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Magnetotelluric Sounding in the Transitional Zone Between the Eastern Alps and Pannonian Basin

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Abstract. Magnetotelluric sounding has detected a correspondence between some seismically active narrow fracture zones at the boundary of the Eastern Alps and an extreme conductivity increase at a depth of about 7 km. The shallow depth (30–40 km) of a conductivity anomaly detected in the deep crust may result from the increased heat flow in the transitional zone between the Pannonian Basin and the Alps. A close relation between the electric and seismic crustal models seems to exist at depths around 7 km.

Key words: Eastern Alps – Pannonian Basin – Magnetotelluric sounding – Electric conductivity anomaly – Tectonics

Introduction

In the years 1978 and 1979, 6 magnetotelluric deep soundings were carried out along the Sects. 04 and 05 of the Alpine Longitudinal Profile (Alpine Explosion Seismology Group 1976) (Fig. 1). These measurements were performed as a cooperative project between the Geodetic and Geophysical Research Institute of the Hungarian Academy of Sciences at Sopron and the Meteorological and Geophysical Institute of Vienna University.

From seismic experiments it is known that the relatively thin crust of the Pannonian Basin (25 km) becomes thicker towards the West, from the margin of the Eastern Alps, up to a thickness of about 50 km. Furthermore, according to other seismic measurements, the crust is not uniform, velocity inversions having been found at depths of 7–10 km and 20–30 km (Gutdeutsch and Arič, 1977). The eastern margin of the Eastern Alps consists of seismically active fracture zones.

Seismological information may be supplemented by information from geoelectric methods, as they reflect physical parameters other than the velocity of elastic waves. The most important factors which determine the electrical resistivity are the fluid content and the temperature of the rocks. The seismic velocity is less sensitive to these factors than the electrical resistivity. These considerations have led us to the idea of performing geoelectric measurements along the Alpine Longitudinal Profile.

Measurements

The distribution of electrical resistivity may be investigated by magnetotelluric deep sounding (Cagniard 1953). This method uses variations of the natural horizontal electromagnetic field for the determination of the electric impedance Z and the resistivity ρ as functions of the period T.

The equipment consisted of telluric and magnetic sensors and an analogue recording instrument. Chart speeds used were 2 cm/min for daytime and 0.6 cm/min for nighttime. The maximum scale value for electric potentials was 10 µV/mm. Magnetic variations were transformed into electric signals by Hungarian-made MTV-2 variometers with a maximum scale value of 0.01 nT/mm (Adám and Major 1967). The noise level in the measurement area was rather high. It was possible to more or less avoid regional noise caused by industry, mines, electric railways etc., but noise caused by local consumers, mainly by electrical installations on farms was unavoidable. As the low resistivity sedimentary cover is thin, local noise had high energy. In the evening hours the so-called "TV-noise" appeared (including also noise of other origin such as public lighting). Due to these types of noise the long period variations (substorms) could be used only from 11 p.m. local time till the early morning, while for shorter period variations (pulsations) the most advantageous time of the day was the early morning till about 7 a.m..

Data Processing

As a first step an appropriate number of recording intervals with low noise level and different frequency content were chosen at each measuring point. The length of the intervals was determined by the acceptable signal/noise ratio, being generally between 10 min and several hours. From each of these 300–1,000 digital values were obtained.

The digital data were processed on the HP2100 computer of the Geodetic and Geophysical Research Institute in Sopron, using the program described by Verö (1972). This program calculates the impedance elements by filtering in the time-domain. The level of acceptance for every sequence of 10 points is that the coherencies Coh(E_xH_y) and Coh(E_yH_x) should be greater than 0.9, with the exception of the station Lassnitz where the level had to be decreased to 0.6 because of the extremely low resistivity, i.e., low E-amplitudes. The output of the program consists of impedance polar diagrams, resistivities in different directions, directions of the extrema, ρ_{max} and ρ_{min}, and phase characteristics of the impedance.

Results

The results of the data processing are: Sounding curves ρ_{max} and ρ_{min} (Fig. 2), phase curves φ_{max} and φ_{min} in the directions of ρ_{max} and ρ_{min} (Fig. 3), and polar diagrams of the main and secondary impedances.

The sounding curves and the phase curves are drawn as

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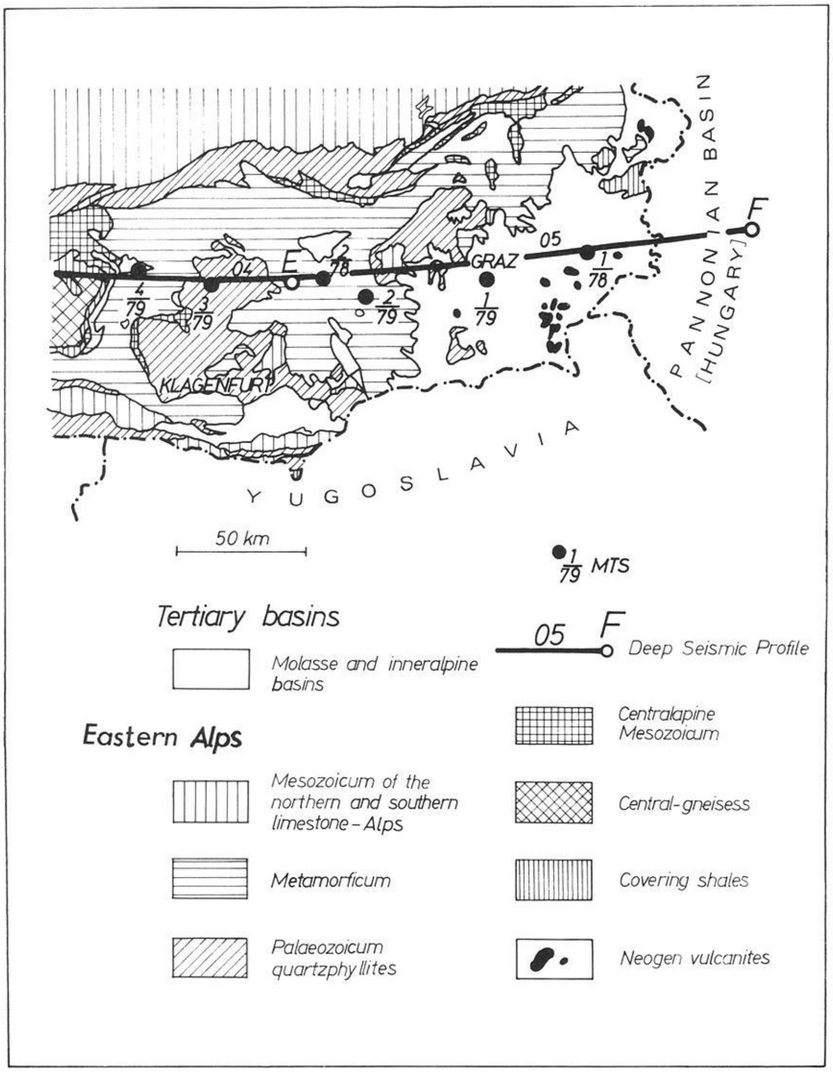


Fig. 1. Geologic map of Southeastern Austria (after P. Beck-Manyetta, Geologische Bundesanstalt, 1964) with magnetotelluric sounding points (*black dots*) and the Alpine Seismic Crustal Profile

near as possible to the median values of the corresponding quantities in period ranges containing a sufficient number of data; error bars denote mean square errors of the medians determined from the scatter of the individual values.

The sounding curves were approximated by 1D models, separately for ρ_{max} and ρ_{min} curves. Depth and resistivity values result from these calculations, errors of the depths are deduced from families of theoretical curves. A complete agreement between observed and theoretical curves (model) was not always reached, e.g., sharp peaks and valleys at the station Oberpreitenegg could not be approximated. These 1D models may only be regarded as first approximations. Following the tectonic model and the theory of field distortion (for details see next section), we aimed at a close fit of the decreasing parts of the E-polarization curves. In Fig. 2 the dashed curves represent the best approximations of the ρ_{min} curves. From the parameters of these models, the depths to the top of conductive zones are given in Table 1. The phase curves computed on the basis of the models differ from the observed ones in the majority of cases (see the dashed curves in Fig. 3 and also Berktold et al. (1976); Berdichevsky and Dmitriev (1976) also do not use phase curves in the description of 2D distortions). The digitization method could be responsible for a minor part of the deviations. These errors, however, will be at least partly randomized because of the rather high number of sections used.

Table 1. Depths of conductive zones (1D-models) derived from ρ_{min} – curves in the period range of the measurements

Station	Depth (km)	
Rehgraben (1/78)	26 ±6	162±15
Breitenbuch (1/79)	9 ±1	37± 2.5
Oberpreitenegg (2/79)	7.5±0.6	35± 3.5
St. Georgen (2/78)	32 ±8	
Lassnitz (3/79)	5.5±1.2	
Lasaberg (4/79)	8.5±1	

Interpretation of Data

Distortion Effects

Since the curves ρ_{min} and ρ_{max} as well as the models determined on the basis of these curves differ from each other, the problem is to decide which sounding curve is less influenced by near-surface distortion of the electric field. In the measuring area field distortions could be caused by:

(a) the mountain frame (edge effect);
(b) fracture tectonics;
(c) the varying thickness of surface sediments (S-effect);
(d) a combination of these effects.

In the following these possibilities will be investigated.

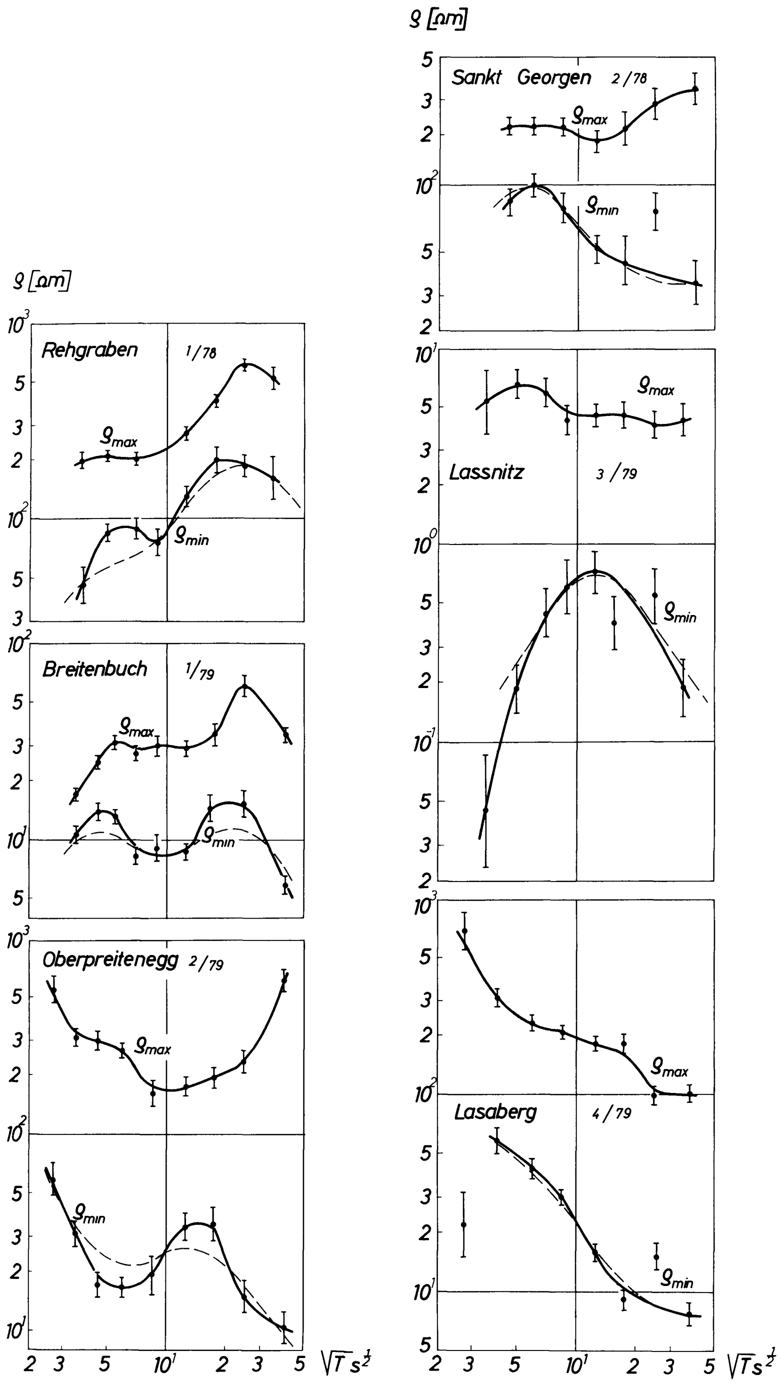


Fig. 2a, b. ρ_{min} and ρ_{max} sounding curves measured at the stations shown in Fig. 1

(a) Near to elongated high mountains bordering deep sedimentary basins with a sharp transition between, in the H-polarization case, the sounding curves obtained in the basin are distorted into ρ_{min} curves (i.e., the ρ_{min} direction is perpendicular to the boundary of the basin) and indicate apparent conductive layers (e.g., on the Kara-Kum platform in the vicinity of the Kopet Dagh mountains). This is the "edge effect" (Berdichevsky and Dmitriev 1976).

In our area an edge effect could be suspected first of all in the Graz Basin (Fig. 4). At point 1/78 the direction of Z_{xymin} (and of ρ_{min}) is, however, nearly parallel to the nearest part of the basin edge. So the edge effect can be excluded here.

West of Graz in the vicinity of point 1/79 the basin edge turns by nearly 90°. Accordingly, in this area there are two directions of the basin edge, therefore the directions of ρ_{max} and ρ_{min} cannot be predicted on the basis of an edge effect. The other four measuring points lie in mountainous areas with thin sedimentary cover where the preconditions for the appearance of the edge effect are not valid.

(b) In Fig. 4 a correlation between fracture tectonics and the directions of Z_{xymax} may be inferred. The Z_{xymax} axes are perpendicular to well-known tectonic lines such as the Lavanttalzone at point 2/79 and the Metnitz-Strassburg-St. Veit fracture zone, which is seismically active (Drimmel 1979), at point 3/79. At the site Lassnitz the resistivity values are extremely small, 0.03–5 Ωm for 20 s pulsations. A similar correlation may be

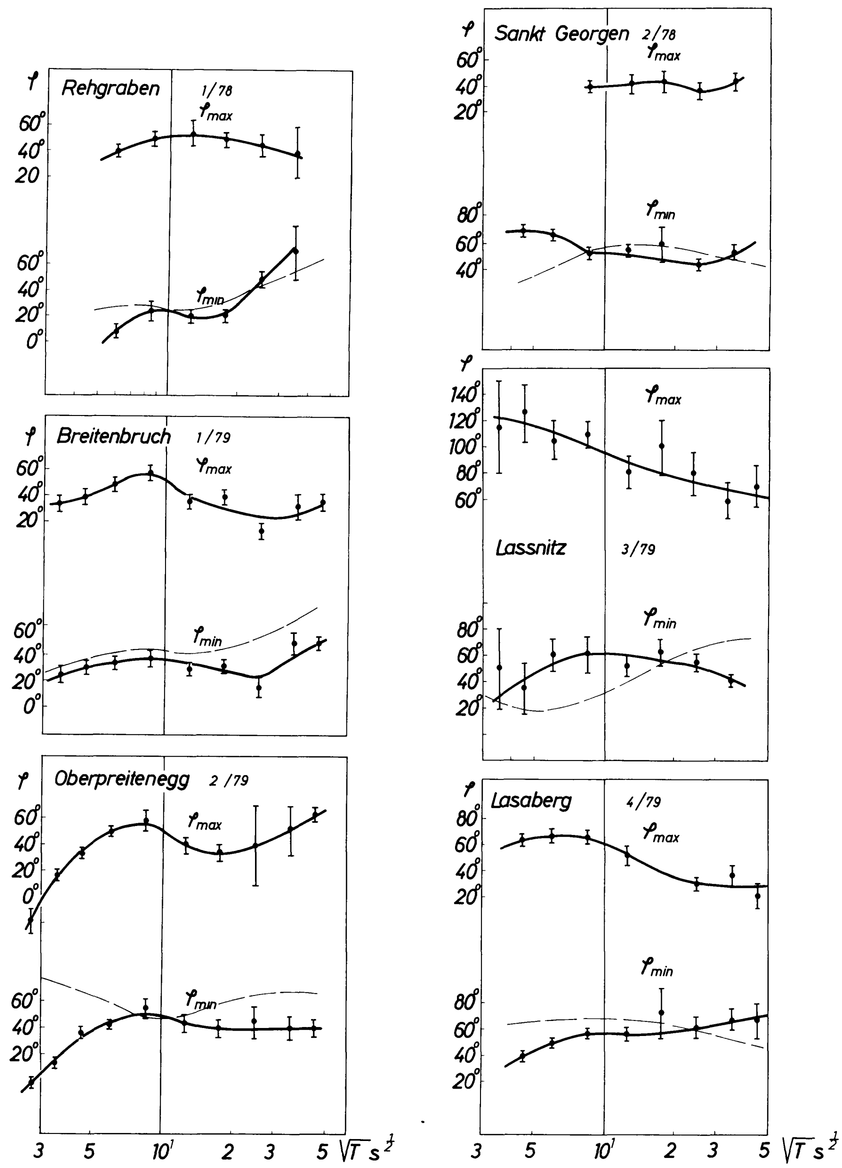


Fig. 3a, b. φ_{min} and φ_{max} phase curves measured at the stations shown in Fig. 1

inferred from the direction Z_{xymax} with the "Raab-Störung" in the Graz Basin (point 1/78) as well as some NNW-directed faults in the vicinity of point 1/79, the latter being nearly parallel to the Metnitz- and Lavanttal-fractures. In this area the heat flow reaches values as high as 100 mWm^{-2} possibly due to convective heat conduction through the fracture zones (see heat flow map by Čermák and Hurtig (1979)). The situation is similar to the geothermal conditions in the Pannonian Basin. The above-mentioned fracture zones may be considered as 2D structures.

A correlation between narrow fracture zones and magnetotelluric Z_{xymax} directions has already been observed in the Pannonian Basin (Ádám 1969; Stegena et al. 1971) and especially in its western part, i.e., in the area of the Transdanubian conductivity anomaly (Ádám 1976a, b, 1977) where more than 50 magnetotelluric soundings have been carried out. Figure 5 shows the tectonic structures and the directions of Z_{xymax} around Lake Balaton. There the directions are also perpendicular to the nearest fractures, and the Z_{xymax} axes are nowhere directed parallel to the strike direction of the fractures which are narrow in this area, whereas in the case of broad fracture zones such a parallelism is observed, as in the case of the 40 km broad Rhine-Graben covered by thick sediments (Haak 1970; Reitmayer 1971).

2D model-calculations for the Transdanubian anomaly (Tátrallyay 1977) proved that in the case of a narrow ($\leq$10 km) two-dimensional conductive body embedded into a highly resistant medium, the direction of Z_{xymax} is not directed parallel to the direction of strike above the body. Consequently both outside and above the body the curve ρ_{min} corresponds to the case of E-polarization which best approximates the 1D layered model above the centre of the structure. Moving away from the centre, the depth to of the top of the conducting body deduced from the ρ_{min} curves increases and so differs from the real one. Therefore it is called "apparent depth" (see one of Tátrallyay's models in Fig. 6).

(c) If the "narrow fracture" model (Tátrallyay 1977) is covered by sediments of varying thickness, a galvanic distortion appears. This is the so-called S-effect. For its detailed description see Berdichevsky and Dmitriev (1976). A consequence of this effect is that the descending branch of the ρ_a curves in the case of H-polarization is shifted along the ρ axis. The extrema of the curves are found at the correct periods but at different appar-

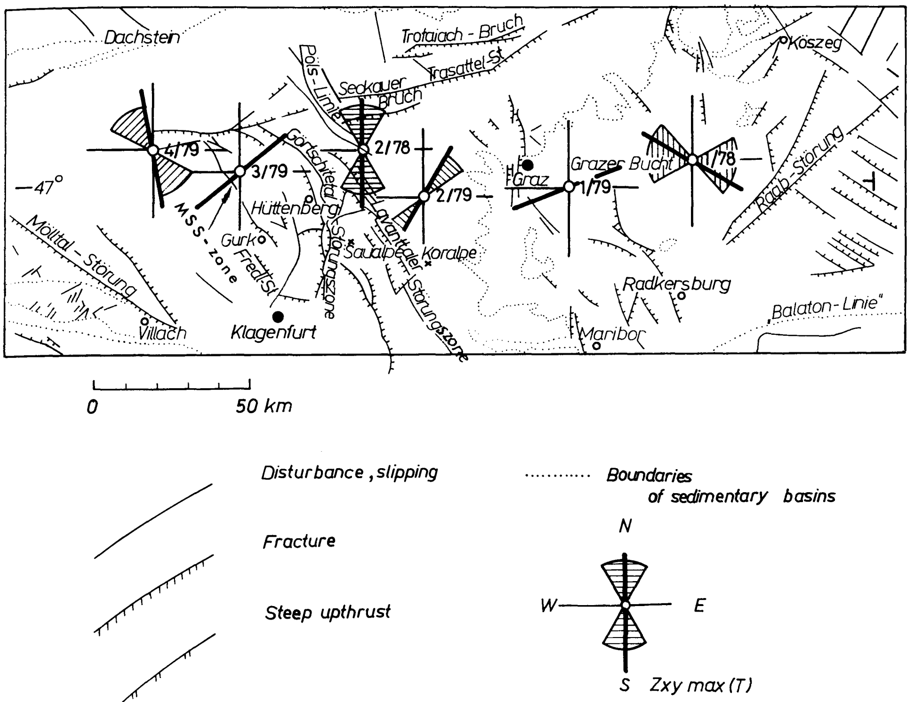


Fig. 4. Tectonic map of the southeastern part of Austria (after Tollmann 1970) with the major axes of the Z_{xy} polar diagrams, Z_{xymax} and the angular range of their variations with the period T (MSS-zone: Metnitz-Strassburg-St. Veit zone)

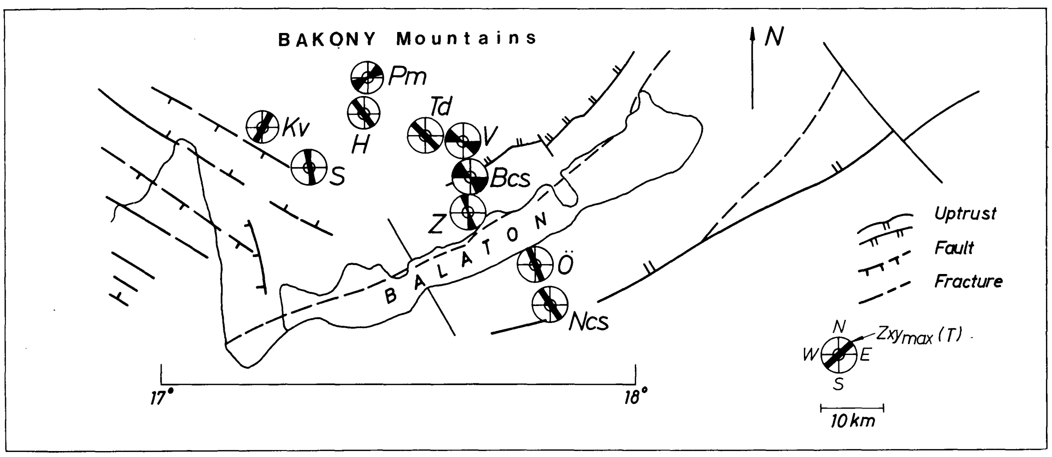


Fig. 5. Tectonic map of Transdanubia around Lake Balaton with the major axes of the Z_{xy} polar diagrams, Z_{xymax} and the angular range of their variations with the period T

ent resistivity levels. The parameters of the conductive layer calculated from the H-polarized ρ_a curves are in close correlation with the horizontal conductivity $S_1 = h_1/\rho_1$ of the sediment while the data (depth, horizontal conductivity) of the conductor derived from E-polarized ρ_a curves do not depend on S_1 values and surface geo-electric conditions. Accordingly, more reliable information about the depth of the conductive formation can be inferred from the E-polarized ρ_a curves.

On the basis of the above criterion the equivalence of the E-polarization and ρ_{min} curves has been supported statistically for the Transdanubian MT-data (Ádám 1980) assuming that the sedimentary basin is preformed by the same fractures which contain the conductor. Some relevant results are summarized in Fig. 7a–c.

Figure 7a shows a plot of the apparent depths h of the conductive body from the curves ρ_{min} and ρ_{max} (1D models) against the horizontal conductivity $S_1 = h_1/\rho_1$ of the uppermost layer. Depth values $h_{\rho_{min}}$ calculated from the ρ_{min} curves depend considerably less on S_1 than depth values $h_{\rho_{max}}$ determined from ρ_{max} curves. This is a good criterion for the E-polarization. The scatter of the depths $h_{\rho_{min}}$ is also considerably smaller than scatter of $h_{\rho_{max}}$.

Figure 7b shows the occurence frequencies of depth values calculated for the same period range from ρ_{min} and ρ_{max}. The distribution of $h_{\rho_{max}}$ has several smaller maxima in correspondence with surface geological conditions (thin sediments, Triassic or Permian rocks). This agrees with the conclusions drawn from Fig. 7a. The $h_{\rho_{min}}$ values have two separate maxima at depths of about 7 km and 13 km, in accordance with the anomalous zones in the northern and southern Bakony Mountains.

Figure 7c shows the dependence of horizontal conductivity S of the conductive body on the depth of its top. S values

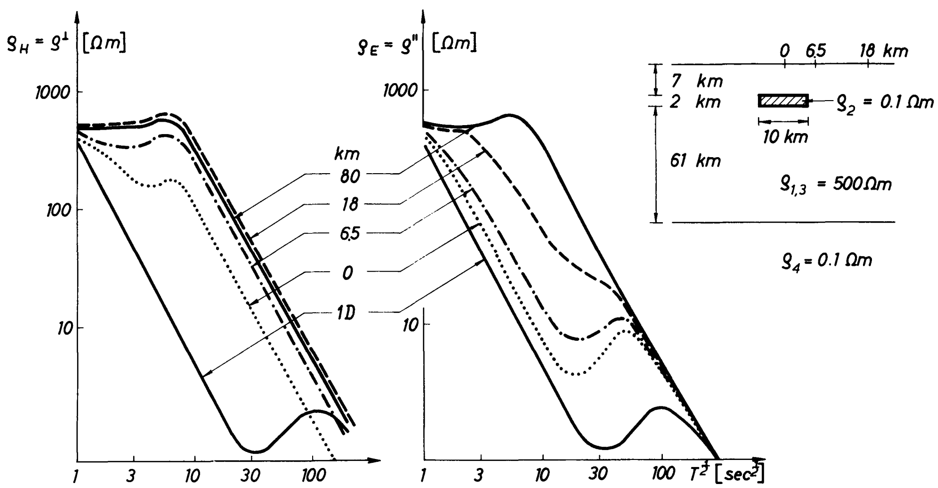
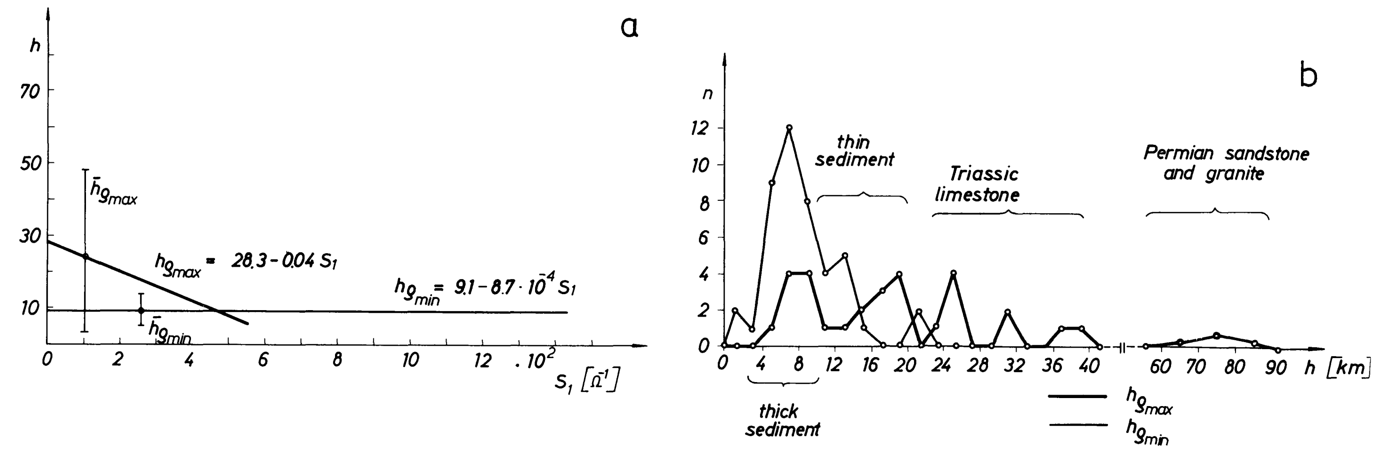


Fig. 6. Synthetic-magnetotelluric sounding curves over a model representing a narrow fracture zone with a conducting body at a depth of 7 km. 6.5, 18, 80 km are the distances of the "measuring point" from point 0. The 1D model shown for comparison has the same conductor depth and thickness (after Tátrallyay 1977)



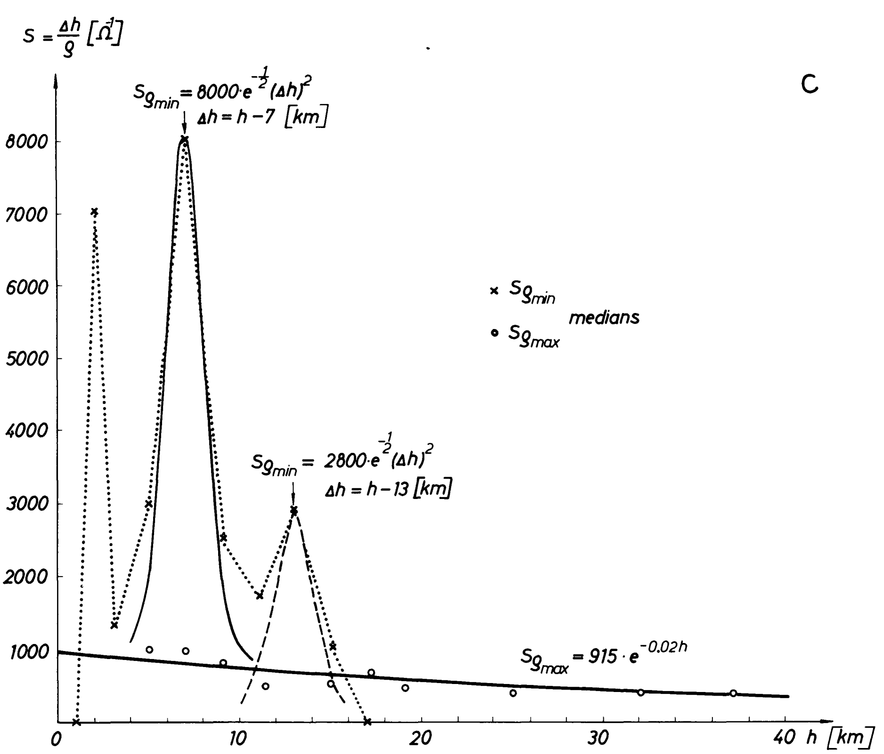


Fig. 7 a–c. Statistical relationships between the geoelectric parameters of the Transdanubian conductivity anomaly (after (Ádám 1980): **a** The depths of the conducting body calculated from ρ_{min} curves ($h_{\rho_{min}}$ and ρ_{max} curves ($h_{\rho_{max}}$) vs the horizontal conductivity of the uppermost layer, $S_1 = h_1/\rho_1$. **b** Occurrence frequencies of $h_{\rho_{min}}$ and $h_{\rho_{max}}$ values. For the peaks of $h_{\rho_{max}}$ the surface geologic formations are also given. **c** Horizontal conductivity S of the conducting layer vs depth of its top calculated on the basis of ρ_{min} curves ($S_{\rho_{min}}$) and ρ_{max} curves ($S_{\rho_{max}}$)

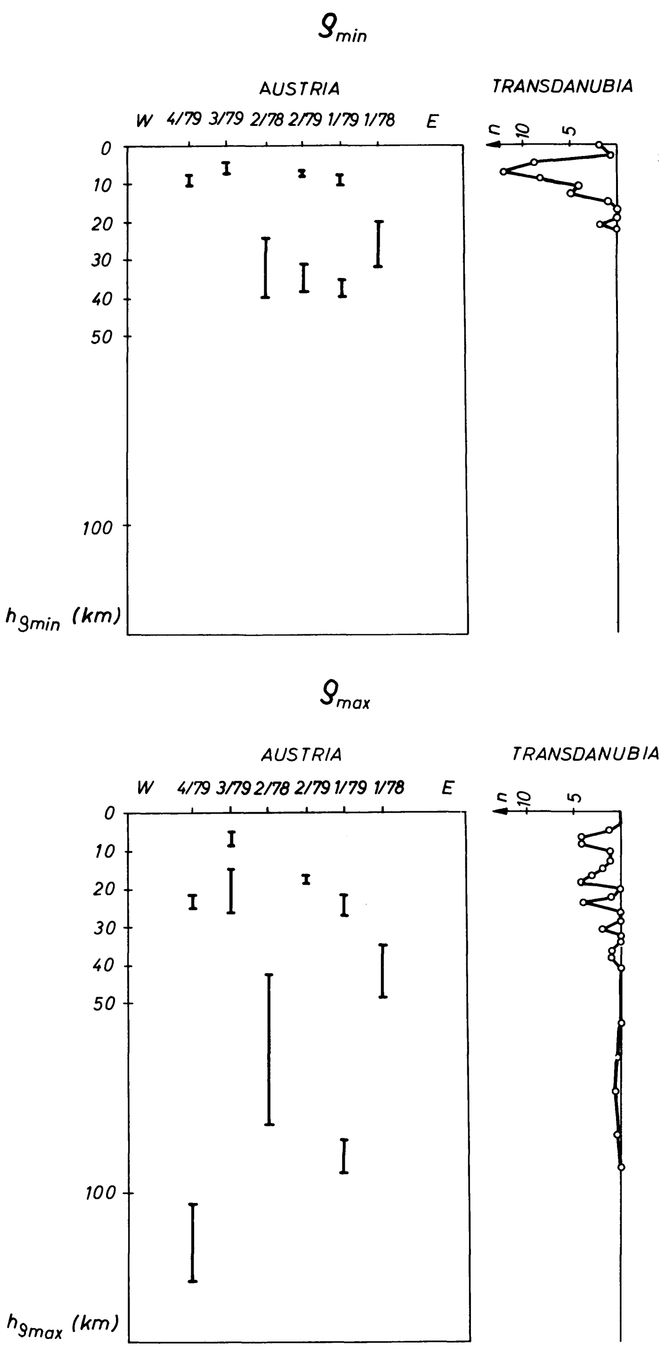


Fig. 8a, b. Depths of conducting bodies in the Styrian Alps with their error limits calculated on the basis of ρ_{min} and ρ_{max} curves. For comparison, the occurrence frequencies of $h_{\rho_{min}}$ and $h_{\rho_{max}}$ are also shown for Transdanubia

were determined by 1D model fitting. The values of $S_{\rho_{max}}$ decrease continuously (nearly exponentially) with the depth, while the distribution of the values $S_{\rho_{min}}$ has two peaks at depths of 7 km or 13 km corresponding to the real conducting zones of Fig. 7b. The peaks can be approximated by two functions of the form $S_0 e^{-\frac{1}{2}(\Delta h)^2}$. If the depth values do not coincide with the position of the peaks at 7 km and 13 km, the point is not above the centre of the anomalous body but above its flank according to Fig. 6. In summary we find again that ρ_{min} curves bear the real information about the conductive bodies in the fracture zones.

Interpretation

As the correlation between the fracture tectonics and the direction of Z_{xymax} is similar in the two regions compared above – Transdanubia and Eastern Alps – primary attention should be paid to the curves ρ_{min}. Although only six paris of sounding curves were measured in Austria, the distribution of the depths of the conductive bodies is very similar to those found in the region of the Transdanubian anomaly (Fig. 8). Depth values calculated from ρ_{max} show considerably greater scatter than those calculated from ρ_{min}, especially in the second depth range below 30 km. The shift of $h_{\rho_{max}}$ towards greater depths corresponds to the *S*-effect.

According to the ρ_{min} curves the first depth range lies at 6–9 km. This agrees with the occurrence frequency peak of $h_{\rho_{min}}$ values in the region of the Transdanubian anomaly (Fig. 8). The curves ρ_{min} indicate a second conductive anomaly at depths of 30–40 km (Table 1).

Conclusions

The two regions, Transdanubia and the Eastern Alps, have several similar geophysical and tectonic features. The fractures in Transdanubia which divide the Hungarian Central Mountains into different parts are nearly parallel to the north-northwest directed fractures of Lavanttal and Metnitz. The fractures in Transdanubia are seismically active. In these zones the conductive formations are shallower, e.g., at a depth of 2–3 km at Bakonybél (Ádám 1976b). The heat flow in both regions is much greater than on the average. The earth's crust becomes thicker at the margin of the Eastern Alps – supposedly along the fractures – and also under the Bakony Mountains, i.e., under the central part of the Transdanubian conductivity anomaly. The earth's crust under the Bakony Mountains is thinner than 30 km whereas it amounts to 50 km in the Eastern Alps, the region of the present measurements. This may be why, in the Graz Basin and west of it (Lavanttal), an additional conductive zone exists in the earth's crust at 30–40 km depth as a result of the great heat flow, whereas in the Pannonian Basin the second conductive zone is indicated in the upper mantle at depths greater than 40 km (Ádám 1978).

On the basis of laboratory investigations, Duba et al. (1978) and Duba (personal communication 1980) confirmed the present interpretation of the Transdanubian anomaly: "The σ-anomaly is most likely caused by a geothermal fluid in the fractured region". This may also be valid for the conductive zones at about 7 km depth in the Eastern Alps.

Deep seismic investigations have found a low velocity zone in the same depth range (7–10 km), but only in the fracture areas. The deeper low-velocity zone appears between 20 km and 30 km (Gutdeutsch and Arič 1977). Accordingly, a close relation between the electric and seismic crustal models seems to exist only in the first depth range.

The present study is a first attempt to determine the conductivity structure of the transition zone between the Eastern Alps and the Pannonian Basin. It shows that a rough estimate of the depth of highly conductive layers can already be made. More detailed results may be reached in the future by additional MT soundings along the present profile and on profiles perpendicular to it.

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References

Alpine Explosion Seismology Group: A lithospheric seismic profile along the axis of the Alps, 1975. I: First Results. Pure Appl Geophys **114**, 1109–1130, 1976

Ádám, A., Major, L.: Stabilized high-sensitivity immersion magnetic variometer for magnetotelluric investigations (Type MTV-2). Acta Geod. Geophys. Mont. Hung. **2**, 211–215, 1967

Ádám, A.: Appearance of the electrical inhomogeneity and anisotropy in the results of complex electrical exploration of the Carpathian Basin. Acta Geod. Geophys. Mont. Hung. **4**, 187–197, 1969

Ádám, A.: Results of deep electromagnetic investigation in the Pannonian Basin. In: Geoelectric and Geothermal Studies, A. Ádám, ed.: pp 547–561. Budapest: Akadémiai Kiadó 1976a

Ádám, A.: Distribution of the electrical conductivity in seismic (deep) fractures in Transdanubia. Acta Geod. Geophys. Mont. Hung. **11**, 277–285, 1976b

Ádám, A.: The Transdanubian crustal conductivity anomaly. In: Special Issue based on the 3rd Workshop on Electromagnetic Induction in the Earth, held in Sopron, July 1976 (Contributed papers), A. Ádám, U. Schmucker, eds.: Acta Geod. Geophys. Mont. Hung. **12**, 73–79, 1977

Ádám, A.: Geothermal effects in the formation of electrically conducting zones and temperature distribution in the Earth. Phys. Earth Planet. Int **17**, 21–28, 1978

Ádám, A.: Statistische Zusammenhänge zwischen elektrischer Leitfähigkeitsverteilung und Bruchtektonik in Transdanubien (Westungarn). Acta Geod. Geophys. Mont. Hung. **15**, 1980

Berdichevsky, M.N., Dmitriev, V.I.: Distortion of magnetic and electric fields by near-surface lateral inhomogeneities. Acta Geod. Geophys. Mont. Hung **11**, 447–483, 1976

Berktold A., Beblo, M., Kemmerle, K.: On the distribution of the electrical conductivity below the Eastern Alps. Geol. Rundsch. **65**, 715–732, 1976

Cagniard, L.: Basic theory of the magnetotelluric method of geophysical prospecting. Geophysics **18**, 605–635, 1953

Čermák, V., Hurting, E.: Heat Flow Map of Europe. Enclosure for Terrestrial Heat Flow in Europe. V. Čermák, L. Rybach eds. Berlin, Heidelberg: Springer-Verlag 1979

Drimmel, J.: On the assessment of maximum earthquakes in the Alps and adjacent areas. Tectonophysics **55**, 1–5, 1979

Duba, A., Piwinskii, A.J., Santor, M., Weed, H.C.: The electrical conductivity of sandstone, limestone and granite. Geophys. J. R. Astron. Soc. **53**, 583–597, 1978

Gutdeutsch, R., Arič, K.: Eine Diskussion geophysikalischer Modelle des Grenzbereiches zwischen Ostalpen und Pannonischem Becken. Acta Geologica Hung. **XXI, 4**, 287–296, 1977

Haak, V.: Das zeitlich sich ändernde, erdelektrische Feld, beobachtet auf einem Profil über den Rheingraben: eine hiervon abgeleitete Methode der Auswertung mit dem Ziel die elektrische Leitfähigkeit im Untergrund zu bestimmen. Dissertation, 140 pp. 1970

Reitmayr, G.: Räumliche Verteilung und Periodenabhängigkeit der Vorzugsrichtung des erdelektrischen Feldes und erste Ergebnisse der Auswertung von magnetotellurischen Messungen auf einem Profil über den Rheingraben. Protokoll über das Kolloquium „Erdmagnetische Tiefensondierung“ in Rothenberge/Westf. vom 14–16. September 1971 P. Weidelt, ed.: pp. 155–177, 1971

Stegena, L., Horváth, F., Ádám, A.: Spreading Tectonics Investigated by Magnetotelluric Anisotropy. Nature **231**, 442–443, 1971

Tátrallyay, M.: On the interpretation of EM sounding curves by numerical modelling using the S.O.R. method. In: Special Issue based on the 3rd Workshop on Electromagnetic Induction in the Earth, held in Sopron, July, 1976. (Contributed papers) A. Adam, v. Schmucker, eds. Acta Geod. Geophys. Mont. Hung. **12**, 279–285, 1977

Tollmann, A.: Die bruchtektonische Zyklenordnung im Orogen am Beispiel der Ostalpen. Geotekt. Forsch. **34**, I–II, 1–90, 1970

Verö, J.: On the determination of magnetotelluric impedance tensor. Acta Geod. Geophys. Mont. Hung. **7**, 333–351, 1972

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