Magnetotelluric and deep geomagnetic induction data in the Bohemian Massif

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Abstract
Manifestations of the increased tectonic activity (seismic activity, remnants of Tertiary volcanism and riftogenesis) in the Bohemian Massif are bound to geologically extremely complicated regions with a system of discordant structures and a mosaic of fault zones. The presented results concern the deep geoelectrical features of the tectonic transition between the Saxothuringian and Moldanubian tectonoblocks on the territory of West Bohemia, in close vicinity to the German deep drilling experiment KTB (Kontinentale Tiefbohrung der BRD). Three first-order tectonic lines demarcate the region under study – the Litoměřice deep fault to the north, the West Bohemian deep fault zone to the east, and the Central Bohemian fault to the south. As a whole, the region involved is characterized by a regionally increased seismic activity with the most active zone just beyond the northern end-point of the profile investigated. The contribution can be considered an example of possible interpretation of MT/MV/AMT data in geologically extremely complicated conditions with evidently discordant structures affecting the geoelectrical data.

Key words *magnetotelluric – electromagnetic modelling – Bohemian Massif*

1. Introduction

The unique geoscientific experiment of deep drilling KTB in Oberpfalz (Germany) has attracted an enormous concentration of geoscientific research in the region involved, as well as in its broad regional surroundings. Within all those studies geoelectrical research has played an important role, particularly as regards the structural features of the region and sources of outstanding geoelectrical anomalies indicated in the area (Haak *et al.*, 1991; ELEKTB-Groupe, 1994).

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Due to the specific localization of the KTB drilling experiment only a few kilometers to the west of the Czech-German border, the geoelectrical measurements in SW and West Bohemia are an integral part of the regional tectonic studies of the borehole-connected research activities. The principal objectives of the deep and audio MT measurements in SW Bohemia were to contribute to regional geophysical studies carried out in a broader vicinity of the KTB and to trace the anomalous geoelectrical zones observed in the immediate neighbourhood of the KTB, further to the east. The project is part of a broader complex of investigations into the structure and dynamics of the western margin of the Bohemian Massif, including the structural conditions, sources and mechanisms of recent tectonic mobility and seismic activity of the region.

Geologically, the broader FRG/Czech surroundings of the KTB site can be characterized as a region where different zones of the Bohemian Massif, representing the easternmost part of the European Hercynides, make contact (Suk *et al.*, 1984). Specifically, the KTB drilling site is located near the western margin of the Bohemian Massif, and a few km south of the structurally important boundary of the Moldanubian and Saxothuringian blocks of the Central European orogenic belt. The boundary, along which the two segments of the earth crust collided about 320 million years ago and the Moldanubian rocks were overthrusted on the Saxothuringian ones, is believed to be the Erbendorf line. Its continuation into Western Bohemia is assumed to be the Litoměřice fault zone, situated to the north of our interest region. In the West, this region makes an immediate contact with the KTB area, and on the Czech territory it is demarcated by the central Bohemian deep fault in the south and the West Bohemian fault zone in the east (fig. 1).

The region under study belongs to areas with highest seismic activity on the Czech territory (fig. 2). Just a few km to the north of our main profile there is one of the most active regions in Central Europe due to the relatively frequent earthquake swarms. Earthquakes with magnitudes greater than 4.5 occur rarely in this region. The occurrences of swarms have been reported frequently since 1552, the last great swarm being recorded in 1985-1986 (Horálek *et al.*, 1996).

Our studies were not particularly devoted to the geoelectric analysis of seismic regions, but the structural investigations may be of interest

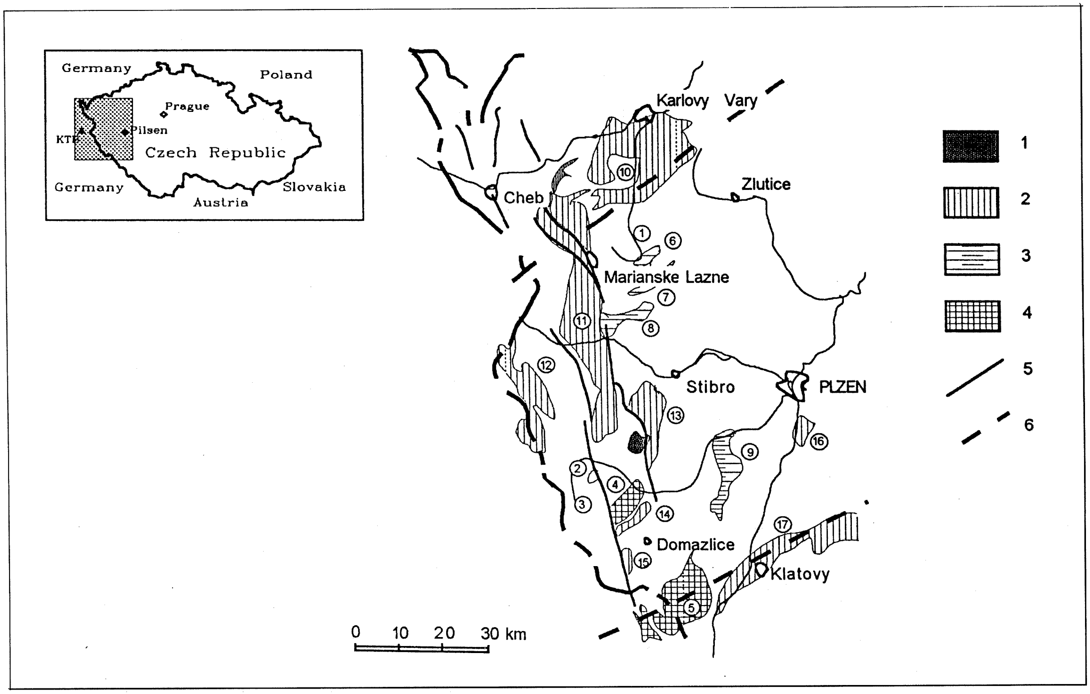

Fig. 1. Geological scheme of SW Bohemia. The region under study is a bulge of the Moldanubian tectonic unit to the north along the West Bohemian fault zone. Moldanubicum is built up from intensively metamorphized crystallic complexes interspersed with granitoid plutons of hercynian age. 1 = Sedmihorsko stock (ring intrusion); 2 = granites and granodiorites of hercynian age; 3 = granites and granodiorites of cadomian age; 4 = basic magmatites; 5 = ultrabasic intrusives; 6 = main faults; 7 = deep faults. Labels in circles – individual granitoid massifs of the West Bohemian Pluton (after Mísař *et al.*, 1983).

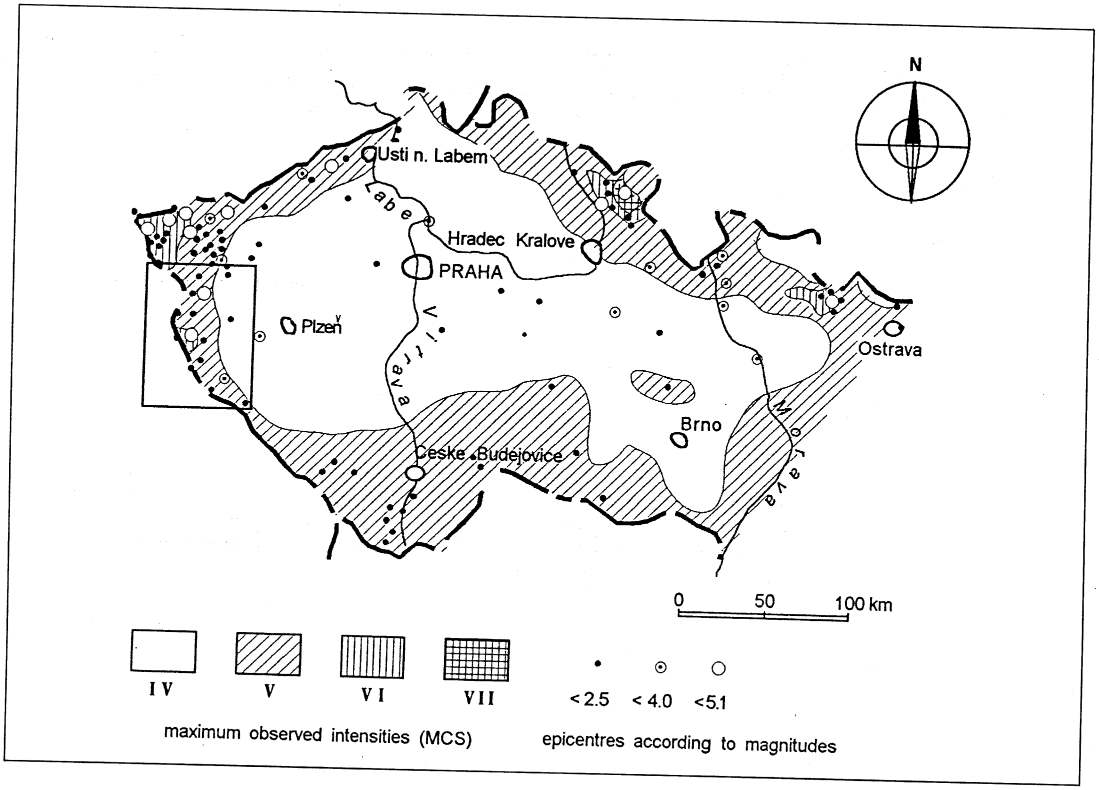

Fig. 2. Map of highest intensities of earthquake and earthquake epicentres on the territory of the Czech Republic (after Mísař *et al.*, 1983).

from the point of view of comparing seismoactive regions under various conditions, especially in areas with highly complex geological structure.

The induction geoelectrical studies in the region included are based on a series of field experiments carried out within the period 1991-1995. The field measurements included the following experiments (fig. 3):

– Long period magnetotelluric (MT) and magnetovariational (MV) measurements (period range from 10 s to about 1 h) at 14 field stations arranged along a regional profile, about 100 km in length, immediately along the Czech-German border. The profile was situated between the KTB drill site and the West Bohemian fault zone with enhanced tectonic activity. At seven of those long-period MT stations audiomagnetotelluric (AMT) data (frequency range 10^3 Hz-10 s) were supplemented, in cooperation with the University of Frankfurt/M., Germany.

– Additional AMT measurements at twenty field stations, in cooperation with the Italian co-authors, along two local profiles. The first profile, crossing the northern section of the main profile, near to Tachov, touches the northern end of the seismoactive Tachov fault and tries to detect structural changes towards the main fault zone. The second local profile, situated near the southern end of the main profile (Kdyně), was chosen to study the anomalous conductive zone indicated at the crossing of the Central Bohemian fault. Recently, additional long-period MT measurements have been supplemented along these two local profiles, both with 4 stations arranged to cross the principal tectonic lines of the respective locality.

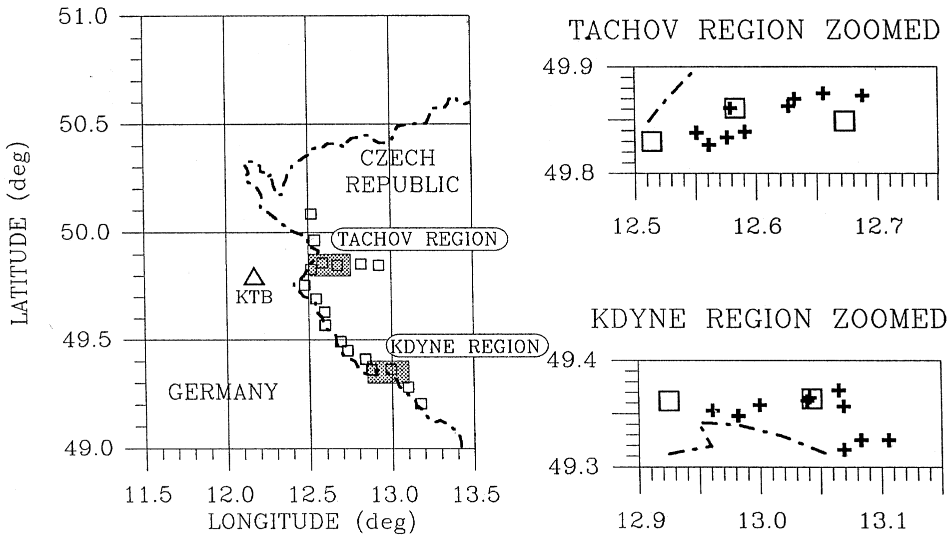

Fig. 3. Layout of the AMT/MT/MV profiles in West Bohemia.

2. Regional MT/MV studies

A detailed analysis of the regional induction studies in SW Bohemia was already presented in (Červ *et al.*, 1993a,b, 1994). Therefore, only a brief summary of the principal interpretation results will be given here. A preliminary estimation of the induction effect of the structure involved was based on the analysis of long-period MV data, in particular on the spatial and frequency behaviour of the geomagnetic transfer functions. The geomagnetic transfer functions are commonly presented in the form of the induction arrows, defined in the frequency domain as

$$\mathrm{Re\,TF} = [\mathrm{Re\,A}, \mathrm{Re\,B}],\ \mathrm{Im\,TF} = [\mathrm{Im\,A}, \mathrm{Im\,B}],$$

where $H_z = \mathrm{A}\ H_x + \mathrm{B}\ H_y$, and H_x, H_y, H_z are the spectral densities of the time variations of the components of the earth's magnetic field. The real induction arrows reflect the integral effect of the in-phase induced currents within the Earth, and are considered rather undistorted indicators of the structural strike of the medium.

Figure 4 shows the real induction arrows along the regional NW-SE profile for a series

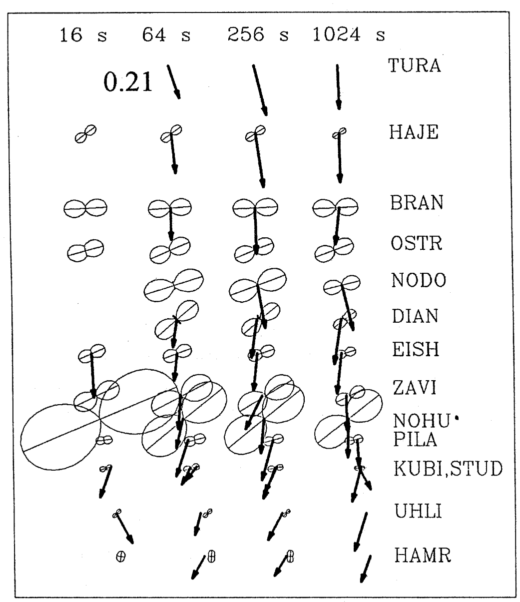

Fig. 4. Polar impedance diagrams $Z_{xy}(\alpha)$ and real induction arrows along the main profile in West Bohemia for four periods of the magnetotelluric field.

of periods. The arrows display an almost uniform orientation towards the south along the entire profile, which matches the over-regional pattern observed across the whole system of the Central European Variscan belts. Along our profile, the real induction arrows are generally quite large, with moduli as much as 0.3 in the north of the profile, and decreasing gradually towards the south, to values like 0.15.

Structurally, induction arrows indicate a deep quasi-2D regional structure, striking E-W, and a systematic decrease of the induction effect towards the south, connected either with a gradual resistivity increase towards the south, or with a fade-away of the effect of a conductivity contrast situated somewhere to the north of our profile.

Magnetotelluric data display a rather 3D character along the whole profile. Diagonal impedances do not vanish after rotating the impedance tensor into Swift's principal direction. Main impedances display huge anisotropy, often more than 10 in terms of max/min impedance ratio in the principal direction. Substantial change of the impedance pattern occurs in the south of the profile, in particular an abrupt drop of the resistivities is observed when crossing the line of the Central Bohemian fault.

The hypothesis of a 2D E-W regional strike and generally 3D galvanic distortions of the data was widely verified by the MT decomposition techniques by Bahr (1991) and Groom and Bailey (1989) (Červ *et al.*, 1993b, 1994). In such a case induction arrows and both *XY* and *YX* impedance phases can be considered undistorted functions of the regional structure and can be used to model the deep basement.

Several modelling and inversion experiments were carried out for the above magnetotelluric functions derived from the experimental data along the profile. Two representative modelling results are presented here.

Model A (fig. 5) is based on a previous experiment of Tauber (1993) and Eisel (1990), who proposed a thin, segmented well-conducting layer at the depth of about 10 km to be responsible for the distribution of the induction arrows and impedance phases near to the KTB location. With the same model as a starting approximation to our data, we interpreted moduli of the induction vectors and *YX*-phases (*E*-polarization) for the resistivities and positions of the blocks, using Marquardt's method (Pek, 1987). A satisfactory fit to the experimental data could be obtained (Červ *et al.*, 1994). A deeper situated layer seems to better conform *XY* (*H*-polarization) phases, but slightly increased misfit in *YX*-phases occurs when placing the thin layer deeper.

Model B (fig. 6) was obtained by applying a 2D version of the controlled random search method (Martinez, 1988) to invert the moduli of induction vectors and both the impedance phases, *YX* and *XY*, for the resistivities of individual blocks. The conductive layer with conductance close to that from model A is preserved in the model. Notice the dipping insulator beneath the southern section of the profile, which can also contribute to the anisotropy of impedance phases.

Within the concept of the static shift the particular form of the polar impedance diagrams cannot be solved. The physical sources of the distortions reduce to an algebraic multiplication of the regional impedances by a frequency independant distortion matrix. Modeling of the distortion effects of the upper crustal structure is based on a detailed model of the immediate vicinity of the KTB borehole presented by Eisel (1992). He interpreted the large anisotropy, typical of his broad-band AMT/MT data from the immediate vicinity of the KTB drilling site, as an effect of the dyke macroanisotropy. In his model of the Erbendorf-Vohenstrauss Zone (ZEV) the principal feature is a highly anisotropic block situated in the upper to middle crust immediately below the ZEV. Towards the NE, this block seems to submerge into greater depths. The huge anisotropy of the block, with the anisotropy ratio exceeding two orders of magnitude, is considered to be caused by NW-SE striking, steeply dipping cataclastic zones filled with fluids, graphite and other conductive materials. These zones are actually observed on the borehole lithology, and in a broader vicinity of the drill site are detected by large anomalies of the spontaneous polarization.

Model C (fig. 7) is based on Eisel's idea of an anisotropic block beneath the KTB site, re-

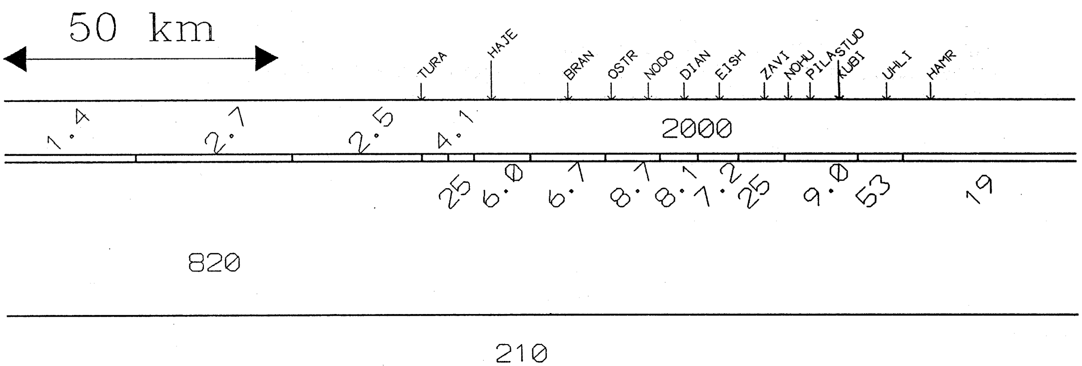

Fig. 5. Model A obtained by inverting the real induction arrows and *YX*-phases by using Marquardt's technique.

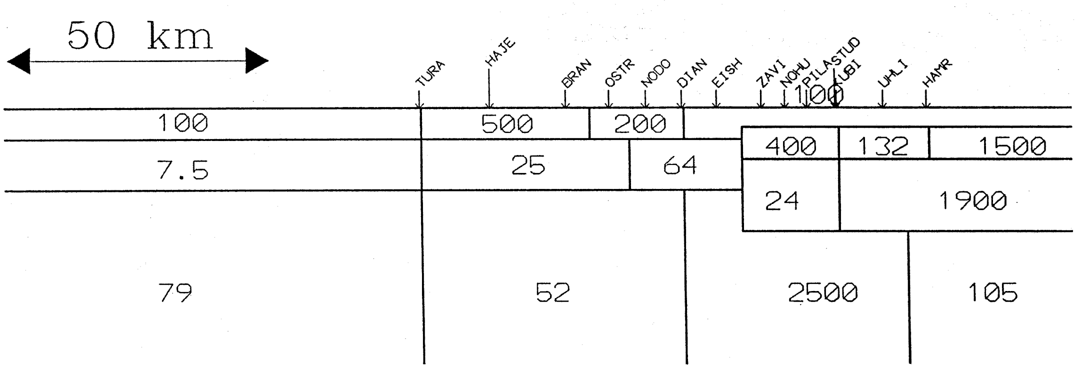

Fig. 6. Model B obtained by inverting the real induction arrows and both *YX* and *XY*-phases by means of the controlled random search technique. Equal scale for both the horizontal and vertical directions.

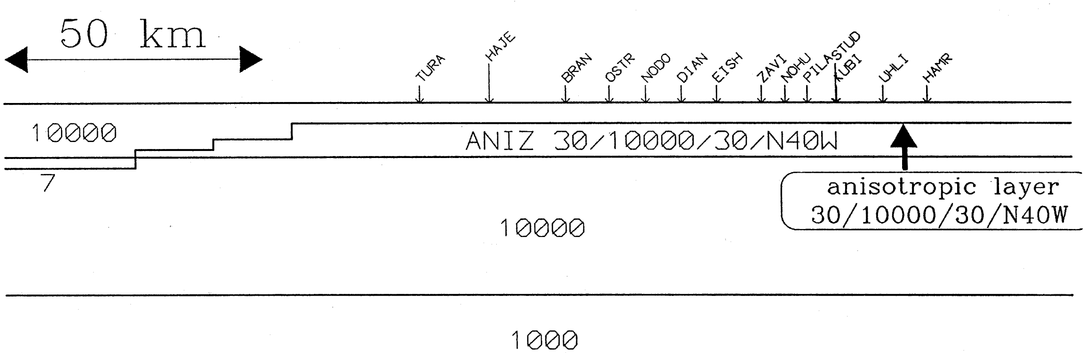

Fig. 7. Model C containing a speculatively extrapolated anisotropic layer, anisotropy strike N40°W, in the upper crust beneath the main profile.

sulting from highly conducting, graphitized, nearly vertical dykes, observed in that locality. A speculative model was devised, in which the anisotropy of more than two orders was extended beneath the whole profile in a form of a several kilometer thick anisotropic layer, anisotropy strike N40W degrees. Even though speculative, the model gives a comparable fit to induction arrows and impedance phases as the previous models. Moreover, it explains the systematic difference of strikes indicated by induction arrows on the one hand and by impedance diagrams on the other. It also gives an approximately correct anisotropy of MT curves of slightly less than 10, and fits the systematic deviations in the azimuth of real induction arrows along the profile.

Regional long-period induction studies confirm a close similarity of the geoelectrical structure in SW Bohemia to that found in the immediate vicinity of the KTB borehole. The geoelectrical section can be characterized as a slightly distorted 2D regional structure, striking EW, with large distortions resulting from an upper crustal structure which express high effective anisotropy with the direction of preferred conductivity NW-SE to NNW-SSE. Within the period range studied a more detailed picture of the distorting layer cannot be obtained.

3. Local AMT studies

3.1. *Kdyně region*

Local high-frequency AMT (period range 10^{-2}-10^{2} s) studies were concentrated into two particular regions of the main profile with specific features observed in long-period MT/MV data. The first local region, near to the town of Kdyně, is situated near the southern end of the West Bohemian paleorift, near a crossing of two significant tectonic lines – the Bohemian Quartz Lode from the north and the Central Bohemian fault from the NE. Geophysically this area represents a highly anomalous zone, with indications of large density contrasts within the crust. It is marked by large positive magnetic anomalies arranged along a SW-NE line running into the Bohemian Massif.

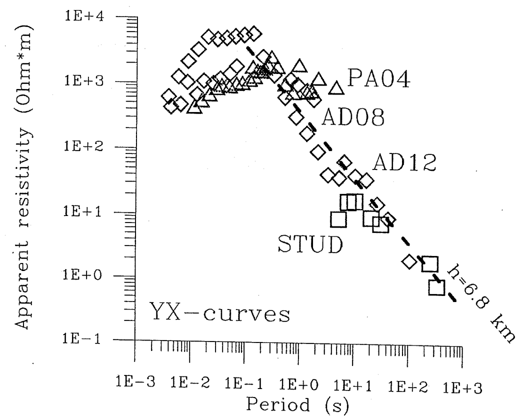

Fig. 8. Form *YX*-apparent resistivity curves measured within a small area of about 300×300 m^2 at the location STUD on the southern local AMT/MT profile. Long-period asymptote of the curves indicates the depth to the conductor approximately 6.8 km.

Long-period MT measurements at sites KUBI and STUD display an anomalous drop of apparent resistivities, particularly at the latter station where values less than 1 Ωm are reached between 10-100 s.

AMT data confirm the highly conductive zone, particularly when approaching the east end of the local AMT profile. Figure 8 shows measurements from both long-period MT and high-frequency AMT measurements from the site STUD, where repeated experiments were carried out across an area of 300×300 m^2. Estimates of the depth of the conductor vary within broad limits – from about 1 to 10 km.

3.2. *Tachov region*

The local area near the town of Tachov was selected for detailed AMT investigations due to its close position with respect to the KTB locality. Geologically, the area falls into a contact zone between the Bohemian Forest Mts. and Tepla-Barrandien zone, and is marked by two significant fault zones – the Tachov fault, considered a seismoactive fault, and the Mariánské Lázně fault (fig. 9).

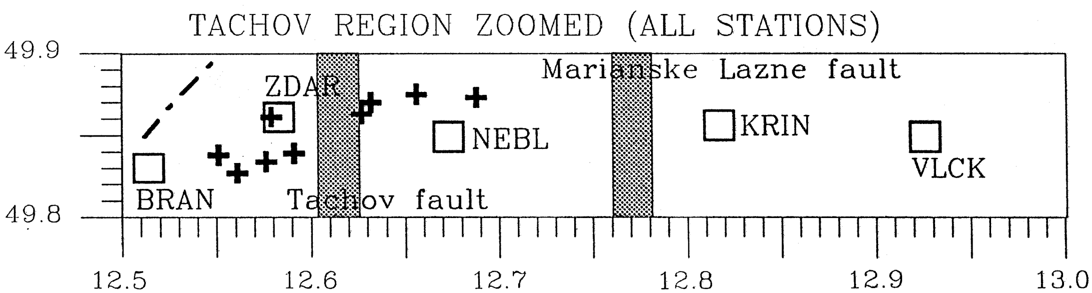

Fig. 9. Positions of the AMT/MT stations along the northern local profile with respect to the approximate locations of the principal fault zone in the region.

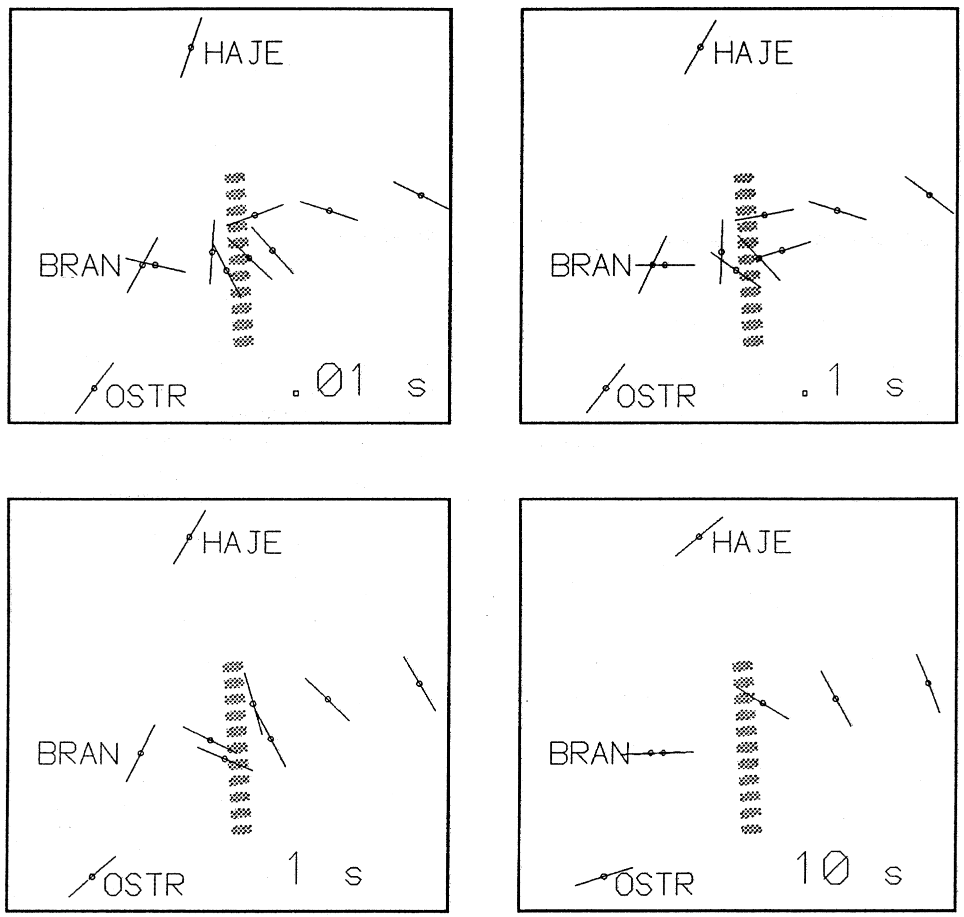

Fig. 10. Directions of the major axes of the principal polar impedance diagrams $Z_{xy}(\alpha)$ in the Tachov region for periods 0.01-10 s. The thick line, which approximately coincides with the northern end of the Tachov fault, indicates the most rapid change of the principal direction.

AMT data in this area exhibit a jump in principal Swift directions, as if the stations were separated by a S-N striking line situated along the Tachov fault. To the west of this line the impedance diagrams are directed, according to major axes, predominantly SW-NE-wardly, whereas to the east they are SE-NW-directed (fig. 10).

Long-period MT data are in accord with AMT directions and do not display any significant change if crossing the Mariánské Lázně fault. This pattern of the spacial distribution of the principal directions of the MT curves could indicate that the dominant feature of NW-SE anisotropy in the MT data does not continue further to the east of the line identified approximately with the Tachov fault. At stations in the immediate vicinity of the Tachov fault, a shallow highly conductive body (less than 2 km) is indicated.

1D interpretations of the MT curves to the east of this fault indicate a deep conductor, between 10-20 km deep, most pronounced in the approximately EEN-WWS direction which well coincides with the regional strike derived from the induction arrows. A marked decrease of the resistivity of nearsurface layers (several hundreds of meters up to 1 km) is observed towards the east, which can be connected with the fluid enrichment of the Mariánské Lázně fault.

Geoelectrical data in the studied region show rather complex structure with typical 3D features. Clearly it has not been possible so far to connect directly the structural phenomena with the seismic activity of the region. Nevertheless, the presence of highly conductive and anisotropic anomalous geoelectrical structures within the region may be of interest with regard to the seismic regime of the area, if similar correlations are considered from other seismo-active regions (*e.g.*, Ádám, 1994).

4. Conclusions

From the geoelectrical studies carried out so far on the western margin of the Bohemian Massif the following conclusions can be drawn:

– The geoelectrical manifestation of the local structures in the region involved is influenced by the effect and displays on the background of a rather intricate regional structure. The typical features of the regional structure are: 1) a quasi 2D character with the structural strike in approximately the E-W direction, and 2) a complex distorting layer in the upper to middle crust, which exhibits a considerable anisotropy with a large regional part, striking NW-SE to NNW-SSE. The regional structure shows a close structural similarity with that obtained in the immediate KTB area.

– The local AMT studies in the Kdyně region confirmed the highly conductive anomalous zone at the crossing of the Central Bohemian fault and the Bohemian Quartz Lode.

– The local AMT studies in the Tachov region display a structural change along the seismoactive Tachov fault, which seems to be connected with the termination of the crustal conductive layer at the fault line, and is manifested by a change of principal MT directions when crossing the fault.

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