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Periadriatic lineament in the Alps studied by magnetotellurics

A. Ádám[1], G. Duma[2], R. Gutdeutsch[3], J. Verő[1], and Á. Wallner[1]

[1] Geodetical and Geophysical Research Institute of the Hungarian Academy of Sciences, Pf. 5, H-9401 Sopron, Hungary
[2] Zentralanstalt für Meteorologie und Geodynamik, Hohe Warte 38, A-1190 Wien, Austria
[3] Universität Wien, Institut für Meteorologie und Geophysik, Währingerstr. 17, A-1090 Wien, Austria

Abstract. The "Periadriatic lineament" (or "Insubric lineament"), as a main tectonic zone, separates the unmetamorphosed southern Alps from the metamorphosed western and eastern Alps. One of its continuations to the east is the Balaton-line. In three parts of it – along the Gail Valley, the Karawanken and Balaton lines – deep magnetotelluric soundings have detected a conducting crustal formation with depths varying between 7 and 17 km. This conducting crustal formation is probably narrow and correlated with the three lineaments. The reason for the increased conductivity in the middle crust may be a deep fracture zone, where cracks and pores are saturated by electrolytes. The basic model of the interpretation and the EM distortions are discussed.

Key words: Magnetotellurics – Periadriatic lineament – MT distortions – Gail Valley – Karawanken – Tectonic effects

Introduction

Within the framework of the topic "Geophysical investigations in the transition between Alps and Pannonicum", joint Austro-Hungarian magnetotelluric (MT) measurements were continued in 1981 and 1983 in two sections of the Periadriatic lineament, along the Gail Valley and the Karawanken, in order to investigate the deep geoelectric structure of this primary tectonic zone.

The Periadriatic lineament

The Periadriatic lineament belongs to the tectonic line system between Lanzo in the western part of the Po-Plane and Pohorje in Yugoslavia. Earlier it was tentatively identified with the Insubric line that divides the western and eastern Alps exposed to Alpine metamorphism from the unmetamorphosed southern Alps. Recent investigations (Ahrendt, 1980) revealed, however, that the Insubric line forks from the Periadriatic lineament near the Tauern window and its continuation lies in the Defferegen-Auterselve-Valles (DAV) line and not in the Pusteria-Gail Valley line. Towards the east the Insubriatic line continues, according to Kovács (1983), in the Rába-line that divides the Penninian, the Lower and Upper eastern Alpine units, from the Transdanubian Central Mountains verging southward The Periadriatic lineament taken in a stricter sense continues in the Balaton line. It is probable that the 3- to 5-km-broad tectonic zone of the Karawanken lineament becomes broader toward the ENE (Fig. 1). Kovács supposes that the 800-km-long chain of Periadriatic magmatites is continued in Hungary in the narrow, elongated, late-Variscan Balaton-Velence granitic zone as well as in the Palaeogene andesites of Hahót-Pusztaszentlászló, Velence and Recsk and thus he speaks about a Gail Valley-Balaton lineament.

Simply the age of the mentioned late-Variscan granite intrusions indicates that the Periadriatic lineament or its precursor had already been active at that time and was rejuvenated during the Alpine tectonogenesis.

Basis of geophysical investigations

The considerable horizontal and vertical movements along the Periadriatic lineament – their scale is being discussed – produced large dragged structures. These have also caused a change of the physical parameters, hence the tectonic zone can be traced by geophysical methods and from their results conclusions can be drawn about the deep structures and the physical processes in the zone.

This assumption has been confirmed by a 70-km-long and about 10-km-broad conductivity anomaly indicated by MT soundings along the Balaton-line at a depth of 7–9 km [see Fig. 2, after Varga (1980)].

Measurement sites and equipment

The magnetotelluric and telluric measuring points along the Gail Valley and the Karawanken lineament are shown in small topographic maps (Fig. 1 b and c) and in Tollmann's tectonic map (Fig. 3). Three MT soundings were carried out near the Karawanken lineament (Ebriach, Blasnitzen and Zell Pfarre) and a reference point was measured at Klein St. Paul, about 40 km to the north of it. Two MT soundings (Schlanitzen and Sittmoos) were measured, each together with a telluric satellite point (Schimanberg and Plöckenhaus), in the Gail Valley. The reference point here was Weissensee, about 10 km to the north of the Gail Valley but south of the DAV line.

In the Karawanken the MTS sites Ebriach and Zell Pfarre lie over limestone plateaus covered by only a few metres of loose sediments. In the close environment of Blas-

Offprint requests to: A. Ádám

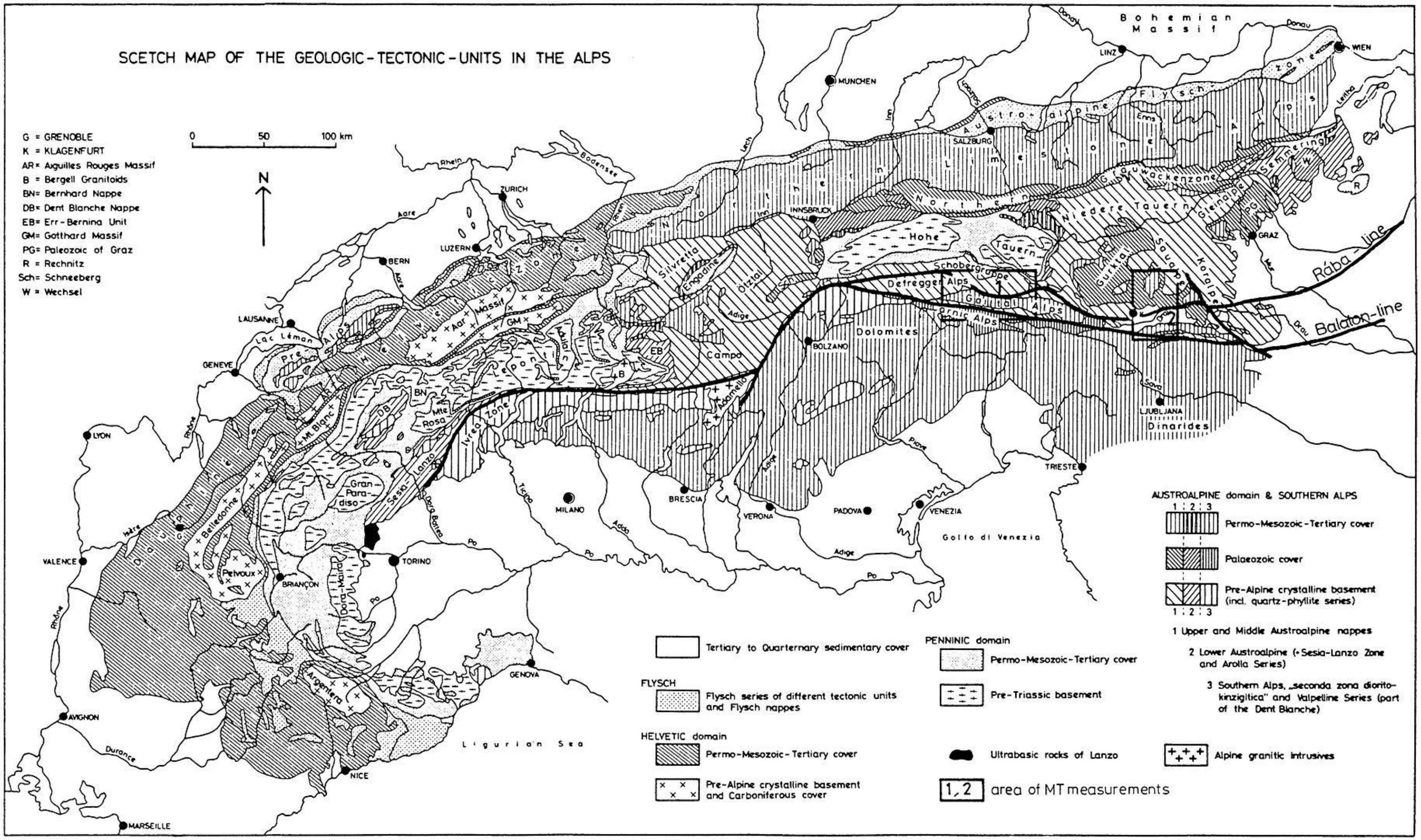
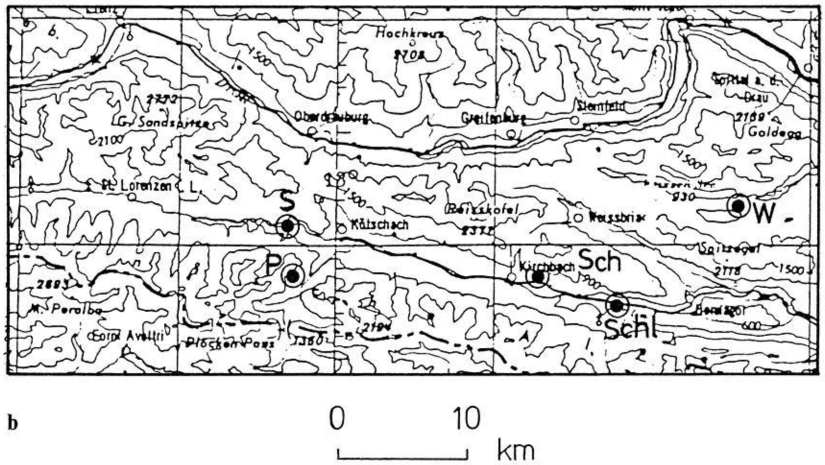
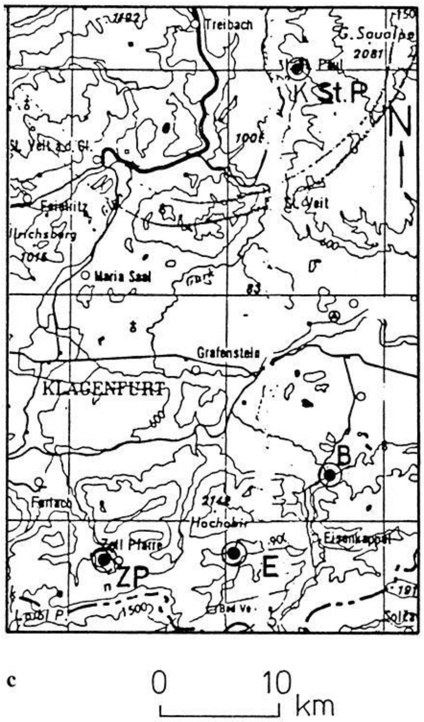

SCETCH MAP OF THE GEOLOGIC-TECTONIC-UNITS IN THE ALPS
G = GRENOBLE
K = KLAGENFURT
AR = Auguilles Rouges Massif
B = Bergell Granitoids
BN = Bernhard Nappe
DB = Dent Blanche Nappe
EB = Err-Bernina Unit
GM = Gotthard Massif
PG = Paleozoic of Graz
R = Rechnitz
Sch = Schneeberg
W = Wechsel
0 50 100 km
N
Bohemian Massif
WIEN
LINZ
MUNCHEN
SALZBURG
INNSBRUCK
ZURICH
LUZERN
BERN
LAUSANNE
GENEVE
LYON
VALENCE
AVIGNON
MARSEILLE
NICE
GENOVA
TORINO
BRIANÇON
MILANO
BRESCIA
VERONA
PADOVA
VENEZIA
TRIESTE
BOLZANO
LJUBLJANA
GRAZ
Golfo di Venezia
Ligurian Sea
Rába-line
Balaton-line
Dolomites
Dinarides
Hohe Tauern
Schobergruppe
Defregger Alps
Gailtal Alps
Carnic Alps
Niedere Tauern
Grauwackenzone
Semmering
Gleinalpe
Koralpe
Saualpe
Gurktal
Ötztal
Silvretta
Engadine
Campo
Adamello
Ivrea Zone
Sesia-Lanzo
Mte Rosa
Gran Paradiso
Dora-Maira
Pelvoux
Belledonne
Argentera
Mt. Blanc
Aar Massif
Adula
Lac Léman
Bodensee
AUSTROALPINE domain & SOUTHERN ALPS
1 : 2 : 3
Permo-Mesozoic-Tertiary cover
Palaeozoic cover
Pre-Alpine crystalline basement (incl. quartz-phyllite series)
1 Upper and Middle Austroalpine nappes
2 Lower Austroalpine (+Sesia-Lanzo Zone and Arolla Series)
3 Southern Alps, „seconda zona diorito-kinzigitica" and Valpelline Series (part of the Dent Blanche)
Tertiary to Quarternary sedimentary cover
FLYSCH
Flysch series of different tectonic units and Flysch nappes
HELVETIC domain
Permo-Mesozoic-Tertiary cover
Pre-Alpine crystalline basement and Carboniferous cover
PENNINIC domain
Permo-Mesozoic-Tertiary cover
Pre-Triassic basement
Ultrabasic rocks of Lanzo
Alpine granitic intrusives
1,2 area of MT measurements

Fig. 1a



b



c

Fig. 1. a Geological and tectonic map of the Alps according to Frey et al. (1974). *Thick lines* indicate main tectonic lines (Periadriatic, Insubric, Balaton and Rába-lines). Measuring areas are also given. *1* Gail Valley, *2* Karawanken. **b** Measuring sites ⊙ in the Gail Valley. *P* Plöckenhaus, *S* Sittmoos, *Schl* Schlanitzen, *Sch* Schimanberg, *W* Weissensee. **c** Measuring sites ⊙ in the Karawanken. *ZP* Zell Pfarre, *E* Ebriach, *B* Blasnitzen, *K.St.P* Klein Sankt Paul

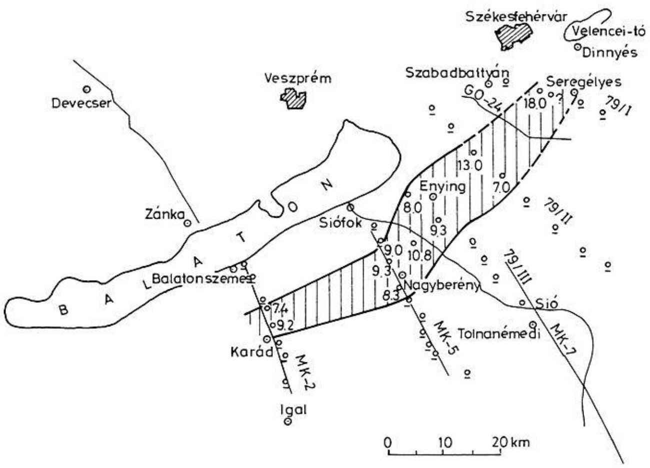


Fig. 2. Depth values of the conductivity anomaly measured along the Balaton line according to Varga (1980)

nitzen no outcrops are visible but limestone rubble lies on the ground.

In the Gail Valley the measuring sites Schlanitzen and Schimanberg lie on slopes at a height of about 150 m above the bottom of the Gail Valley. The thickness of the loose sediments does not exceed some tens of metres at these points. The station Sittmoos is on a terrace at about 200 m above the bottom of the Lesach Valley. In a side valley less than 1 km away from Sittmoos, the limestone is in tectonic contact with the typical schists of the Periadriatic lineament. The station Plöckenhaus is on the bare rocks. Weissensee is at the bottom of a small valley with very few loose sediment.

The MT instrument consisted of telluric and magnetic sensors and a 4-channel analogue recorder. The speed of the record (photo-paper) was 20 mm/min in daytime and 6 mm/min during the night. The minimum scale value of the electrical channels was 10 μV/mm, that of the magnetic variometers (MTV-2) 0.02 nT/mm. From a lower limit of $T = 15$ s upwards, the measuring system ensures linear transfer. Analogue recording enables visual selection of the least disturbed sections of the records for digitizing and data processing (Ádám et al., 1981).

Data processing

The electromagnetic variations to be used for processing are further limited by severe coherence conditions in the MT computer program: Coh $(E_y H_y) \geq 0.9$ and Coh $(E_y H_x) \geq 0.9$. The output of the program run on a HP 2100 computer contained: impedance polar diagrams, weighted extreme values of resistivity (ρ) and their phases (φ) and directions (α). Mean values with their standard deviations were computed as a function of period from the data ρ, φ and α (e.g. see Ádám et al., 1981).

In the Gail Valley synchronous records were taken at two telluric stations in addition to the nearest magnetotelluric stations, the latter being used as the base for the former. Absolute ellipses for both stations were computed from the filtered amplitudes, then the relative ellipses characterizing the connection of the geoelectrical structure of the two points were deduced (see Appendix). With knowledge of the impedance components at the MT base station

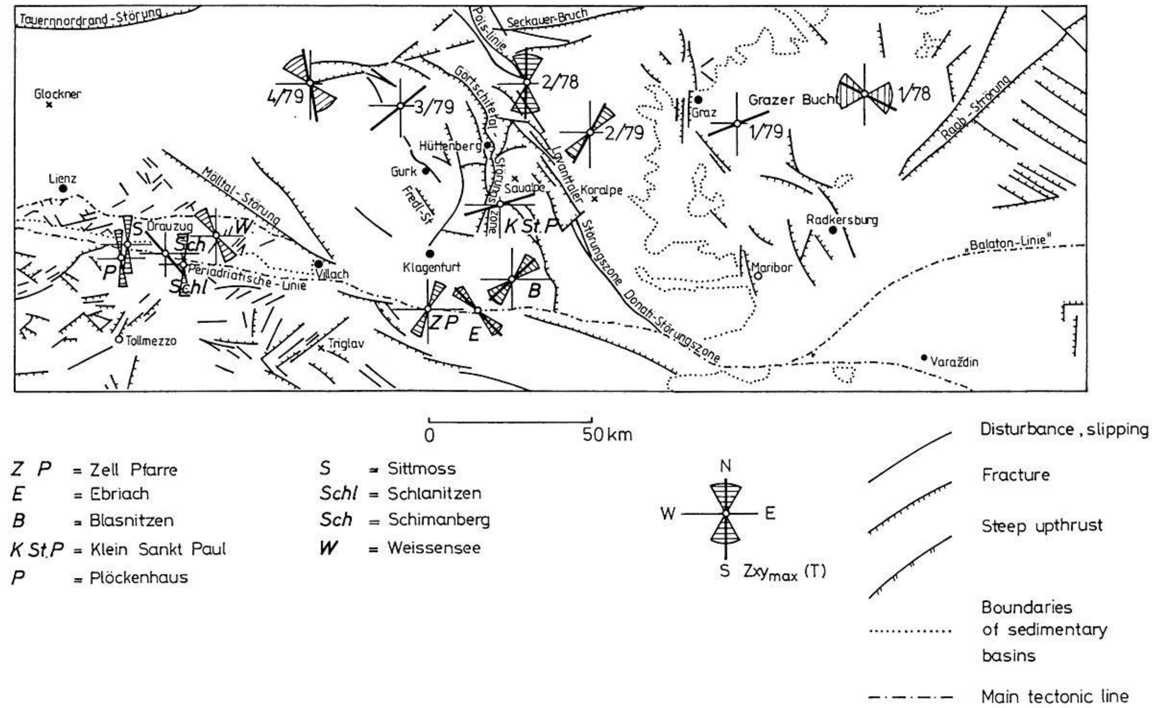


Fig. 3. Tollmann's tectonic map of the eastern Alps and the directions of maxima of the magnetotelluric impedances (Z_{xymax}) together with their change as a function of the period (T)

$[Z^B]$, the MT impedance polar diagrams can be deduced for the telluric satellite station:

$[Z^{sat}] = [T]\,[Z^B]$.

Results

The ρ_{min}, φ_{min} and $\alpha_{Z_{xymin}}$ values at Schlanitzen (in the Gail Valley) with curves representing the best-fitting 1-D models are shown in Fig. 4 as examples. A combined interpretation of the resistivity and phase curves by means of a 1-D inversion method – e.g. Fischer et al. (1981) – did not lead to consistent results. The reason is obvious: in such a strongly tectonized structure the geolelectrical data can be approximated even in an advantageous case at best by a 2-D model. The deviation of the model curve from the measured φ values can be regarded as a certain measure of inhomogeneity, as model curves were primarily fitted to the ρ values.

Hence, only as a first step, the best-fitting models to the values ρ_{min} and ρ_{max} (Fig. 5a–g) were determined by the theoretical 1-D model calculation. The model curves corresponding to these models are also illustrated in Fig. 5a–g. The data on depth and conductance of the crustal conductive layer are compiled in Table 1. On Tollmann's tectonic map (Fig. 3), the directions of the maximum impedances (Z_{xymax}) are also plotted.

For the telluric station Plöckenhaus, only strong man-made impulses could be processed as their amplitudes exceeded natural telluric signals several times. An absolute ellipse was computed from these disturbances. The direction of its major axis shows a variation of only a few degrees as a function of period (Fig. 3).

For station Schimanberg, MT data were computed at first by using the magnetic records of its base station Schlanitzen. Then magnetotelluric ρ_{min} and ρ_{max} values of

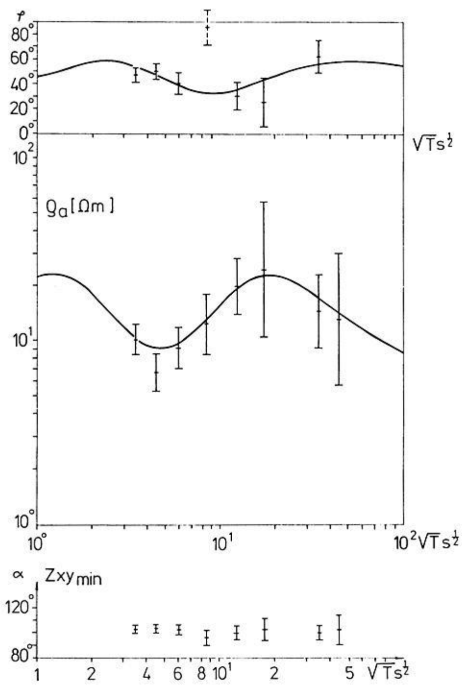


Fig. 4. The measured resistivity (ρ_a) and phase (φ) values as well as impedance directions ($\alpha_{Z_{xymin}}$) as a function of period with their standard deviations and the curves of 1–D layer models fitted to them for Schlanitzen

Schimanberg were also calculated from the MT impedance values of the Nagycenk observatory, Hungary, via telluric relative ellipse (see Appendix). The magnetotelluric resistivity values resulting from the two bases show a considerable difference (Fig. 6), attributed to differences in the magnetic

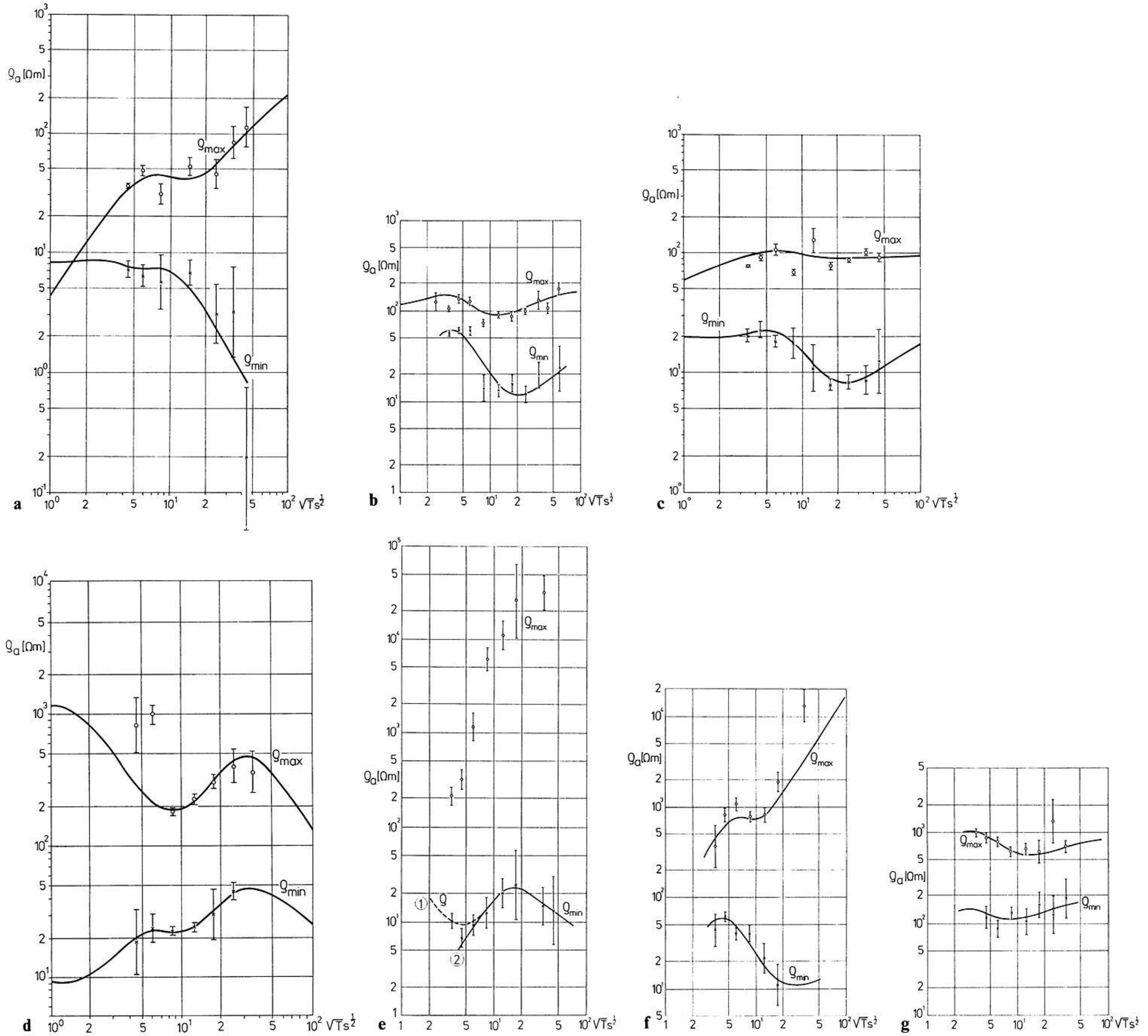


Fig. 5a–g. The average ρ_{min} and ρ_{max} values with their error bars and best-fitting 1-D models for:

a Station Ebriach
ρ_{min} model: $h_1 = 4$, $h_2 = 8.5$, $h_3 = 5$ [km]
$\rho_1 = 8.2$, $\rho_2 = 4$, $\rho_3 = 0.1$, $\rho_4 = 10$ [Ωm]
ρ_{max} model: $h_1 = 0.5$, $h_2 = 17$, $h_3 = 35$ [km]
$\rho_1 = 3$, $\rho_2 = 120$, $\rho_3 = 40$, $\rho_4 = 500$ [Ωm]

b Station Zell Pfarre
ρ_{min} model: $h_1 = 1.2$, $h_2 = 14$, $h_3 = 4.5$ [km]
$\rho_1 = 15$, $\rho_2 = 100$, $\rho_3 = 1.8$, $\rho_4 = 50$ [Ωm]
ρ_{max} model: $h_1 = 1$, $h_2 = 20$, $h_3 = 20$ [km]
$\rho_1 = 80$, $\rho_2 = 150$, $\rho_3 = 50$, $\rho_4 = 200$ [Ωm]

c Station Blasnitzen
ρ_{min} model: $h_1 = 13$, $h_2 = 8$, $h_3 = 3$ [km]
$\rho_1 = 20$, $\rho_2 = 3$, $\rho_3 = 10$, $\rho_4 = 30$ [Ωm]
ρ_{max} model: $h_1 = 1.8$, $h_2 = 28$, $h_3 = 30$ [km]
$\rho_1 = 50$, $\rho_2 = 120$, $\rho_3 = 70$, $\rho_4 = 100$ [Ωm]

d Station Klein St. Paul
ρ_{min} model: $h_1 = 2.2$, $h_2 = 16$, $h_3 = 4.2$, $h_4 = 80$ [km]
$\rho_1 = 10$, $\rho_2 = 45$, $\rho_3 = 8$, $\rho_4 = 170$, $\rho_5 = 10$ [Ωm]
ρ_{max} model: $h_1 = 20$, $h_2 = 18$, $h_3 = 300$ [km]
$\rho_1 = 1000$, $\rho_2 = 70$, $\rho_3 = 1000$, $\rho_4 = 10$ [Ωm]

e Station Schlanitzen
ρ_{min} model: $h_1 = 3.5$, $h_2 = 1.1$, $h_3 = 35$ [km]
① $\rho_1 = 20$, $\rho_2 = 2$, $\rho_3 = 60$, $\rho_4 = 5$ [Ωm] or
$h_1 = 1.1$, $h_2 = 35$ [km]
② $\rho_1 = 2$, $\rho_2 = 60$, $\rho_3 = 5$ [Ωm]
ρ_{max} model cannot be calculated (strongly distorted)

f Station Sittmoos
ρ_{min} model: $h_1 = 1$, $h_2 = 16$, $h_3 = 4$ [km]
$\rho_1 = 10$, $\rho_2 = 120$, $\rho_3 = 1.5$, $\rho_4 = 20$ [Ωm]
ρ_{max} model: $h_1 = 2.8$, $h_2 = 100$, $h_3 = 12$ [km]
$\rho_1 = 55$, $\rho_2 = 10{,}000$, $\rho_3 = 100$, $\rho_4 = 100{,}000$ [Ωm]

g Station Weissensee
ρ_{min} model: $h_1 = 1$, $h_2 = 20$, $h_3 = 10$ [km]
$\rho_1 = 70$, $\rho_2 = 150$, $\rho_3 = 50$, $\rho_4 = 200$ [Ωm]
ρ_{max} model: $h_1 = 55$, $h_2 = 45$ [km]
$\rho_1 = 1{,}000$, $\rho_2 = 300$, $\rho_3 = 1{,}000$ [Ωm]

Table 1. Depth of the conductive formation (h) and S value in the Periadriatic lineament

I. Karawanken	II. Gail Valley			
Site	on the basis of			
	ρ_{min}		ρ_{max}	
	h [km]	$S\,[\Omega^{-1}]$	h [km]	$S\,[\Omega^{-1}]$
I. Ebriach	12.5	50,000[c]	17	875
Blasnitzen	13.0	2,700–3,000	30	430
Zell Pfarre	15.2	2,500	21	400
Klein St. Paul[a]	18.2	525	20	257
II. Sittmoos	17	2,650[c]	103	120
Schimanberg[b]	16	[c]	40	[c]
Schlanitzen ①	3.5	550		
	39.6	[c]		
Schlanitzen ②	36.1	[c]	–	–
Weissensee[a]	21	200	55	150

[a] Outside the lineament (side effect)
[b] On the basis of telluric measurements
[c] It appears as conductive basement on the MTS curve

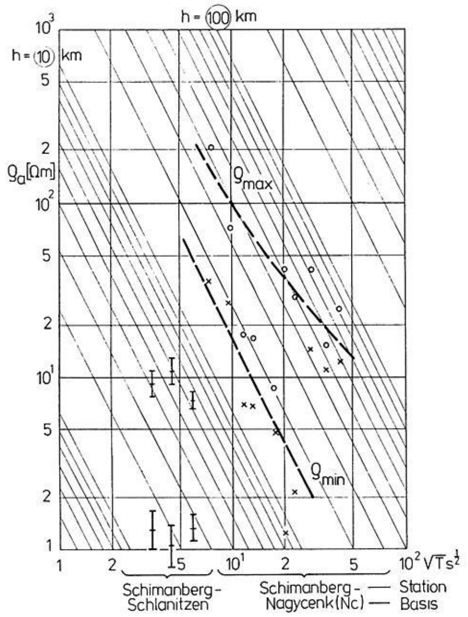


Fig. 6. MT resistivity values of Schimanberg as calculated with the magnetic field variations in Schlanitzen and in Nagycenk. The h depth-lines of perfectly conducting layers have been calculated by the formula: $h = \frac{1}{8}\sqrt{10\rho T}$

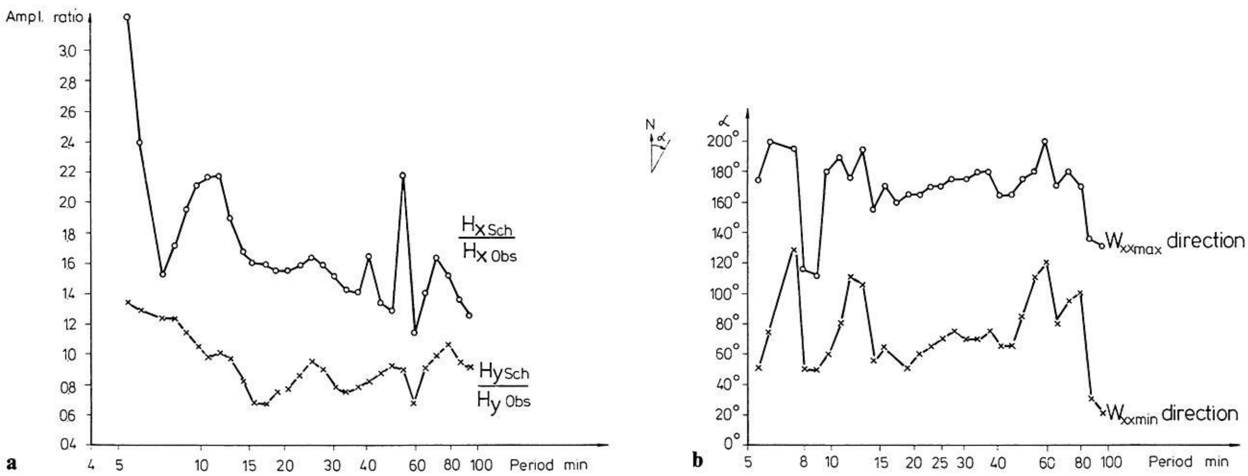


Fig. 7. a Amplitude ratios of the time variations of the horizontal magnetic field components measured at stations Schlanitzen and Nagycenk. **b** Directions of the major ($W_{xx\max}$) and minor ($W_{xx\min}$) axes of the W_{xx} polar diagram

field variations between Nagycenk and Schlanitzen. As there was only so-called "slow recording" of the magnetic field with a film speed of 15 mm per h in the Nagycenk observatory during the field work in Austria, the periods used in the analysis are greater than that measured at station Schlanitzen. In the latter case, the scatter of data is also shown.

As a result of the great electrical inhomogeneity at Schlanitzen, there is a significant increase in the time variations of the magnetic $H_x(H)$ field component and a smaller decrease in the magnetic $H_y(D)$ variations with respect to the data of the Nagycenk observatory in the period range longer than 15 min.

The transfer function between the variations of the horizontal magnetic field components at Schlanitzen (Sch) and Nagycenk (Obs):

$$H_{x\mathrm{Sch}} = W_{xx}\, H_{x\mathrm{Obs}} + W_{xy}\, H_{y\mathrm{Obs}}$$
$$H_{y\mathrm{Sch}} = W_{yx}\, H_{x\mathrm{Obs}} + W_{yy}\, H_{y\mathrm{Obs}}$$

have been calculated by the same computer program as in the case of magnetotelluric soundings (Verő, 1972; Ádám et al., 1981). The filtered amplitude ratios Schlanitzen/Nagycenk vs. period and the direction of the major and minor axes of the W_{xx} polar diagram vs. period are shown in Fig. 7a and b. The $W_{xx\max}$ direction is perpendicular to the Periadriatic lineament except at a few short and long periods strongly influenced by uncertainty in the data. The exceptional character of the point Schlanitzen is also indicated by the steep rise of the ρ_{max} curve, steeper than the theoretical limit $+63.5^0$, by resistivities higher than $10^5\,\Omega$m and by a great anisotropy increasing with period (Fig. 5e).

Interpretation of the data

A common characteristic feature of the MT sounding curves (Fig. 5a, b, c, e, f) measured in the immediate vicinity of the Periadriatic lineament is a well developed decreasing branch on the ρ_{min} curves uniformly indicating the conducting body in the crust. This indication is less characteristic on the ρ_{max} curves and it is combined with a strongly increasing branch at Ebriach, Schlanitzen and Sittmoos.

These results of magnetotelluric measurements are probably caused by a narrow conducting body embedded in resistive host rocks. This interpretation is supported by the following geological and further geophysical data:

a) According to Kovács (1983), the Periadriatic lineament is 3–5 km wide in the Karawanken.

b) The width of the conductivity anomaly along the Balaton line does not exceed 10 km (Fig. 2). As already mentioned, the Balaton line is considered as the continuation in Hungary of the Periadriatic lineament.

c) In Fig. 8 model curves calculated by the finite difference method for a conducting dyke of 10 km width and 7–9 km depth can be seen (Tátrallyay, 1977; Ádám, 1981; Ádám et al., 1981). The measured anisotropy shown by ρ_{min} and ρ_{max} curves is similar to that expressed by the ρ_E and ρ_H curves in the case of a narrow dyke.

d) The directions of the ρ_{max} (or Z_{xymax}) values are perpendicular to the strike of the lineament (Fig. 3) according to the dyke model independent of the position of the measuring sites (see the geological and topographical descriptions of the stations). For example, in Zell Pfarre the direction of the nearby valley is north-south without a corresponding change in the direction of the axes.

e) At increasing distances from the dyke an apparent immersion of the conductive body and a decrease of its conductance are observed. According to this phenomenon the MT sounding curves at Klein St. Paul differ strongly from those in the Karawanken lineament and the MT curves at Weissensee from those in the Gail Valley both in character and in the greater depth and lower conductance of the conducting dyke (Table 1 and Fig. 9). It is very likely that these reference points lie outside the tectonic zone.

f) The very steep rise, the high resistivity values and the anisotropy increasing with depth characterize the ρ_{max} curves first of all in Schlanitzen and also in Ebriach and Sittmoos. Such characteristics develop immediately besides the boundary of different electrical conductivities (inhomogeneities) on H-polarized sounding curves due to electric charges as proved both by physical model experiments (Ádám et al., 1983) and model calculations (Praus, 1976). This phenomenon also hints at the narrowness of the conductive body.

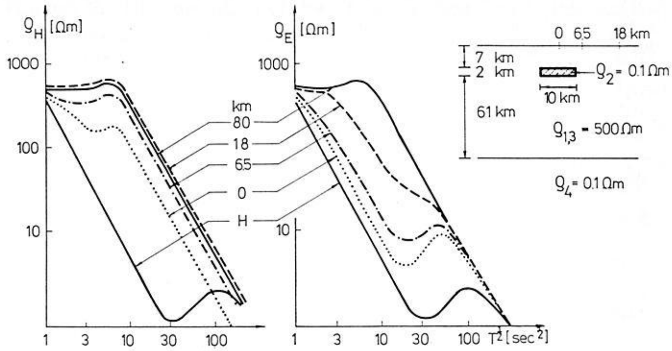


Fig. 8. Synthetic magnetotelluric sounding curves over a model representing a narrow fracture zone with a conducting body at a depth of 7 km. 6.5, 18, 80 km are the distances of the "measuring point" from point 0. The 1–D model shown for comparison has the same conductor depth and thickness (after Tátrallyay, 1977)

g) In addition to the electric field, the magnetic variation field also gets strongly distorted as a result of the conducting body as shown, e.g. for Schlanitzen, in Fig. 7. Similar distortions are seen at all points above the lineament and this distortion also decreases with distance from it. They will be dealt with in a subsequent paper.

As can be seen in Fig. 8, in the case of a narrow conducting dyke, more reliable information is yielded about the depth and the conductance of the dyke by the E-polarized $\rho_{min}(=\rho_E)$ curves. In addition to this, in the case of E-polarization, the S-effects due to the thickness changes of the near-surfaces sediments are less (Berdichevsky and Dmitriev, 1976). This is why the geoelectric layer sequences calculated on the basis of the best-fitting ρ_{min} curves only are shown in Fig. 9a and b and are used in the interpretation.

The crustal anomaly in the Periadriatic lineament is considered to be caused by fluids in the increased pores and

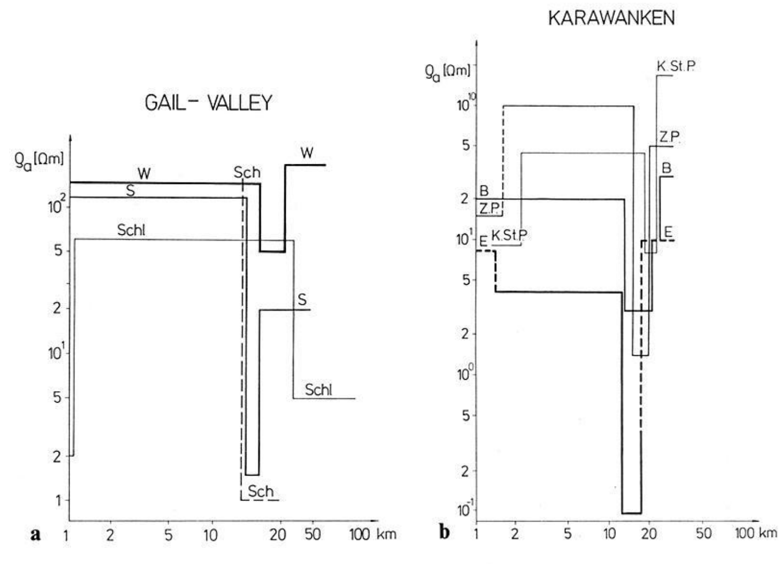


Fig. 9a and b. The geoelectric layer sequences calculated on the basis of the best-fitting ρ_{min} curves in **a** the Gail Valley and **b** the Karawanken

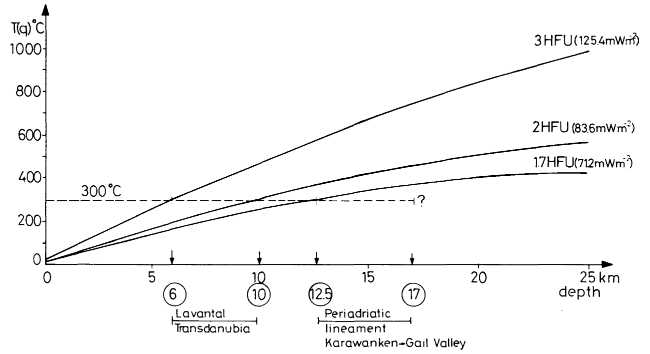


Fig. 10. Temperature-depth curves in the case of different surface heat flow after Haenel (1970) and the depth of the conductive formations (in *circle*) in Transdanubia and the eastern Alps (Ádám, 1985)

cracks of the fractures. The maximum conductivity of the fluids can be expected at the depth of the isotherms of about 300° C according to Quist et al. (1970).

The conductive "layer" lies in the Karawanken lineament at a depth of 12–15 km (Table 1) and its conductance is greatest in Ebriach. The conductive zone is somewhat deeper in the Gail Valley lineament (16–17 km). These depth values can be compared with those of the crustal anomalies in the Lavant Valley and in Transdanubia; in both areas depths of 6–10 km were found (Ádám et al., 1981; Ádám, 1981; Varga, 1980). The differences between the depths measured in these different areas can be of different origin (e.g. different crack and pore porosity, content and salinity of the electrolyte, deep temperature or regional heat flow as its surface indication, etc.). As very different heat flow values were measured in the areas under study, a comparison of heat flow values with the anomaly depth values seems to be reasonable. Both in the Lavant Valley and in Transdanubia heat flow reaches the value 100 mWm^{-2}, while along the Periadriatic lineament the heat flow map of Čermák and Hurtig (1979) gives heat flow values about 30–40 mWm^{-2} less. Since the 300° C isotherms lie deeper in the Periadriatic lineament – as concluded from the surface heat flow – the greater depth of the crustal anomaly seems to be in accordance with geothermics here, as shown in Fig. 10.

The seismic activity is concentrated in the eastern region of the Periadriatic lineament (between Villach and Eisenkappel). The hypocentres lie shallower (Drimmel, 1980) than the crustal conducting zone. On the basis of the heat flow and the conductivity distribution it can be supposed that the Periadriatic lineament represents an older tectonic formation than the fractures in Transdanubia and the Lavant Valley. The greater age of the Periadriatic lineament is supported by a shift of the latter along the Lavant Valley.

Thus, MT measurements along the Periadriatic lineament have also proved to be an effective tool for tracing great tectonic zones and investigating their physical conditions even within the rugged topography of the eastern Alps.

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Appendix

Magnetic or telluric absolute ellipses can be used for the transformation of magnetic or telluric values from one station to another in order to compute MTS curves for the latter (and also for the determination of the distortion of the geomagnetic variations). As a basis, simultaneous filtered complex amplitudes of the geomagnetic or telluric field are used at two (or more) stations. The real and imaginary parts of the square- and product-sums at both stations

$$X^{r^2}+X^{i^2}=X^2; \qquad Y^{r^2}+Y^{i^2}=Y^2$$
$$X^r\,Y^r+X^i\,Y^i=XY \tag{1}$$

enable the determination of the (instantaneous) geomagnetic or telluric absolute ellipse. (The values of X and Y, the north and east components, are sampled roughly in time intervals corresponding to one complete period of the filtered signal.)

The data of the absolute ellipse are as follows (Verő, 1960):

$$\tan 2\alpha=\frac{2XY}{X^2-Y^2} \tag{2}$$

$$A,B=\sqrt{\frac{X^2+Y^2\pm\sqrt{(X^2-Y^2)^2+4(XY)^2}}{n}}. \tag{3}$$

Here α is the direction of the major axis of the absolute ellipse, A and B are the lengths of the major and minor axes, n is the number of data points.

The components of the tensor transforming an ideal circularly polarized wave into the observed one are:

$$a=A\cos^2\alpha+B\sin^2\alpha$$
$$d=A\sin^2\alpha+B\cos^2\alpha$$
$$b=c=0.5(A-B)\sin 2\alpha. \tag{4}$$

In these formulas it is supposed that distortions occur only in the direction of the major and minor axes, i.e. the above tensor is a symmetric one. Thus, the instantaneous stationary ellipses of the base (index 0) and secondary (without index) station have the following form, if the components of the circularly polarized field are denoted by x and y:

$$X=ax+by \qquad X_0=a_0x+b_0y$$
$$Y=bx+dy \qquad Y_0=b_0x+d_0y. \tag{5}$$

By eliminating x, y from these equations, the relative ellipse between the base and the secondary station is obtained:

$$X=a_R\,X_0+b_R\,Y_0$$
$$Y=c_R\,X_0+d_R\,Y_0 \tag{6}$$

where the components of the relative ellipse $[T]$ are:

$$a_R=(ad_0-bb_0)\quad 1/t_0$$
$$b_R=(ba_0-ab_0)\quad 1/t_0$$
$$c_R=(bd_0-db_0)\quad 1/t_0$$
$$d_R=(da_0-bb_0)\quad 1/t_0 \tag{7}$$
$$t_0=a_0d_0-b_0^2. \tag{8}$$

With the help of Eq. (6) any geomagnetic or telluric variation can be transformed into variations at the other (secondary) station, or even instantaneous absolute ellipses can be transformed either for MT or for geomagnetic sounding purposes.

With this method the necessity of strictly simultaneous data points is eliminated, and the original MT-processing programme can be used with a subroutine containing Eqs. (1)–(8).

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