MAGNETOTELLURIC AND AUDIOMAGNETOTELLURIC MEASUREMENTS IN FINLAND

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ABSTRACT


Joint Finnish–Hungarian MT (magnetotelluric) and AMT (audiomagnetotelluric) measurements were carried out in Finland in the framework of the international ELAS project. The conditions for MT measurements are favorable at these latitudes. Five MT and 150 AMT stations gave information on the electrical conductivity distribution in the area: AMT results guided the choice of MT sites with minimal near-surface distortion effects and helped the interpretation of the MT soundings; the MT measurements indicate the presence of large conductivity anomalies and can be best interpreted as lateral induction effects of near-surface dyke structures. This result is confirmed by a certain correspondence between the directions of the maximum impedances and of the tectonic zones of the area.

Any information about the upper mantle would require the use of $S_p$ harmonics because of the crustal conductivity anomalies detected by the MT measurements.

INTRODUCTION

The Department of Geophysics, University of Oulu and the Geodetic and Geophysical Research Institute of the Hungarian Academy of Sciences in Sopron have cooperated since 1973 for the adaptation and the application of the magnetotelluric (MT) method in Finland.

Following the introduction of the audio-frequency magnetotelluric method (AMT) in Finland in 1974 (Benderitter et al., 1978), a demand has arisen to extend the period range in order to study deeper geological formations. This is motivated by the following reasons:

(a) Finland belongs geologically to the crystalline Baltic shield area. The shield
very often contains extremely well-conducting metallic or graphitic schists embedded in crystalline formations having resistivities of several $10^4$ $\Omega$m. To trace the conductors to greater depths, or to study the crustal structure underneath them, electromagnetic variations with frequencies less than ELF have to be studied. The lowest frequency used by the AMT instrument ECA 541-0 is 8 Hz.

(b) The interest in the physical properties of the Earth's crust and upper mantle is increasing. A number of international projects ensure the framework of these studies. The International Association of Geomagnetism and Aeronomy (IAGA) started its ELAS project (Electrical Conductivity of the Asthenosphere) in Seattle in 1977 to study the electrical conductivity of the asthenosphere. Finland is also participating in this project. Electric properties of the lithosphere, and of the underlying asthenosphere cannot be measured in the Baltic Shield using ELF above 8 Hz.

This paper describes Finnish-Hungarian experimental MT/AMT investigations carried out in Finland during the summer 1980.

GEOLOGICAL AND GEOPHYSICAL BACKGROUND

Two main points were decisive when choosing the measuring sites (Fig. 1):

(1) For some of the measuring points, geologically homogeneous sites were looked for and especially it was tried to avoid metallic conducting rocks such as graphite, pyrite and pyrrhotite. The site MT1 on the 1800–1900 Ma old Svecokarelian block and sites MT2 and MT3 on the 2600–2800 Ma old Presvecokarelianidic basement, belong to this “normal” group of the measuring points, from which information about the deep structures was expected.

(2) The measurements MT4 and MT5 were made on a major tectonic zone, the Lake Ladoga–Bothnian Bay zone, which was expected to be indicated by MT soundings. The zone contains a great part of the known sulfide ores in Finland. Rokityansky et al. (1979) had found conducting embeddings on the continuation of this zone in the environment of Lake Ladoga.

Zhamaletdinov (1976) found, from geoelectric investigations of the deep structure of the Kola-peninsula, a well-conducting anomaly which inferred a conducting layer at a depth of 10–20 km. The anomaly is not connected to one single conductive layer, but to several zones of immense dimensions, being structurally more or less independent from each other. The significance of the distorting effect of such a structure had not been so far properly considered for the “normal” areas.

The simplified geology of the research area is shown in Fig. 2 together with the main impedance directions which will be discussed later.

Figure 3 shows the aeromagnetic anomaly map of the area. Many of the magnetic anomalies are associated with conductors (graphitic black schists etc.). Thus the choice of the MT sites was guided strongly by the aeromagnetic and-corresponding aeroelectric maps, although the final selection was based on AMT measurements.
Fig. 1. Main structural units of the Precambrian in Finland. *Presto-cokareldic*: 1a = schist and paragneiss, 1b = granulite, 1c = orthogneiss. *Sveokareldic*: 2 = Kareldic schist belt, 3 = Svecofennidic schist belt, 4 = orogenic plutonic rocks. *Presto-cockareldic*: 5 = rapakivi granites, 6 = Jotnian sediments (after Simonen, 1980). MT sounding sites MT1–MT5 are shown on the map.
Fig. 2. Simplified geology of the research area and the directions of the maximum values of $Z_{xy}(T)$ at the measuring sites MT1–MT5. The black area indicates the variation of direction over the period range.

Fig. 3. The aeromagnetic anomaly map of the research area. Measurement sites MT1–MT5.
INSTRUMENTATION

AMT measurements

The Department of Geophysics at the University of Oulu has been using since 1976 a French scalar audio-magnetotelluric equipment manufactured by Société Eca, Paris. The equipment was originally developed at the Centre de Recherches Géophysiques, Garchy (Benderitter et al., 1973).

The amplitudes of the telluric and magnetic fields were measured at nine fixed frequencies from 8 to 3700 Hz. Two induction coils were used, one for the lower (from 8 to 370 Hz) and one for the higher (from 170 to 3700 Hz) frequencies. The telluric field was measured galvanically with steel electrodes. After integration and electronic division of the amplitudes the scalar value of the apparent resistivity at each frequency was read directly from the scale of the resistivity meter. In addition short samples of signals were tape recorded at almost every measuring point for later analysis.

MT measurements

The Hungarian group measured the time-varying electromagnetic field in the period range from about 10 to 2500 s. The equipment consisted of telluric and magnetic sensors and an analogue recording instrument. The minimum scale value for electric potentials was 10 µV/mm. Magnetic variations were transformed into electric signals by Hungarian-made MTV-2 variometers with a minimum scale value of 0.02 nT/mm (Ádám and Major, 1967).

There were no man-made electrical disturbances, partly because the research area is sparsely populated and distances between neighbouring farms are as a minimum 1–2 km, and partly because the electric network is not overloaded. Furthermore, pulsation activity is present at geographical latitudes of 63–64° around summer solstice at all times except for a short time during the night. Thus, a sufficient coverage in the period spectrum could be attained in 2½ days (2 days and 3 nights).

DATA PROCESSING

AMT measurements

The AMT measurements are of scalar type. Thus the processing of AMT data is much simpler than that of MT measurements. The final apparent resistivity value for each discrete frequency at every AMT station is determined as an average of five successive readings. The maximum differences between these individual readings can vary quite a lot, but generally around 10%, depending e.g. on geological conditions and on the frequency. AMT measurements were made in four directions, differing
by 45°. The four sounding curves are a good approximation of tensorial data, provided the measured field is stationary during the whole measuring time at the corresponding AMT point.

**MT measurements**

As a first step an appropriate number of recording intervals with different frequency content (and low noise level) were chosen at each measuring point. The length of the intervals was determined by the acceptable signal/noise ratio, the length being generally between 10 min and several hours. Several sections with overlapping frequency content were processed. From each of these, 600–800 digital values (sometimes more than 2000) were obtained with Δt from 0.7 to several tens of seconds.

The digital data were processed on the HP 2100A computer of the Geodetic and Geophysical Research Institute in Sopron, using the program described by Verő (1972). This program calculates the impedance elements by filtering in the time-domain. The level of acceptance for every sequence of ten points is that the coherencies \( \gamma_{E, H} \) and \( \gamma_{E, E} \) should be greater than 0.9. The output of the program consists of impedance polar diagrams, resistivities in different directions, of the extrema, \( \rho_{\text{max}} \) and \( \rho_{\text{min}} \) and phase characteristics of the impedance. From these data, different kinds of sounding curves can be determined.

**RESULTS AND DISCUSSION**

The final choice of the MT sites was based on the AMT measurements. We looked for sites as free as possible from electric near-surface inhomogeneities. Figure 4 shows that the AMT-results at all five MT points have very small directional variations.

In spite of local homogeneity being ensured, the directions of the extrema of the main impedance (\( Z_{x_\text{sym}} \) and \( Z_{y_\text{sym}} \)) at longer periods are characteristic and well-correlated with the nearby geology, though changes of this direction vs. period occur (Fig. 2). The points MT1 and MT5 are characterized by a direction stability of \( Z_{x_\text{sym}} \) (\( T \)). These stations lie close to narrow zones of well-conducting dykes. The site MT5 lies most likely very near the contact between the more conducting Lake Ladoga–Bothnian Bay zone and the resistive Fresveckarelicic basement (the Karelian megablock) (Kaikkonen and Pajunpää, 1981; see also Fig. 7). The point MT2 has also a quite constant direction of \( Z_{x_\text{sym}} \) (\( T \)) and its maximum change with increasing period is only 15–30°. On the contrary MT3 and MT4 have a great change of the direction of \( Z_{xy_\text{sym}} \) (\( T \)). These changes of the directions depend on the ratio of the penetration depth and the distance to the nearest conducting anomalous body. In MT2 and MT3 average direction of the maximum impedance is roughly perpendicular to nearby elongated phyllite–quartzite zones (see Fig. 2).
Fig. 4. AMT-sounding curves in four directions at the measuring sites MT1–MT5 (partly completed by VLF-R results).
Figures 5a–e show the \( \rho_{\text{min}} \) and \( \rho_{\text{max}} \)-curves at each location with associated error bars corresponding to the standard deviations. Figure 6 depicts both the AMT and MT parts. AMT curves here are averages of four AMT points within 300–500 m from the MT site in the direction of \( \rho_{\text{min}} \). As Fig. 4 shows, the resistivity values in different directions are generally similar.

The connection of the MT sounding curves with the AMT ones is uncertain due to the gap between \( 1/8 \) and \( 10 \) s in the period range measured. The extrapolation of the curves across the gap corresponds to supposing the presence of a conductive layer at appropriate depth.

The MT curves show high anisotropy at the points MT1, MT2 and MT5. These exceptional anisotropies are possibly the effect of a narrow tectonic zone (dyke) filled with well-conducting formations (ores, graphite) embedded in the resistive (\( \rho_o > 10^4 \) \( \Omega \)m) rocks indicated by the short period part of the \( \rho_{\text{max}} \)-curve. As we mentioned earlier the site MT5 is located most likely very close to the contact between two electrically different geologic units. The anisotropy at the points MT3 and MT4 is considerably less.
For the interpretation of the induction effect of narrow dykes, models studied by Tâtrallyay (1977a, 1977b) give certain informations (see fig. 8 in Ádám et al., 1981, further Ádám, 1981). They show that the $E$-polarized curves for horizontal dykes correspond to $\rho_{\min}$. Above the center of the conducting zone the inversion of these curves gives the true geoelectric structure. Away from the center (i) the apparent depth of the dyke is greater than the distance between measuring point and dykes, (ii) the direction of the maximum impedance $Z_{x,y_{\max}}(T)$ approximates in the vicinity
of the dyke the direction perpendicular to its strike, (iii) the resistivity anisotropy increases with decreasing distance between measuring point and dyke.

Close to, but outside the conducting zone neither of the curves ($\rho_{\min}$, $\rho_{\max}$) gives quantitatively precise results about the parameters of the dyke, only qualitative deductions can be made about its existence.

More far away from the anomalous body the $H$-polarized $\rho_{\max}$ curves do not show distortion due to the conducting body, therefore $\rho_{\max}$ curves yield here more realistic layer sequence without any apparent conducting layer.

A tentative 1-D interpretation of the 5 MT $\rho_{\max}$ curves give conducting bodies at depths of 4 (MT1); 4.8 (MT5); 10.5 (MT3); 16.5 (MT4) and 34 km (MT2). Since the results vary greatly from point to point, the depths probably do not refer to a realistic layer structure of the Earth's crust. (The depths of the conductive bodies of the $\rho_{\max}$ curves have even greater scatter.)

If the model of Tátrallyay is used for a qualitative discussion of the measurements at points MT2, MT3 and MT4, one obtains results which are in contradiction with earlier conclusions drawn from the direction of the impedances and the anisotropy of the apparent resistivity. Therefore, in order to find the real structure of the Earth's crust and to understand distorting effects and their connections to the anomalous bodies more detailed MT-measurements and further investigations are necessary. These will include the construction of a 2-D model for the research area.

The near-surface resistivity conditions can be obtained from the $H$-polarized $\rho_{\max}$-curve, which so to say steps across the narrow conductivity anomaly. The $\rho_{\max}$-curves indicate at the sites MT1 and MT5 $2 \times 10^3$–$2 \times 10^4 \Omega \text{m}$ resistivities for the near-surface rocks.

It is not probable that the well-conducting zone appearing on the $\rho_{\max}$-curves at a depth between 100 and 200 km would indicate a real structure of the upper mantle. It can be, however, said, that on the basis of the right-hand side ascending (MT5) or flat (MT1) part of the $\rho_{\min}$-curves, a possible asthenosphere must lie deeper than 100 km. For a more exact determination, records containing longer period variations are necessary. Jones (1981) has recently reported an asthenospheric layer in the Kiruna region (Sweden, on the northwestern edge of the Baltic Shield), between 155–185 km depths. Jones has obtained his result by using the HSG (Horizontal Spatial Gradient) method on magnetometer array data.

Figure 7 shows residual $\rho_z$-profiles at the used AMT frequencies. In Fig. 7a the direction 317° (of the telluric line) is parallel to the general direction of the Lake Ladoga–Bothnian Bay zone. In Fig. 7b the direction of the telluric line is perpendicular to that zone, respectively. The residual profiles are constructed by normalizing the measured $\rho_z$-values at each measuring point by the average regional $\rho_z$-value of each frequency. (For details see Kaikkonen and Pajunpää, 1981.) Using these residual $\rho_z$-profiles and of the whole AMT data we can divide the profile into electrically different geological units: I the resistive Central Finland granitoid complex, III the more resistant Karelian megablock and II the conducting Lake Ladoga–Bothnian Bay zone.
CONCLUSIONS

Magnetotelluric deep sounding was found to be effective in Finland. In comparison with middle latitude stations only 1/2 or 1/3 of recording time was necessary. Since the level of artificial noise was low and the amplitudes of the variations were smaller, the signal/noise ratio and the average quality of the records were better than for example in Hungary.

Our measurements give information about the general distribution of the electrical conductivity in the crystalline shield of Finland. The AMT results have paramount importance for the interpretation of the MT soundings and for the analysis of the near-surface distorting effects. However, in deep sounding the distorting effects of large conductivity anomalies due to near-surface inhomogeneities might be felt even in places where near-surface rocks are found to be electrically homogeneous by AMT measurements.

The main information from MT measurements are the depth of the apparent conductive layers and the direction of the maximum impedances. The depths of the conductive layers from SW to NE along the studied profile are: 4 km, 16.5 km, 4.8 km, 10.5 km, 34 km. As the distances between the points are 35–75 km, the conductive layers cannot be explained by the effect of a single conductive body. On the AMT profile, however, conductive formations can be identified at distances from the MT sites corresponding to the apparent depths. The small number of measurements, lack of electromagnetic information outside of the profile make it hard to definitely associate these formations with the conductors seen in the MT $\rho_{\text{min}}$-curves.

However, the main information deducible from MT measurements, i.e. the existence (and location) of conductive bodies in the Baltic shield, as already supposed by Zhamaletdinov (1976), is supported. This suggestion is further confirmed by the directions of the maximum impedances which are stable in case of nearby conductive bodies, while in case of more distant bodies they turn toward the direction corresponding to the conductive structure when the penetration depth increases.

In order to get information about the upper mantle it is necessary to use variations at periods longer than substorms periods, e.g. harmonics of the daily variations. The MT method is able, due to its direction sensitivity, to determine the direction of tectonic lines and disturbed zones on crystalline shields.

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Fig. 7. Residual $\rho$-profiles (MT1–MT2) at all nine AMT frequencies (after Kaikkonen and Pajunpää, 1981). The values of $\log \rho_z$ (measured)/$\rho_z$ (regional average) are shown on the ordinate axis. The sites MT1–MT5 are indicated by arrows.
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