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Application of the telluric and magnetotelluric methods in selection of sites for nuclear plants

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Abstract. The paper deals with the application of the telluric method and of magnetotelluric soundings including experimental and model data on the localization of tectonic disturbances in connection with the selection of appropriate sites for nuclear plants.

Keywords. Telluric method; magnetotelluric soundings; nuclear plant site; tectonic disturbances.

1. Introduction

One of the important aspects in selecting sites for nuclear plants is to avoid areas of seismically active tectonic disturbances (fractures, faults, strike slip, recent crustal movements etc.). This selection is supported by geophysical exploration. During the first stage of exploration, disturbed zones are identified using a combination of different (e.g. magnetic, geoelectric, electromagnetic and seismic) methods. The sequence of the methods is hierarchical both from the points of view of resolving power and of expenses. In the next stage the present activity of the identified zones is monitored, mainly with seismometers but also with other methods capable of indicating stress accumulation in the crust and its elastic or seismic release. In recent years, Chinese workers draw attention to the fact that areas seemingly inactive from a seismic point of view may also be dangerous, as seismic gaps may indicate accumulation of stresses which should be followed by energy release in due time.

Thus a detailed geophysical study of the tectonics—be it active or inactive—has high significance in the selection of sites for nuclear plants.

The present paper deals with the application of the telluric method and of magnetotelluric soundings for this purpose including experimental and model data on the localization of tectonic disturbances.

2. Methods

2.1 *Telluric method*

The telluric method (IT) is based on the connection between the horizontal electric components (E) of two stations, a basis (B) and a moving station (M):

$$E_{Mx} = T_{xx}E_{Bx} + T_{xy}E_{By},$$
$$E_{My} = T_{yx}E_{Bx} + T_{yy}E_{By}. \quad (1)$$

The quantity called "area of the relative ellipse" is deduced from the matrix

$$\begin{vmatrix} T_{xx} & T_{xy} \\ T_{yx} & T_{yy} \end{vmatrix}$$

which is inversely proportional in sedimentary basins with the conductance S of the sediments ($S = h/\rho_{av}$ where h is the thickness and ρ_{av} the average resistivity of the sediments). Telluric measurements are made in the so-called interval S which is indicated on magnetotelluric (MT) sounding curves by the ascending branch corresponding to the high resistivity basement.

The area values can be transformed by the MT sounding curves of the basis station into S-values of the moving station, and in case of known or constant ρ_{av}, into depth of the basement, i.e. thickness of the sediments. It means that the relief of the basement can be determined together with conductive embeddings (fractures).

The shape of the telluric relative ellipses reflects micro- or macro-anisotropy of the resistivity, thus it also bears structural information. There are several methods for the determination of relative ellipse (see e.g. Porstendorfer 1961).

2.2 *Magnetotelluric sounding*

The basic relations of magnetotelluric sounding (MTS) express the connection between the horizontal electric (E) and magnetic (H) components of the electromagnetic field at a measurement station:

$$\begin{aligned} E_x &= Z_{xx}H_x + Z_{xy}H_y, \\ E_y &= Z_{yx}H_x + Z_{yy}H_y, \end{aligned} \tag{2}$$

for a given frequency or period, T. From these equations the components of the transfer function i.e. of the complex impedance Z, and from Z the apparent resistivity ρ and the phase φ can be obtained vs period being related to the penetration depth of AC, i.e. to the exploration depth. An inversion of these quantities yields the geoelectric layer sequence below the station (1-D model). In case of more realistic 2-D structures, sounding curves at E- and H-polarization are of great importance. These curves are computed by a rotation of the coordinate axes. In the real world, 1-D and 2-D structures exist as limiting cases of 3-D structures. A more detailed description of this method is found e.g. in Ádám (1976) and Kaufmann and Keller (1981).

3. Exploration of the tectonics by TT and MTS methods

In order to present the efficiency of these methods, two simple, but characteristic tectonic forms are chosen: fractures and faults. Let us see how these forms appear in the results of these methods.

(i) Fractures are zones where the rock material is broken due to the effect of tectonic stresses. If it is impregnated by fluids, the conductivity increases with respect to the embedding rock matrix. The situation corresponds to the model of a 2-D conducting dike (figure 1). The effect of the dike on the electric profiles is illustrated by

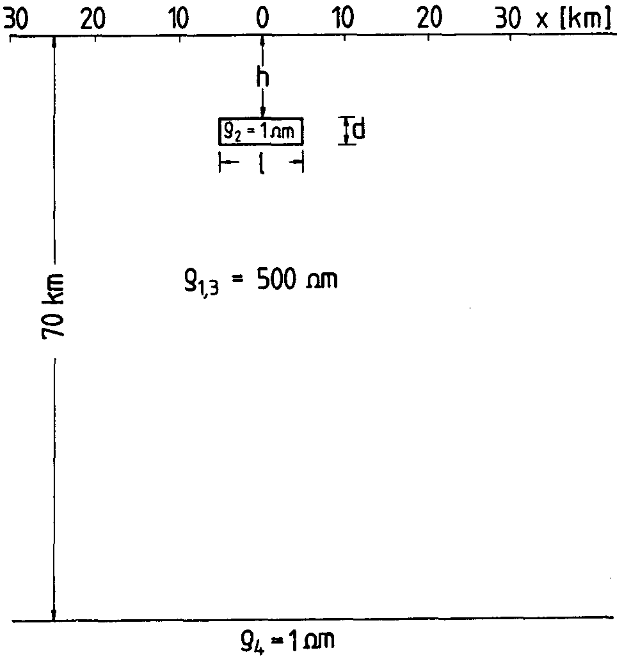

Figure 1. Dike model (Ádám 1987).

pseudo-sections: the apparent resistivity and phase of the impedance are computed from strike (E-pol) and dip (H-pol) electric components, and from the corresponding magnetic components along the profile vs period or depth being proportional to the period. These pseudo-sections outline the conducting dike (figures 2–3, Ádám 1987) accompanied by different distortions of the field. In the E-polarization case inductive lateral effects are characteristic and in the H-polarization case galvanic (charge-) effects increase the apparent resistivity of the embedding rock matrix to values higher than its true resistivity. The interpreter geophysicist has to detect these distortions. The following example proves that only a sufficient number of MTS-s enables an inversion which approximates the real tectonic structure.

MTS curves at different distances from the centre of the dike are presented in figure 4 for the E- and H-polarized cases. If the dike is narrow with respect to the penetration depth, then the major axis of the impedance ellipse (i.e. the direction of $\rho_{\max}$) is perpendicular to the strike of the dike, and $\rho_H(T) > \rho_E(T)$. In the case of thick dikes this situation is valid only for the marginal part of the dike. In the heart of the dike, $\rho_{\max}$ may turn into strike direction. Telluric relative ellipses have a similar trend. Polar diagrams bear therefore structural information.

The effect of the conducting fractures is illustrated by two examples here:

(a) Along a seismically active fracture in the East-Alps (Metnitz-Strassburg-St. Veit) near the village Lassnitz the apparent resistivity was extremely low in the strike direction according to MTS soundings (figure 5b, sounding curves). Analogue records of the electric components have hardly any resemblance to the corresponding magnetic components (figure 5a). Thus a special processing was found necessary in this case. The major axis of the impedance diagram is perpendicular to the strike of the fracture (Ádám *et al* 1981).

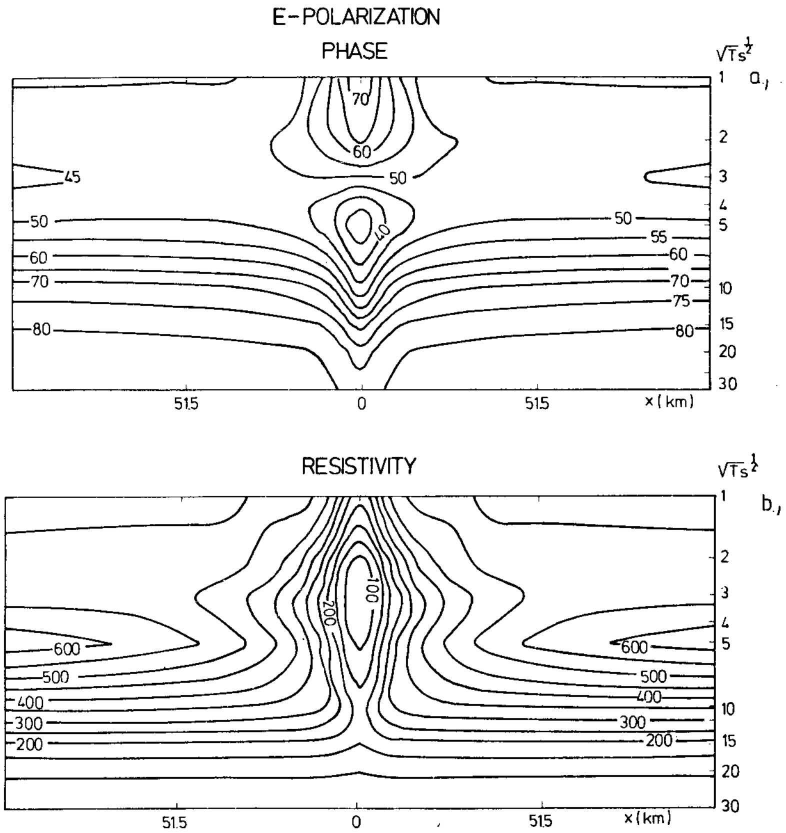

Figure 2. *E*-pol. pseudo profiles of a dike model (parameters: $h=5$, $l=4$, $d=1$ km) (Ádám 1987).

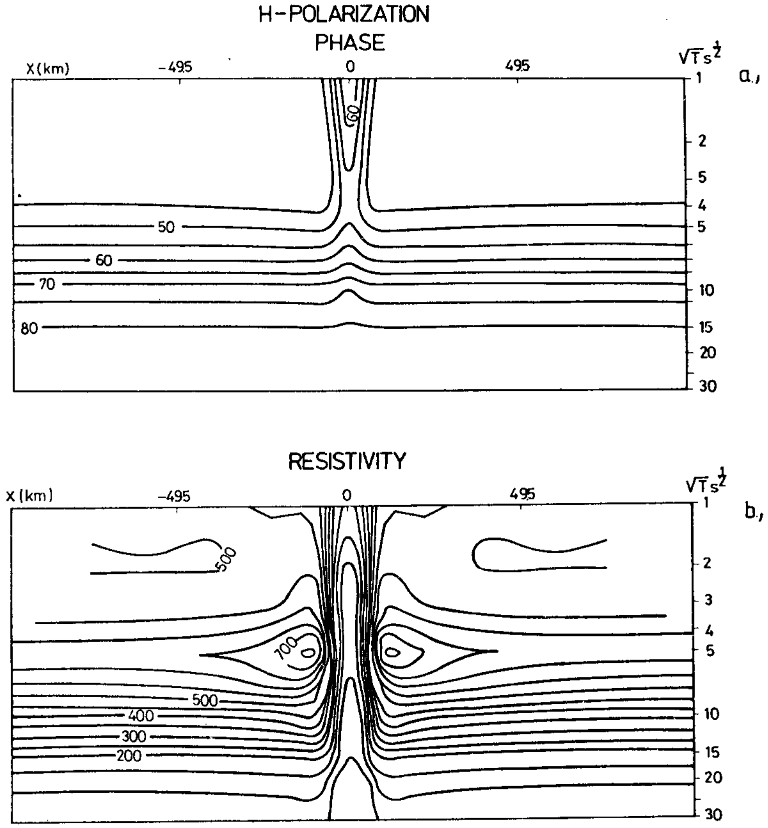

Figure 3. *H*-pol. pseudo profiles of a dike model (parameters: $h=5$, $l=10$, $d=1$ km) (Ádám 1987).

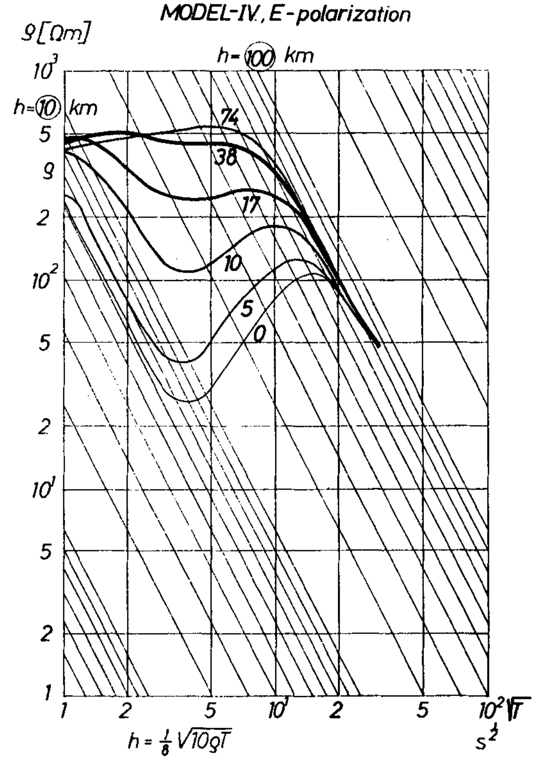

Figure 4a. E-pol. MT sounding curves of the dike model with parameters $h = 5$, $l = 10$, $d = 1$ km (Ádám 1987).

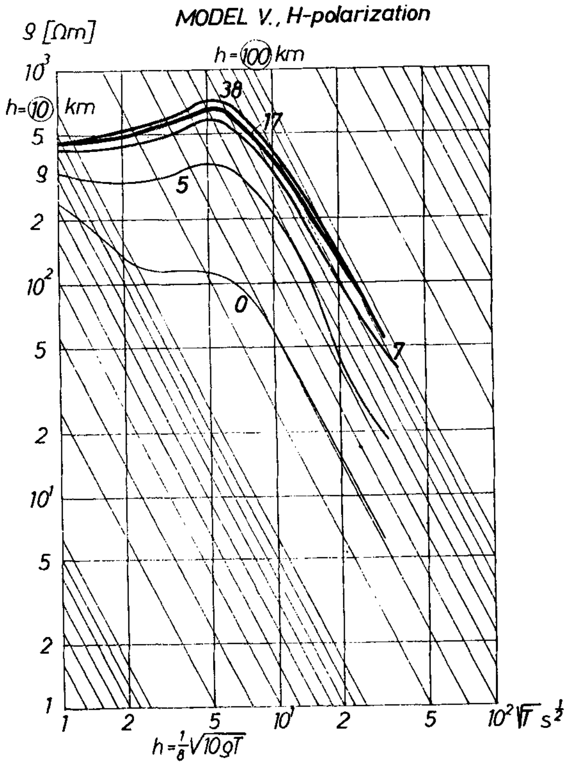

Figure 4b. H-pol. MT sounding curves of the dike model with parameters $h = 5$, $l = 10$, $d = 1$ km (Ádám 1987).

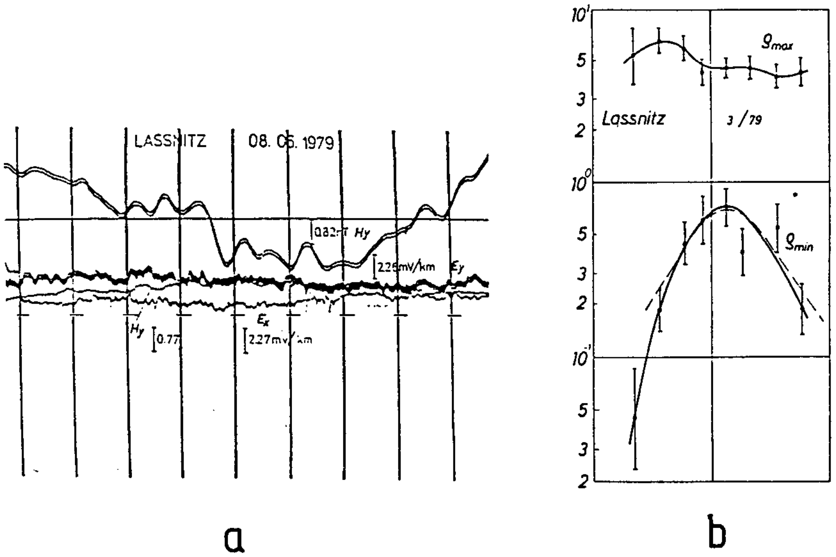

Figure 5. (**a**) Magnetotelluric record in Lassnitz (Eastern Alps). (**b**) MT sounding curves (Ádám *et al* 1981, 1986).

(b) One of the easternmost elements of the Eastern Alps, the Sopron crystalline schist is broken along parallel fractures into blocks before the main limit border fault where the schists sank into a depth of about 1000 m below the sedimentary cover of the Little Hungarian Plain. Such a fracture is detected by TT and MTS measurements as shown in figure 6: Figure 6a is an analogue earth current record, figure 6b the telluric profile and figure 6c shows MTS curves. The fracture below station K-6 is characterized by strong channelling in the fractured rock. Variations in the E_y(E–W) electric components are nearly two orders of magnitude lower than in the component E_x(N–S). The width of the fracture is very small, as, in a distance of 100 m the eccentricity of the telluric ellipse decreases by an order of magnitude (Ádám and Verő 1961).

(ii) The effects of a fault on the EM field are illustrated here by the results of TT and MTS measurements made along one of the main tectonic lines of the Pannonian Basin, being a strike slip combined with normal faults. These investigations were connected to the geological-geophysical exploration of the area of a Hungarian nuclear power plant.

The exploration area near the river Danube is shown on the scheme of the Oligocene tectonics of the Carpatho-Pannonian Basin (figure 7, Balla 1988). The strike slip fault directed SW–NE borders a right-hand shear zone from *S* and meets toward East, the flysch zone which extends into the basin from the area of the outer Carpathians. This Kapos tectonic line crosses the whole Pannonian Basin and several sections proved to be seismically active in the last centuries.

Areal TT measurement have shown a picture of a horst having on both sides deep borders in the basement along the section of this tectonic line studied. Later seismic and some geoelectric measurements have confirmed that the horst emerges from a depth of 1600 m in the deep basin to about 500 m.

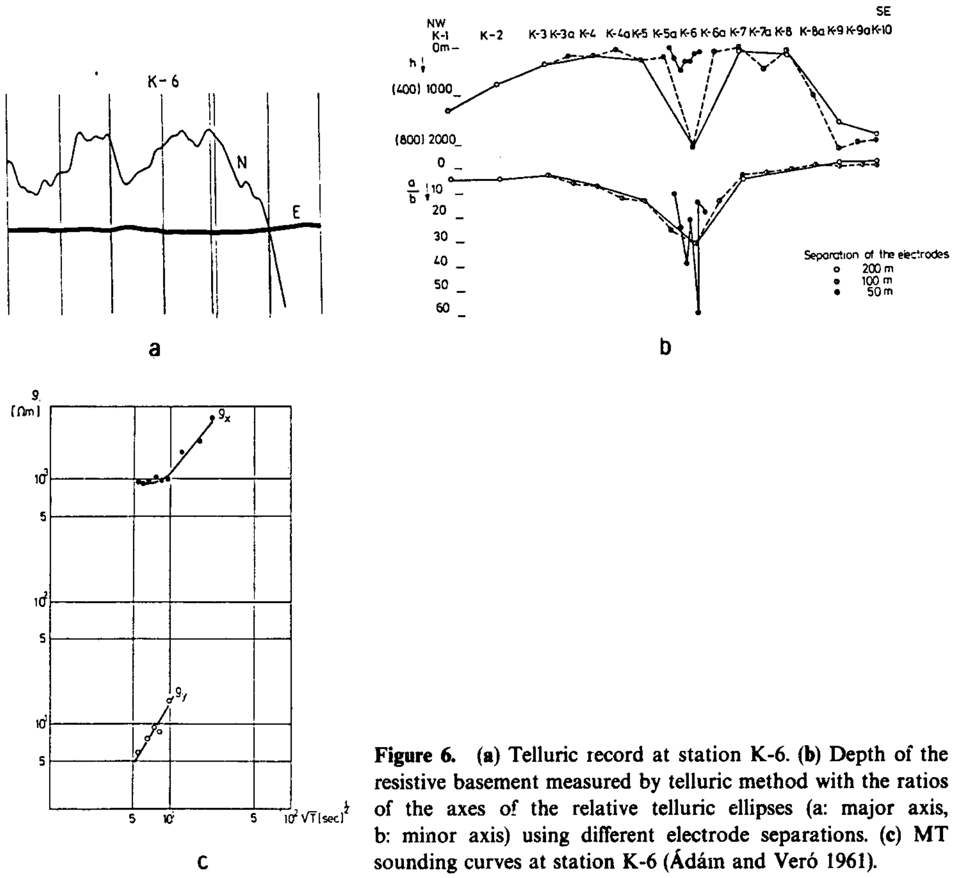

Figure 6. (a) Telluric record at station K-6. (b) Depth of the resistive basement measured by telluric method with the ratios of the axes of the relative telluric ellipses (a: major axis, b: minor axis) using different electrode separations. (c) MT sounding curves at station K-6 (Ádám and Veró 1961).

Two basis stations (B_1, B_2) were used for the TT measurements. At both stations, MT soundings were made, and from an inversion of the ρ and φ extrema, a 1-D model layer sequence was computed together with the horizontal conductance (S) of the sediments (curve $\rho_{\max}$ of B_1 in figure 8). The anisotropy of S is low at both stations (1·2 to 1·3). The area-values were transformed by the $S = (S_{\min} S_{\max})^{\frac{1}{2}}$ of the basis.

Two series of maps illustrate the change of the image of the structure due to a densification of the measurements. The distance of the stations in the first series was 2 km, and 500 m in the second series.

Telluric-relative ellipses are plotted in figure 9. The ellipses measured in the initial network are hatched. As the anisotropy of the basis is low, the relative ellipses reflect rather well the anisotropy of the measurement sites. Ellipses elongated in the direction NW–SE outline the strike of the horst and of the bordering faults respectively, according to the above mentioned strike-slip. Ellipses of small areas in the immediate vicinity of big ellipses hint at deep faults. The structure is clearly shown on the isoarea map (figure 10). The denser isoarea map (figure 11) remains similar in the main elements compared to that in figure 10 and its details refer to a complicated structure of the horst.

The ratio of the major and minor axes (A/B) of the ellipses projected in the direction of the horst gives information in form of a statistical cluster about the fault structures (figure 12).

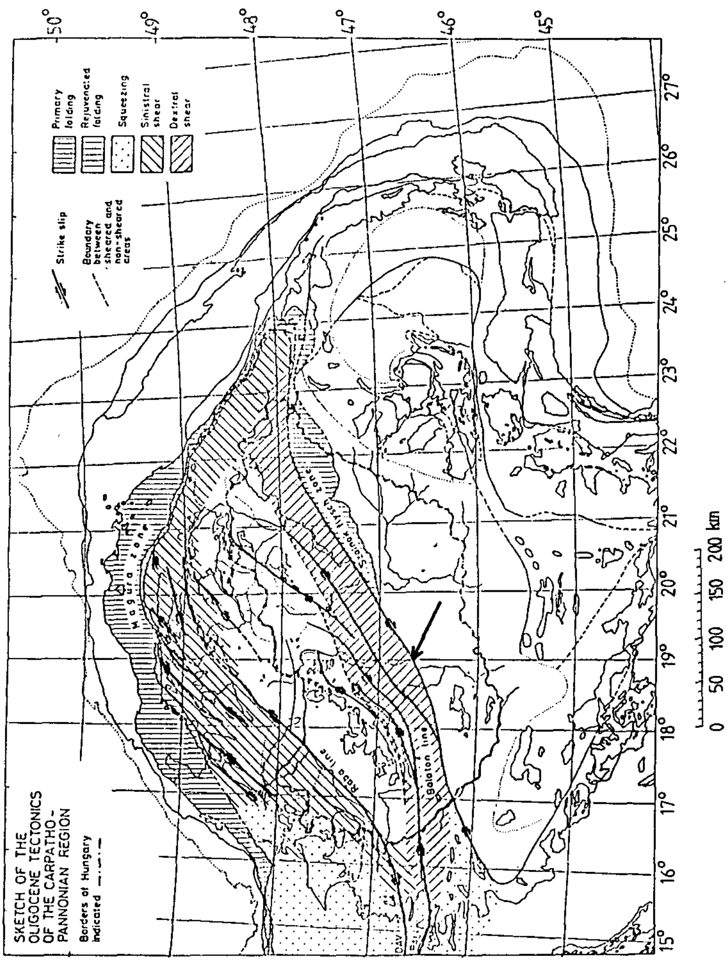

Figure 7. Sketch of the Oligocene tectonics of the Carpatho-Pannonian region from Balla (1988). The arrow in the middle of the map shows the measuring area.

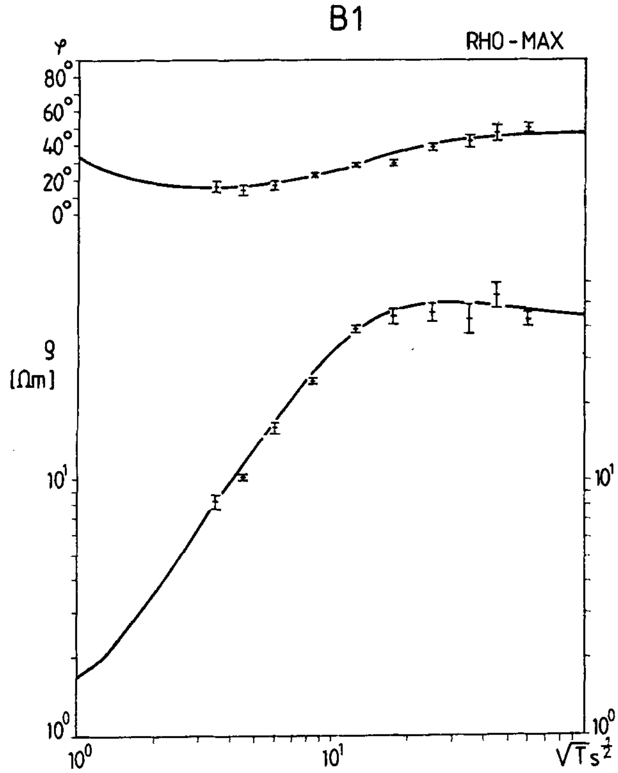

Figure 8. MT sounding curves (ρ: resistivity; φ: phase) at the base B_1. 1-D model: thickness: 0·7, 50 km; resistivity: 2, 100, 40 Ωm.

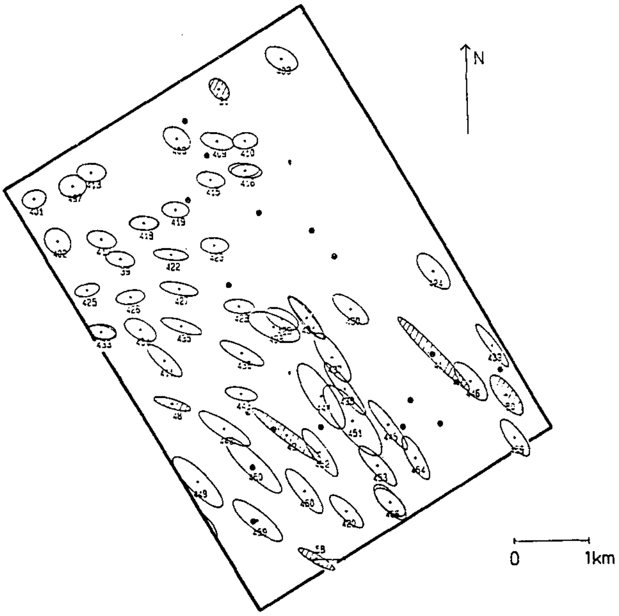

Figure 9. Relative telluric ellipses measured in the area near the Kapos line in the Pannonian basin (the hatched ones were measured initially).

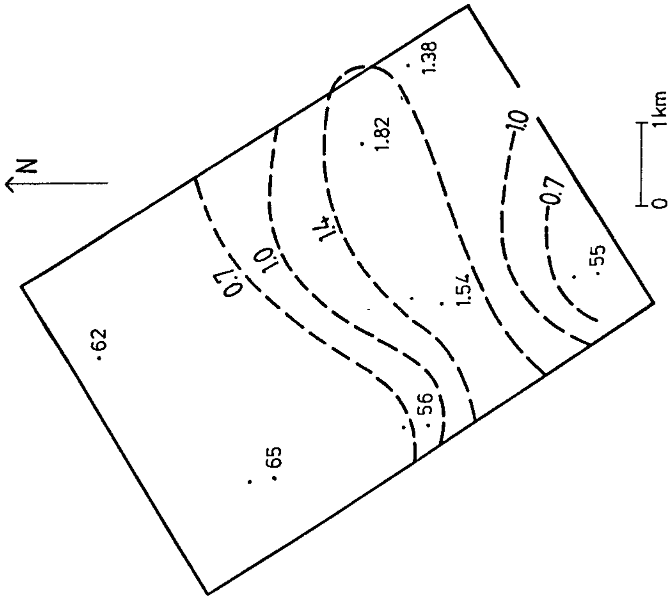

Figure 10. Isoarea map measured in the mentioned area in a network with distance of stations of 2 km.

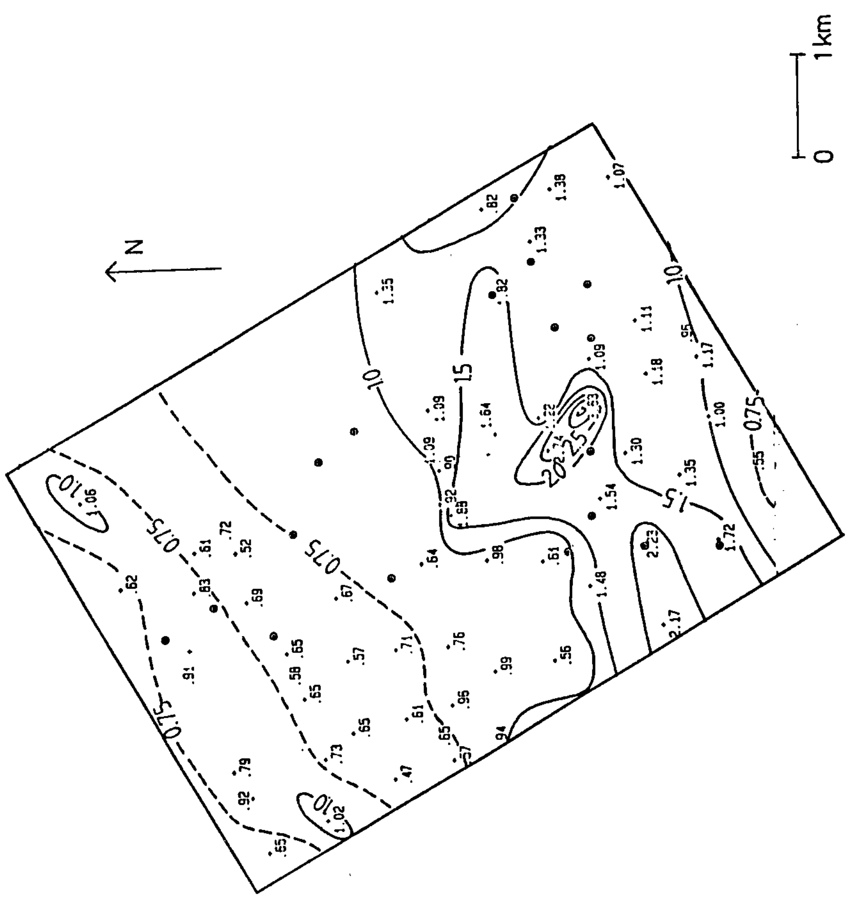

Figure 11. Same as in figure 10 but measured in a denser network with 500 m station distances.

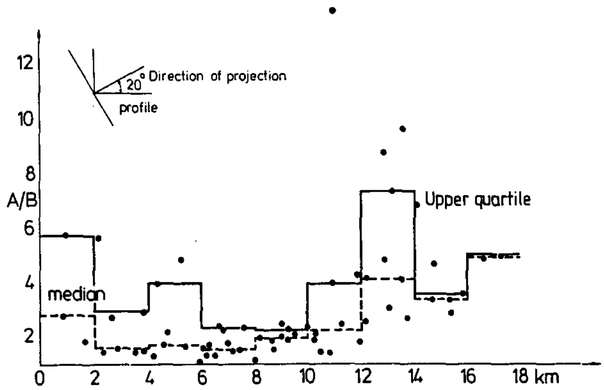

Figure 12. Ratio of the telluric ellipses projected to a given profile.

4. Conclusions

We have presented numerical models and case histories to show that the telluric method and magnetotelluric soundings using natural electromagnetic fields are capable of detecting basic tectonic elements as fractures and faults. These elements can only be explored under a sedimentary cover by geophysical methods. In order to locate sites for nuclear power plants which are free of active tectonic disturbances, less expensive electromagnetic methods should be more extensively used in the future.

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