with a well-defined reduction in resistivity and a shallow resistivity of 200-300 $\Omega \cdot$ m.

– «Eastern sites» (PI03-PI06-PD03-PI01) with no reduction in resistivity and a shallow resistivity of about 1000 $\Omega \cdot$ m.

The data at all the stations show a general increase in the resistivity values for periods greater than 1 s. These preliminary qualitative features were taken into account during the 2D and 3D modelling.

## 4. Modelling and discussion

The first step in modelling was to recognize any connection between the surface geology and the observed qualitative trends of the data. At this stage some geological sections and a gravimetric reconstruction by Behr *et al.* (1989) were used (fig. 4). Some features of the investigated zone were particularly evident:

– The metamorphic basement is not homogeneous, with a prevalence of the mica schists over the phyllites toward SE.

– On a local scale, the whole area can be described as a «structural low», as documented by the occurrence in the north of two syncline cores (Erlbach and Kraslice) that are younger

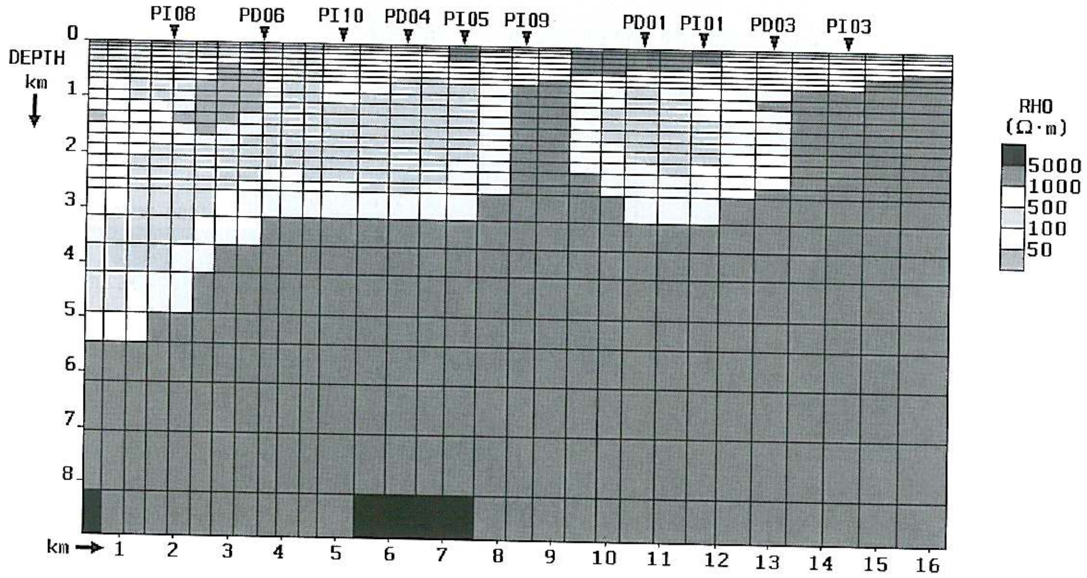

**Fig. 5.** 2D inverse model along the profile A-A' in fig. 1. The vertical axis indicates the depth in kilometers. The inhomogeneous conductive structure could be related to the presence of the buried granitic massif in the metamorphic units. The two synclines of Erlbach and Kraslice are located just above the northern zones of increased conductivities. Although the use of a broken profile where performing the 2D inversion is not properly correct, it allows to enhance the most important features of all the region.

than the surrounding metamorphic layers.

– Granites crop out just outside the study zone but are buried inside it.

Various 2D models were inverted along profiles crossing the whole zone (2D-inversion code by Rodi and Mackie, to be submitted). A profile crossing the «Central», «Northern», and «Eastern» stations (see Section 3.2) best depicts the structural pattern defined by our data. Its position is reported in fig. 1 as a broken line (A-A').

Figure 5 shows the result of this inversion: an almost continuous conductive structure is visible at a depth of 0.5-3 km: it is shallower and rather weakly expressed in the SE and more pronounced (10-100 Ω · m) and deeper in the north. The global shape of this anomalous structure more or less reflects the gravimetric model that, according to Behr *et al.* (1989), characterizes the top of the buried granitic massif. The two synclines, Erlbach and Kraslice, are located just above the northern zones of increased conductivity. This anomalous conductive structure could be connected with the presence of the buried granitic massif in an inhomogeneous metamorphic basement.

The picture that emerges is therefore as follows:

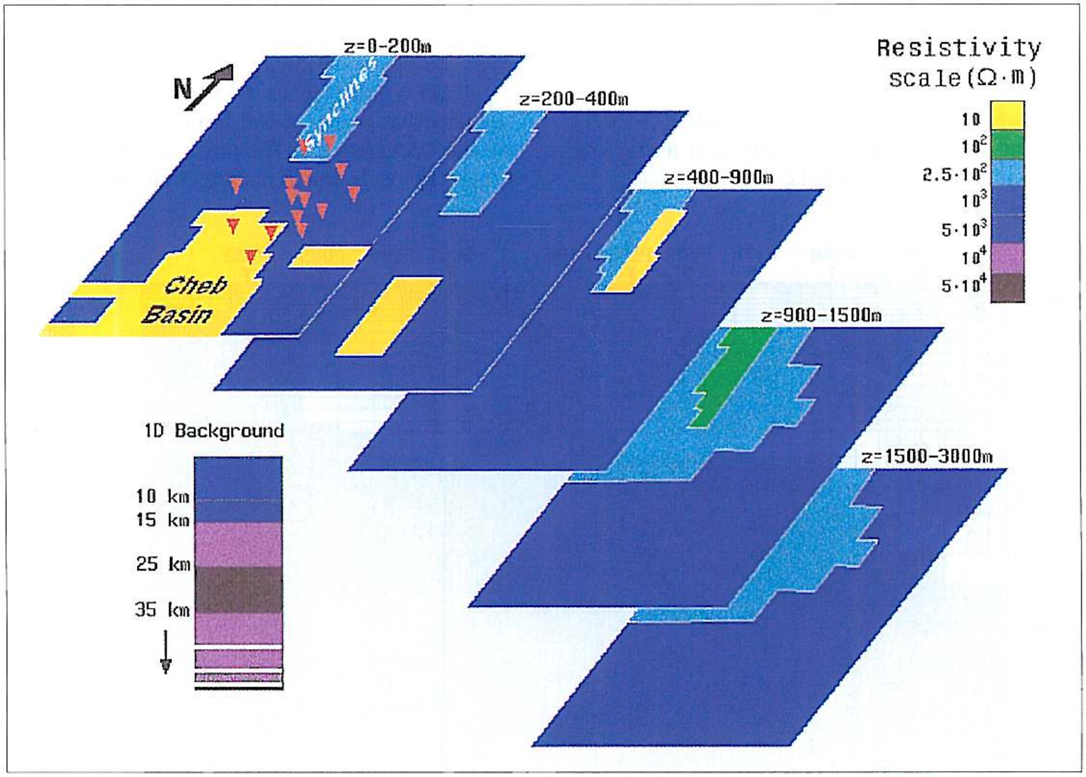

**Fig. 6.** 3D forward model of the investigated area: the different slices represent the $x$-$y$ plane views for increasing depths ($z$). The main anomalous conductive structures are schematically reported: the Cheb sedimentary basin, the Erlbach and Kraslice synclines zone and the (1-3 km deep) conductive structure, probably related to the buried granite massif. The green and yellow (conductive) portions of the syncline are a consequence of the features of the «Northern Sites» PI08 and PD06. They could be related to a difference in rheology between the phyllites and mica schists (see text).

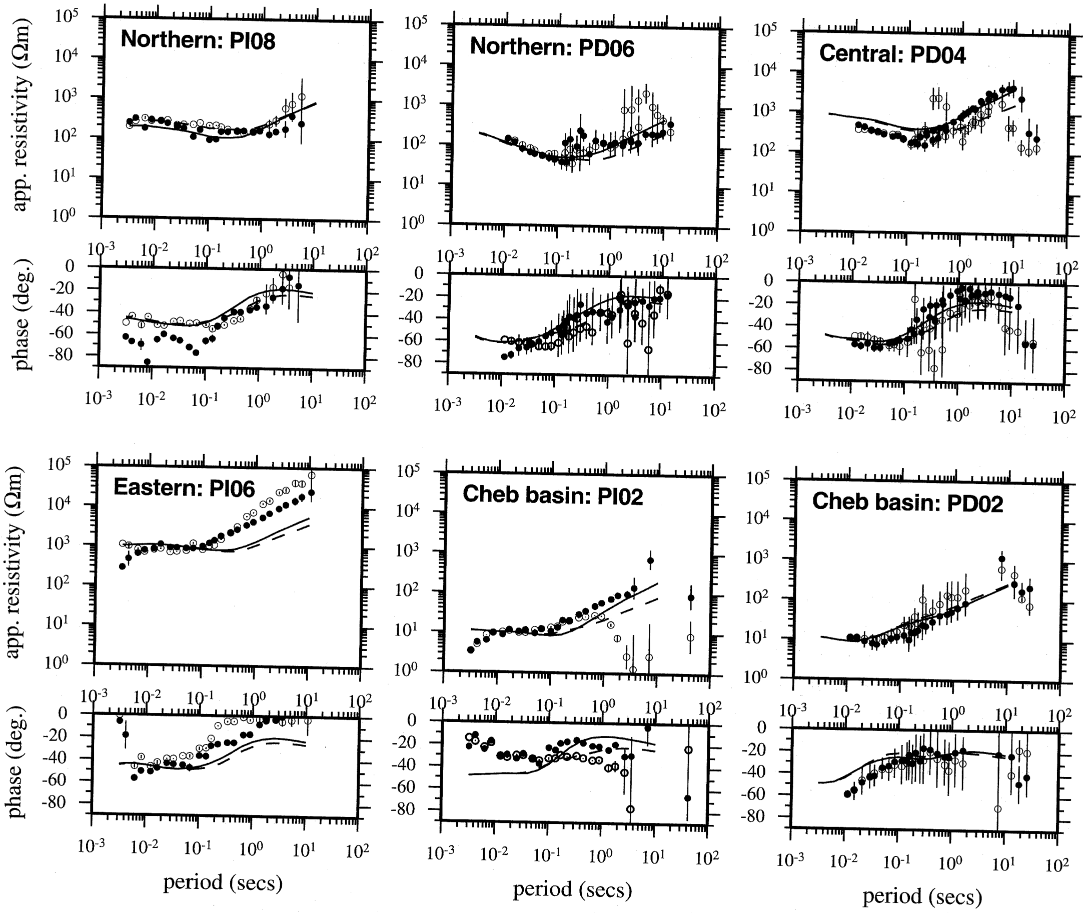

**Fig. 7.** Comparison between field data and the synthetic response of the 3D forward model in fig. 6. The most representative stations of each group (see Section 3.2) have been selected. *xy* and *yx* modes are represented by filled circles (experimental data) and full lines (3D response), and open circles (experimental data) and dashed lines (3D response), respectively.

– An overall physical-chemical effect on the rocks at the top of the granitic block: thermometamorphism, fracturation, tension gashes, paleofluids, alteration paragenesis, which could be responsible for a slight decrease in the resistivity of the entire zone. This would affect all of the aureole around the contact between the granites and the surrounding rocks.

– A lithological effect, related to the prevalence in the northern zones of phyllites over mica schists; this overprints the former general effect and probably enhances it, and could be due, for example, to the different rheology of the phyllites and mica schists.

On the basis of the indications of the 2D inverse models, various 3D forward models (Mackie *et al.,* 1993) were examined to verify the agreement between the field data and the synthetic response of a more realistic three-dimensional structure. The most representative stations were selected from the «Central», «Northern», and «Eastern» groups (see Section

3.2), discarding the stations (for example PI10-PI07) with a strong decoupling of the two polarizations. Those stations whose phase curves did not show a coherent trend and that were very close to other sites with no significant difference between $\rho_{xy}$ and $\rho_{yx}$ were ignored in the modelling procedure, as well.

The results of the 3D modelling are quite satisfactory and the final model (fig. 6) takes into account the geological features, lithological changes and gravimetric reconstruction of the granitic massif (see fig. 4). A comparison between the field data and the synthetic response of this model is presented in fig. 7 for the resistivity and impedance phase curves.

The response of various prismatic and pseudoplanar homogeneous bodies located at the focal depths under the zone of the «Central stations» was also verified. All these bodies influence the apparent resistivity curves in a similar way: there is a reduction in the apparent resistivity values at around 1 s, whose intensity depends on the resistivity contrast between the body and the basement; this reduction is particularly visible on one polarization (*yx* in fig. 2).

Some 2D and 3D forward models (not shown here) have generated a vertical conductive planar or prismatic body, whose lowest resistivity values are limited to the depth of 0.5-3 km. The increasing resistivity of such body with depth, where more resistive units are present throughout the area, also produces synthetic responses that are quite close to that of a simple conductive shallower body.

This is to be expected, considering the non-uniqueness of the problem. Although these models confirm that the sampling rate of data allows the extent to the focal depth, and although not entirely impossible, it would be somewhat speculative to introduce an anomalous conductive structure at the focal depths. So far, it has not been possible to find any direct evidence of it. Within the estimated error, most of the data can simply be explained by the shallow structure mentioned above, as supported by the geological features of the region around the study area. More investigations are however needed in this sector.

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