J Geophys (1986) 59:32–41

Journal of Geophysics

Magnetovariational and magnetotelluric studies of the Oulu anomaly on the Baltic Shield in Finland

T. Korja[1], P. Zhang[2], and K. Pajunpää[1]

[1] Department of Geophysics; University of Oulu, SF-90570 Oulu 57, Finland
[2] Department of Solid Earth Physics; University of Uppsala, S-751 22 Uppsala 1, Sweden

Abstract. The electrical conductivity structure of the Baltic Shield in Finland has been studied by magnetovariational (MV) and magnetotelluric (MT) work. First magnetometer arrays revealed the crustal Oulu conductivity anomaly which consists of a crustal conductive zone and a conductivity boundary. Since 1983 the magnetotelluric technique has been used to study the Oulu anomaly in more detail.

The information obtained from the induction vectors of the MV and MT data are compared. 1D and 2D models of the Oulu anomaly were constructed from MT data using induction vectors as additional information. In the centre of the research area the anomalous body (with a resistivity of 0.5 ohm m) lies below a depth of 4–7 km. Its width is about 25 km and its length is more than 100 km. To the south-west of this anomaly a low-resistive crustal layer exists at a depth of 14 km, whereas to the north-east no crustal layer was identified in the very resistive Karelidic realm.

Key words: Baltic Shield – Crustal conductivity structure – Oulu conductivity anomaly – Magnetotellurics – Magnetovariational studies

Introduction

Since 1980 the deep geoelectric structure of the Baltic Shield has been investigated under a research project in Finland (Hjelt et al. 1985). In order to get information about the electrical conductivity distribution within the Earth's crust, and even within the upper mantle, magnetovariational (MV) and magnetotelluric (MT) measurements have been carried out.

With magnetometer arrays one can map lateral variations in the electrical conductivity of the Earth's crust by measuring time variations of the Earth's magnetic field simultaneously at several sites. Once some conductivity anomaly has been revealed with MV, one can investigate with the magnetotelluric method and try to obtain more knowledge about the depths and conductivity values of the formations which caused the anomaly.

Following the above procedure, several magnetometer arrays have been operated in Finland since 1981. The first arrays were located in central Finland (Pajunpää et al. 1983). These arrays revealed, among others, the conductivity anomaly near Oulu – called the Oulu anomaly [first indicated in the results of Lange (1979) and Küppers et al. (1979)]. After the array studies, magnetotelluric soundings were undertaken in 1983 and 1984 to study this anomaly in more detail. MT measurements were accomplished as a joint project between the universities of Oulu and Uppsala.

The research area of interest (Fig. 1) is situated on the boundary of two of the three main Precambrian tectonolithological units of the Baltic Shield (Laajoki, 1984). The northeastern part belongs to the Karelidic realm where the Archean basement is exposed in many places. Berthelsen (1984) calls this realm the Archean nucleus or age province. It consists of 3,100-2,500-Ma-old Archean and Early Proterozoic rocks; mainly granodioritic gneisses, different kinds of schists (quartz-feldspar and mica) and greenstones. The southwestern part of the research area lies on the 1,900-Ma-old Svecofennidic realm, the rocks of which are granites, granodiorites and migmatic gneisses with granite veins. Between these two units is a geological border. According to Berthelsen (1984), this border is a 2,000-Ma-old fossil plate boundary. However, the existence and the character of this boundary is to some extent unresolved and, according to Berthelsen, it may be impossible to identify this boundary at present. In the middle of the research area above these old Precambrian rocks lies the well-known Muhos formation which consists of unfolded Jotnian silt and shale sediments (1,300 Ma). According to geophysical and borehole data these sediments reach a depth of 1,000 m.

Measurements

Magnetovariational (MV) measurements (or geomagnetic deep soundings) were performed with 31 magnetometers of Gough-Reitzel type (Küppers and Post 1981) which were on loan from the University of Münster. The MV data used in this study were collected with three arrays. The stations with letters A, B, C and II belong to array number II, the stations with letters M and N to array number III and with R to array number VI (see Fig. 2). Based on the results of the array II, the profiles M, N and R were planned to cross the anomaly to locate it better.

When starting with MT one could follow the proposal of Rokityansky (1982) and group the measurements above the anomaly to find out the depth and the conductivity of the anomalous body. This provides very fast results about the character of the anomaly. In our case, however, the location of the anomaly was not very well determined

Offprint requests to: T. Korja

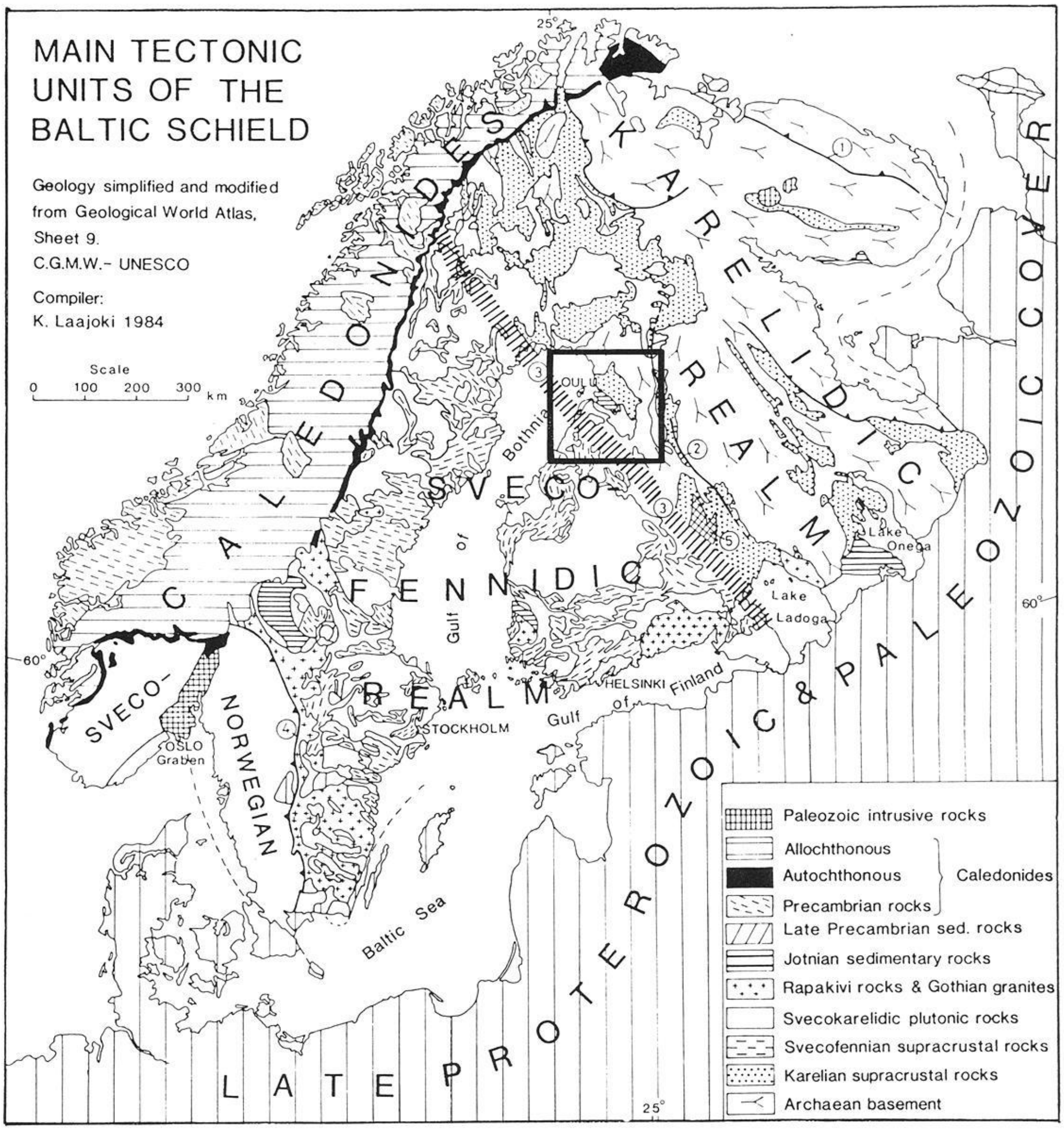


Fig. 1. Main tectonic outlines of the Baltic Shield and the location of the research area. Tectonic zones: *2* Koillismaa-Kainuu-North-Karelia, *3* Raahe-Ladoga. (Map of Laajoki, 1984)

and in addition to the anomalous zone there is also the above-mentioned conductivity boundary. We therefore decided to make profiles across the anomaly. This also give a chance to perfom 2D modelling when constructing a geoelectric model.

The first profile (OULU I) parallels magnetometer profile N, and thus enables a direct comparison of induction vectors. In the northeastern part it enters the Archean basement. The second profile (OULU II), which runs from east to west and crosses the anomaly perpendicularly, is mostly on the younger Svecokarelidic realm. This profile also traverses the Muhos formation, thus making it possible to sound the electrical structure under the sediments.

MT measurements were made with two five-component MT stations on loan from the University of Uppsala. On profile OULU II, mainly horizontal components were recorded. Recordings were usually made simultaneously with both equipments to enable the "remote reference" processing (Gamble et al. 1979) of the data. However, due to timing errors when starting recordings, especially on profile OULU II, it has frequently proved impossible to identify the time shift between two data sets and so far it has proved impossible to apply the RR technique. The data were collected with a digital acquisition system constructed in Uppsala. Signals were divided into two period bands: 2–3,600 s and 0.1–10 s. The sampling intervals and recording times were, correspondingly, 2 Hz and 16 h for long periods and 64 Hz and $^{1}/_{2}$ h for short periods.

A total of 24 MT soundings were carried out. The data from seven sites were useless (due to tape record errors, instrumentation errors, very poor signal to noise ratio etc.) but the data from ten sites on OULU I and seven sites on OULU II were of high enough quality to be analysed.

Induction vectors

Some induction vectors are presented here to show the location of the anomaly and to examine the vectors determined from the MT data. Two main data sets were used to calculate the estimates of the single-station induction vectors:

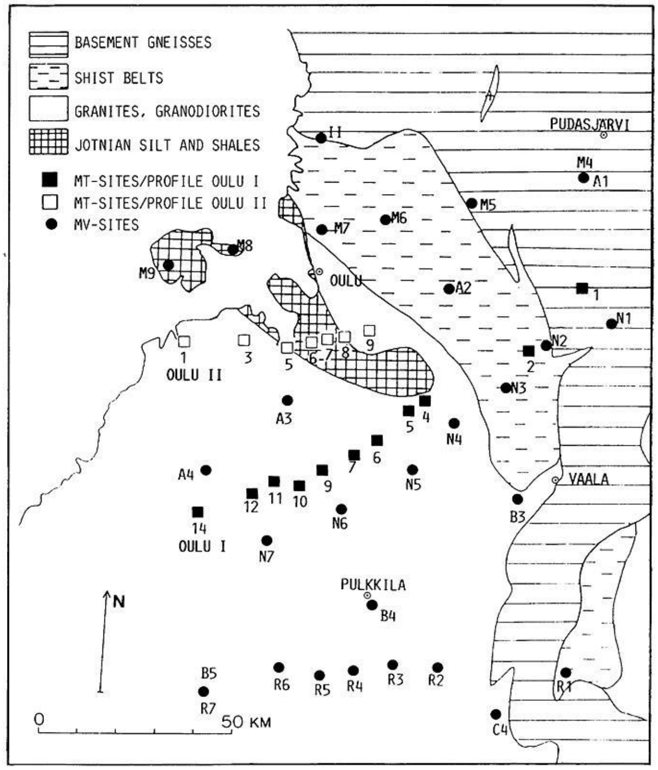


Fig. 2. The simplified geology of the research area and locations of the MV sites (*circles*) and MT sites (*squares*). The geological map is simplified from Simonen (1980)

firstly, the data compiled from the three magnetometer arrays and secondly, the data recorded during the MT measurements on the southern MT profile (OULU I). On the northern profile (OULU II) we measured only horizontal EM-field components.

The two data sets differ from each other in three points. The available period range in the array measurements is from about 60 s up to 1 or even 24 h, whereas in the MT measurements it is from 0.1 s up to 1 h. The recording period in the array operations was about 2 months and in the MT 16 h. This strongly restricts the selection of MT records for analysis. The magnetometer array data allow a control on the source field characteristics, whereas the MT data do not.

The analysis method for the magnetometer array data was described by Jones (1981) and Pajunpää (1984). The transfer functions were calculated from three events of 2–4 h except at stations R1–R6 where only one event of 4 h has been used. The acceptance level of the bias-reduced multiple coherence functions between vertical and horizontal components (see Jones et al., 1983) was 0.8 for the N and M lines and 0.6 for the A and B lines. The acceptance level of the product of the horizontal field spatial wavelength and the inductive scale length (see Pajunpää, 1984) was 0.3. At stations R1-R6, no acceptance criteria were used.

The induction vectors from the MT data were determined using the MT-analysis program of Jepsen and Pedersen (1981). Data sets were averaged using 0.8 as a threshold value of predicted coherencies when accepting data sets for further analysis. From these averaged power spectra, the induction vectors (**A**, **B**) were calculated.

Figure 3a shows the reversed real and unreversed imaginary induction vectors for a period of 100 s around the Oulu anomaly. The imaginary part of the vectors determined from the MT data are not displayed here. If we compare the real vectors of the two data sets we can see that they both reveal the presence of an anomaly, but the vectors from MT data have obviously some large errors (stations 4 and 5). The lack of the source field control may cause heterogenous errors on different days so that every MT station has its own source error. Figure 3c shows the vectors from the MT instruments at 10 s period. They indicate an anomaly between stations 2 and 4. This is in good agreement with the array data, which indicates shallow currents around station N3. Obviously the MT vectors are more reliable at this shorter period than at 100 s due to a larger number of periods (degrees of freedom) in the record and due to a smaller skin-depth of the field. As a conclusion we can say that a group of induction vectors determined from MT records, as here, can be used qualitatively, whereas a single vector should not be used.

Figure 3b shows the induction vectors determined from the arry data at 500 s period. Figure 3a and b give somewhat different pictures of the anomaly. At 500 s there is a clear reversal of the vectors between stations M6 and M7, N5 and N6. Thus the main current at this period flows along that axis striking slightly west of north.

At 100 s the anomaly seems to be much broader on the N line. The vectors are short at stations N3, N4 and N5. The imaginary vectors at 100 s reverse between N2 and N3 and are large at N4 and also at M6. At 10 s the vectors from the MT instruments reverse between stations 2 and 4. This can be explained by a shallow current flowing from about N3 to the northwest. The geological explanation of this shallow current is the schist belt in the same region. The conductive dykes, which are mainly graphite, have concentrated in the southwestern border of this schist belt (Pernu, 1979). Also, the Muhos sediment formation may carry shallow currents affecting station N4 especially. Moreover, the main anomaly has a different frequency response along its eastern and western borders.

The deeper north-south-striking or "main" anomaly and the shallow current in the schist belt meet around station M7, causing very large real induction vectors at stations M6 and II. The width of the "main" anomaly is not well determined. Its length is more than 100 km beginning from about station B4 and continuing north-northwest from station M7. On the R line the anomaly is more like a boundary.

MT data analysis

As mentioned previously, the MT data were collected in two period bands; 2–3,600 s and 0.1–10 s. The data processing was carried out at Uppsala University using a slightly modified version of the program of Jepsen and Pedersen (1981), which estimates several parameters including:

a) The polarization parameters of the horizontal magnetic and electric fields (Fowler et al., 1967).

b) The ordinary and predicted coherencies between the magnetic and electric fields.

c) The magnetotelluric (MT) impedance both in the measuring and rotated directions. By rotating the MT-impedance tensor, a direction is found in which the sum of

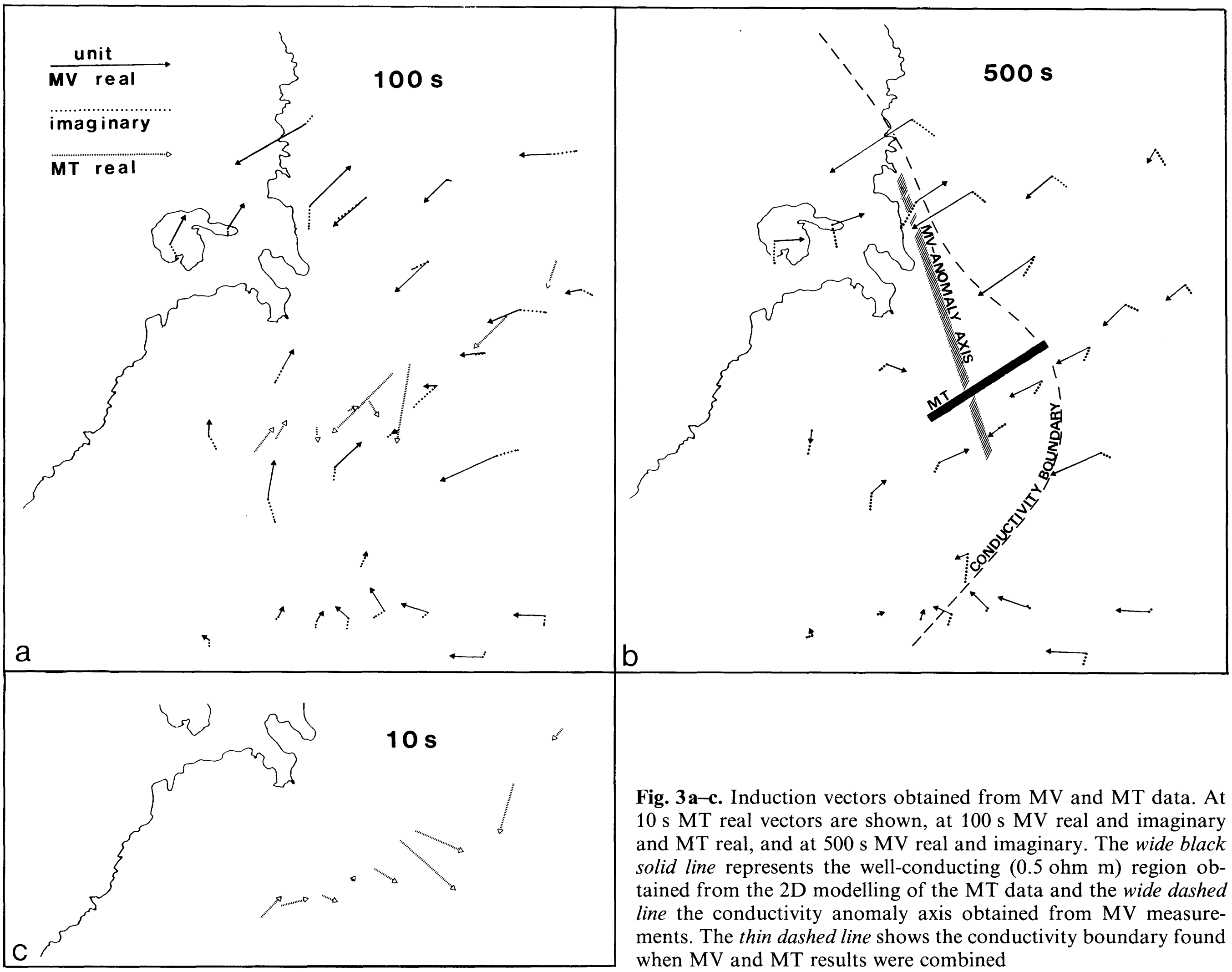


Fig. 3a–c. Induction vectors obtained from MV and MT data. At 10 s MT real vectors are shown, at 100 s MV real and imaginary and MT real, and at 500 s MV real and imaginary. The *wide black solid line* represents the well-conducting (0.5 ohm m) region obtained from the 2D modelling of the MT data and the *wide dashed line* the conductivity anomaly axis obtained from MV measurements. The *thin dashed line* shows the conductivity boundary found when MV and MT results were combined

the diagonal elements of the impedance tensor is a minimum.

d) Apparent resistivity and phase in the unrotated and rotated directions.

As stated above, due to timing problems, only a few of the stations could be processed using the "remote reference" technique. Fortunately, the data was usually of high quality, with the predicted coherence usually 0.8 or higher (a value of 0.8 was used as an acceptance threshold when rejecting poor data segments). This, and the lack of severe polarization in the horizontal magnetic field at most sites, means that the problems sometimes associated with "single-station" data (see e.g. Pedersen and Svennekjär, 1984; Roberts et al., 1984) can be expected to be of small significance for this data set. All data have been processed using the single-station technique.

It is a common practise in MT data analysis to present the estimated apparent resistivities in the rotated directions (see above) on the assumption that these directions are determined by the predominant strike of the Earth structure in the vicinity. In our case the data does not produce a stable "strike" direction. The magnetometer array study of Pajunpää (1984) indicates that the electrical structure in the Oulu area is dominated by a conducting zone which strikes about 340° (N 20° W). Comparison of results of one-dimensional inversion of the unrotated data from the two profiles (Fig. 5) also suggests that the predominant strike is roughly in this direction. Thus, we can conclude that the predominant strike is north-south, the lack of a consistent strike direction in the data presumably being due to the influence of three-dimensionality within the Earth. The two-dimensional modelling of profile OULU I (see below) was carried out assuming this strike Analysis of the data in the measuring coordinate system has an additional advantage; because of complex near-surface structure and the consequent strong polarization of the electric field, it is found that the data quality in the two measuring directions (north-south and east-west) can be very different, and thus the rotation would combine low- and high-quality data leading to a degradation of the "best" data.

Figure 4 shows examples of unrotated apparent resistivities and phases with the associated 68% confidence limits from the profile OULU I (stations 3, 8, 13 and 15 produced no useful data). Examination of the data shows that the profile can be split into three distinct sections. Stations 1 and 2 in the northeastern part have an apparent resistivity about two orders of magnitude greater than those of the central stations. The apparent resistivity at these stations

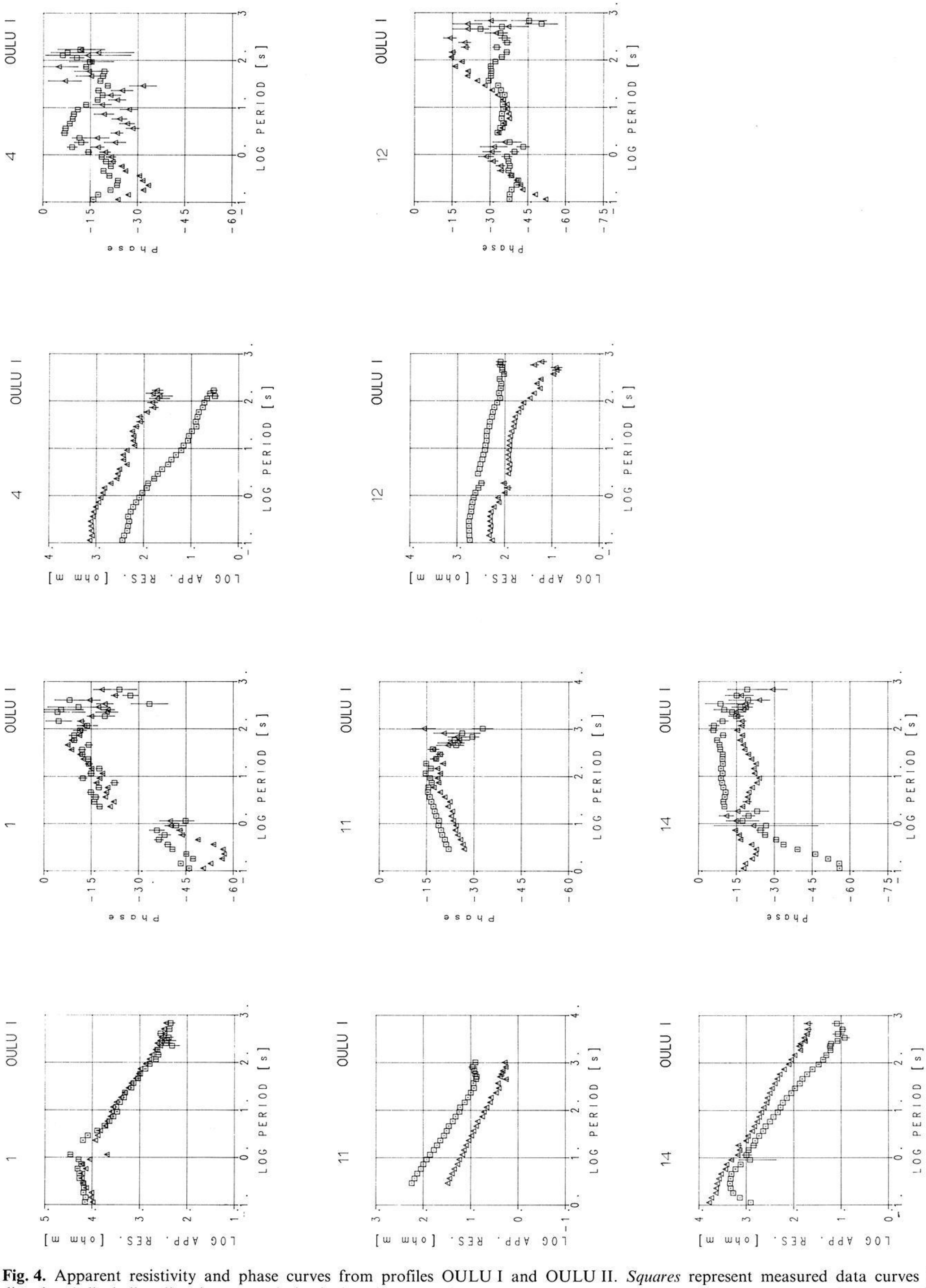
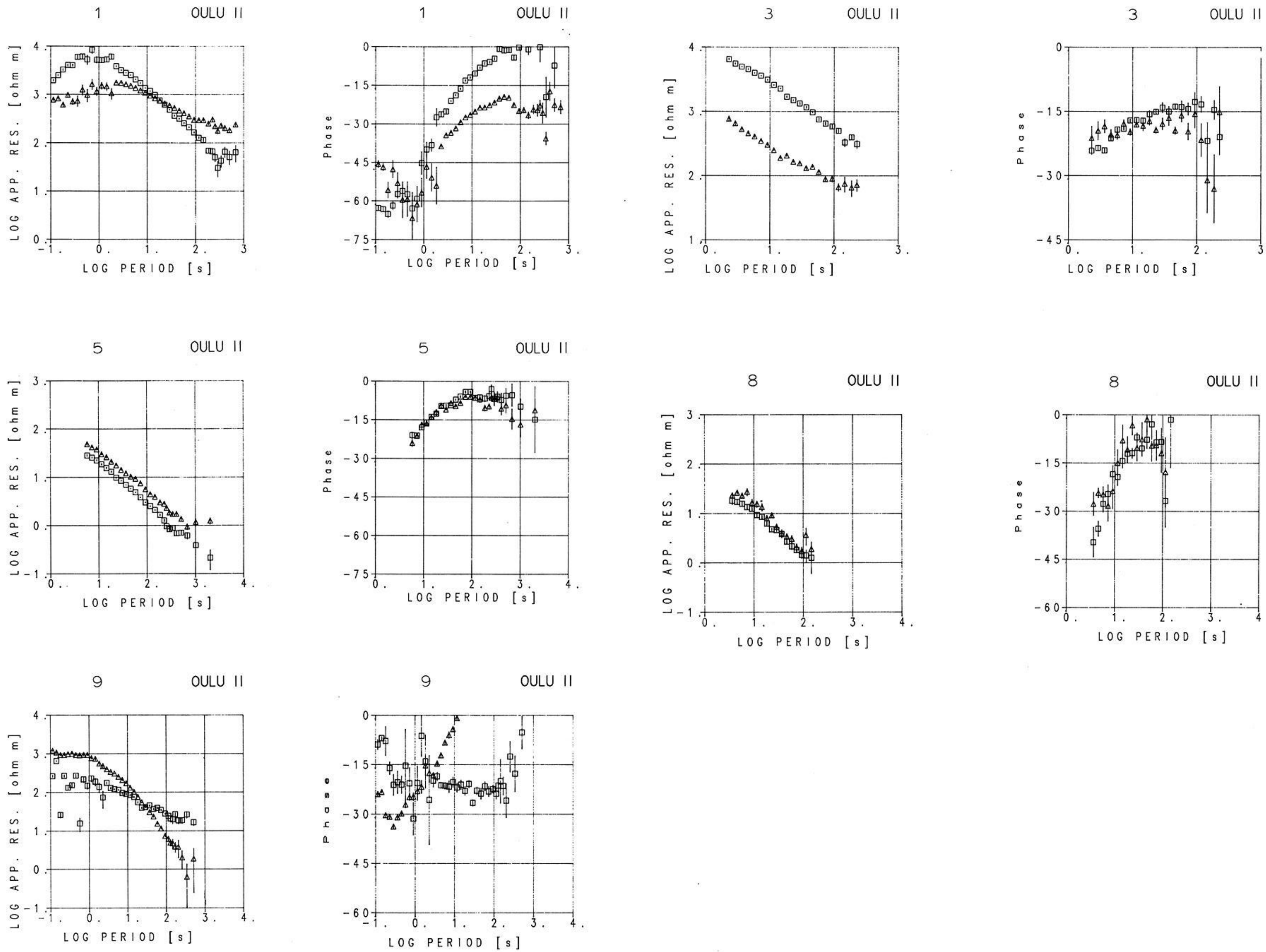


Fig. 4. Apparent resistivity and phase curves from profiles OULU I and OULU II. *Squares* represent measured data curves in NS direction (telluric line direction – *E*-polarization) and *triangles* in EW direction (*H*-polarization). *Vertical bars* show the 68% confidence limits. Apparent resistivity values and periods are presented in logarithmic scale


1 OULU II
LOG APP. RES. [ohm m]
LOG PERIOD [s]
1 OULU II
Phase
LOG PERIOD [s]
3 OULU II
LOG APP. RES. [ohm m]
LOG PERIOD [s]
3 OULU II
Phase
LOG PERIOD [s]
5 OULU II
LOG APP. RES. [ohm m]
LOG PERIOD [s]
5 OULU II
Phase
LOG PERIOD [s]
8 OULU II
LOG APP. RES. [ohm m]
LOG PERIOD [s]
8 OULU II
Phase
LOG PERIOD [s]
9 OULU II
LOG APP. RES. [ohm m]
LOG PERIOD [s]
9 OULU II
Phase
LOG PERIOD [s]

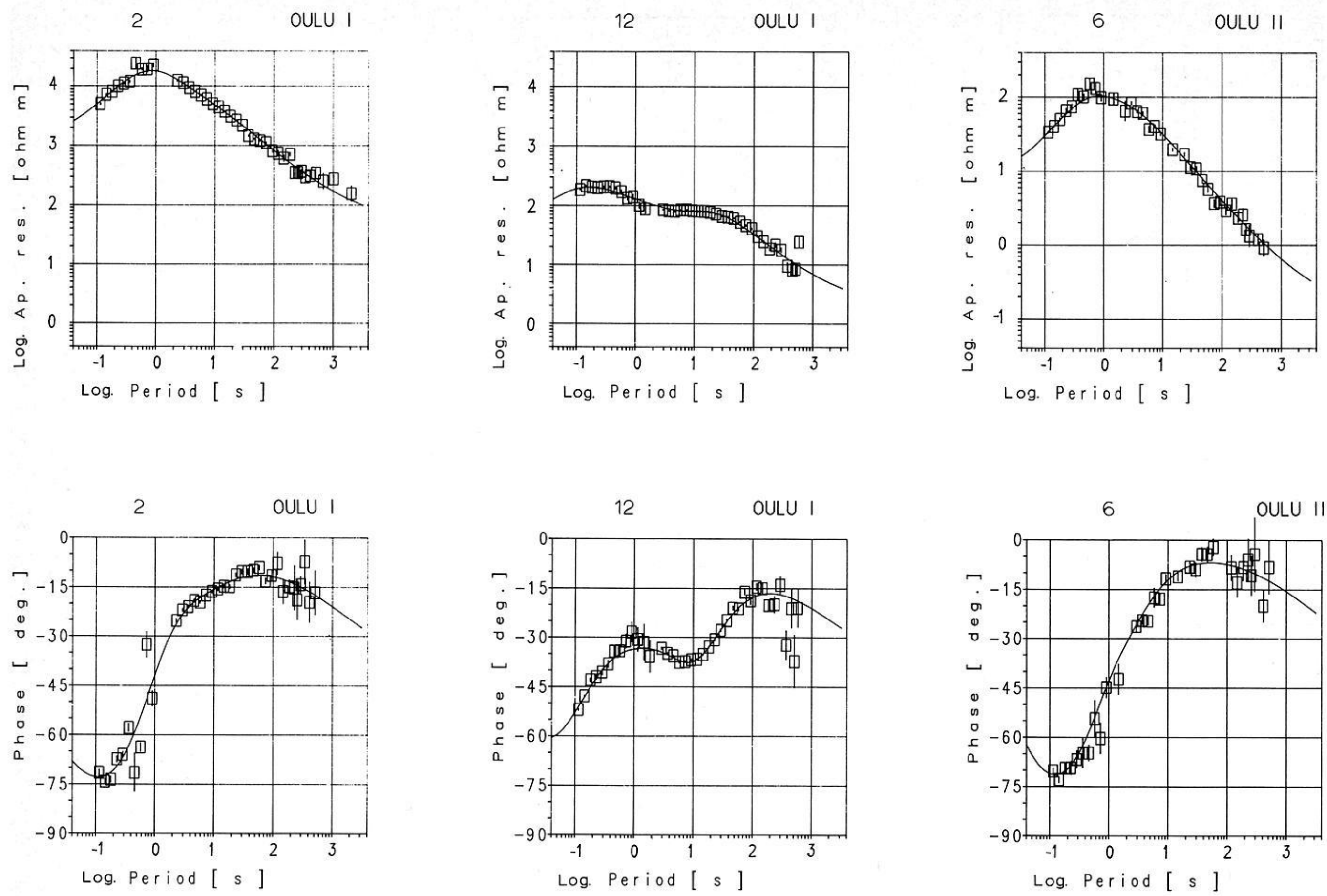


Fig. 5. Apparent resistivity and phase curves and corresponding 1D-fitting curves from MT sites 2/OULU I, 12/OULU I and 6/OULU II. *Squares* represent measured EW data (telluric line direction = EW, *H*-polarization) and *solid line* best fitting the data. Corresponding models are shown in Fig. 6. *Vertical bars* show the 68% confidence limits. Apparent resistivity values and periods are presented in logarithmic scale

(from 4 to 12) is similar, both in magnitude and frequency dependence. The phase shows some differences from site to site. The apparent resistivity at station 14, at the south-western end of the profile, is one order of magnitude greater than at the central stations.

The data along profile OULU II shows similar behaviour to that along profile OULU I. Stations 1 and 3 and station 9, at either end of the profile, were resistive compared to the central stations (5–8) (stations 2 and 4 produced no useful data). The east-west component at station 9 is anomalous in both amplitude and phase especially at periods 1 s and longer. The apparent resistivity changes too rapidly with frequency to be consistent with induction in a "one-dimensional" Earth by a uniform inducing field. The phase (over 90°) is also inconsistent with "one-dimensional" induction. As the data is of high quality, this is presumably a manifestation of two- or three-dimensionality within the Earth. In some sites on both profiles the so-called static shift or parallel shift phenomena in apparent resistivity curves due to the horizontal and vertical current gathering in three-dimensional resistivity heterogenities (Park, 1985) can be seen. For instance, the shape of the apparent resistivity curve of site 8 on profile OULU II is similar to those of sites 5, 6 and 7 but the curve is sifted downwards, which means that site 8 is closer to an edge of the conductive body. Also, when comparing the EW apparent resistivity curve of 1/OULU II and 3/OULU II, it can be seen that at the longer periods (over 1 s) 3/OULU II is shifted downwards due to the fact that it is closer to the conductive zone under sites 5, 6, 7 and 8/OULU II.

One-dimensional modelling of the MT data

One-dimensional inversion, by using the program of Johanssen (1977), was undertaken for all stations on both measuring directions (north-south and east-west). Figure 5 shows some examples of the data fit in EW direction, i.e. in *H*-polarization. In most cases a one-dimensional model can give us quite a reasonable fit to the data. It indicates that to some extent the measuring area can be approximated by a one-dimensional model; at least it can give us some general ideas about the geoelectric structure in the area. Figure 6 shows the results of 1D inversion of the east-west apparent resistivity and phase (*H*-polarization) for all sites along both profiles. The *H*-polarization was chosen, instead of *E*-polarization, on a conductive zone mainly because at some sites we had rather poor data in *E*-polarization (not shown on Fig. 4).

From these one-dimensional "cross-sections" we can clearly see that on both profiles there exists a highly conducting layer in the middle part of the profiles. The depth to the conducting layer is about 7 km for profile OULU I

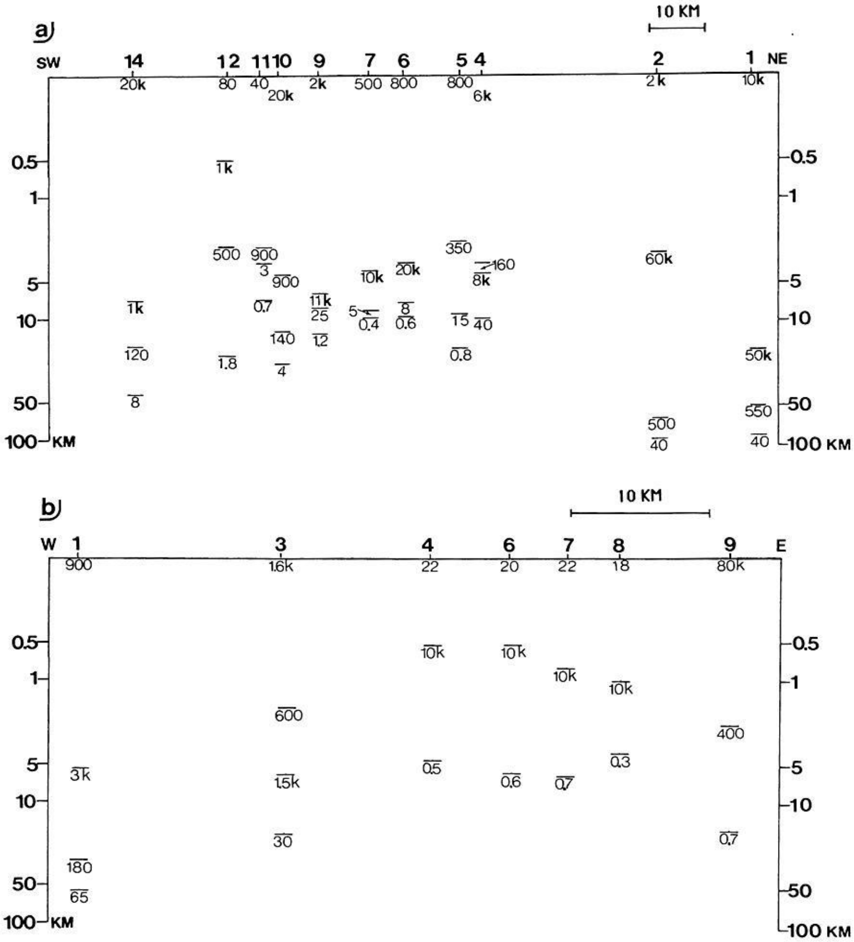


Fig. 6a and b. Geoelectrical cross-section obtained from the 1D modelling of the data measured in EW direction (*H*-polarization). **a** the cross-section from OULU I and **b** from OULU II. *Numbers* denote the resistivity value of the corresponding layer in ohm m ($k=10^3$)

and about 4 km for profile OULU II. The difference in depths is quite clear and, according to the SVD analysis, h_2 is really the best resolved parameter (A.G. Jones, personal communication). The different structure features, when comparing central parts with SW part of both profiles, indicate that there is a geoelectric boundary between the central and the SW parts. However, due to insufficient data we cannot locate the exact position of this boundary. On the contrary, a very clear geoelectric boundary was found on profile OULU I between sites 2 and 4. The SW part of the profile OULU I is generally more conductive than the NE part where no crustal conducting layer was identified, at least down to 100 km. On profile OULU II (at sites 5–8) the Muhos formation can be clearly identified. The resistivity value (20 ohm m) is of the same order as was found from borehole measurements, but the thickness of sediments ($\sim$400 m) is less than that from the borehole (950 m). This contradiction could be due to the lack of resolution of the parameters of the surface layer. According to the SVD analysis, h_1 is not well-resolvable (A.G. Jones, personal communication).

Two dimensional modelling of the MT data

On the basis of the one-dimensional inversion, a two-dimensional model was constructed for profile OULU I with north-south as a geoelectric structure direction. Modelling was performed using the program of Brewitt-Taylor and Weaver (1976). Figure 7 shows the data and response from profile 1 at two selected periods, 100 s and 10 s, for both *E*- and *H*-polarization. The final two-dimensional model is shown in Figure 8. At some stations it was impossible to obtain a good fit to the data (especially to the phase). This may be due to the presence of three-dimensional structure within the Earth. While such three-dimensional effects clearly have some significance to the inversion and modelling procedures, we believe that the models presented here are a valid first approximation. This two-dimensional model also presents a conducting zone at a depth of 7 km to the east and 14 km to the west with a conductivity less than 5 ohm m (even 0.5 ohm m at its central part). Both depths, i.e. depths to the upper surface of the conductive zone, appear well resolved. It is not possible to decide how far southwest this layer extends but by the data from station 14 (OULU I) we can suppose that this site is beyond the conductive zone (or the most conductive zone) or close to its edge. The northeast part of profile 1 is on a very resistive area; down to about 100 km we are still unable to find any conducting layer. Towards the southwest the lower crust becomes quite conductive but, due to the "skin-depth effect", we cannot get more detailed information about the deeper structure. In this case the two-dimensional model in the southwest part below 30 km is very uncertain.

As seen in Fig. 3b the MV anomaly axis agrees with the MT model, although the MT model is very wide. As discussed above, the anomaly determined from MV is strongly frequency dependent. At 500 s the strongest current concentration is clearly in the western part of the MT

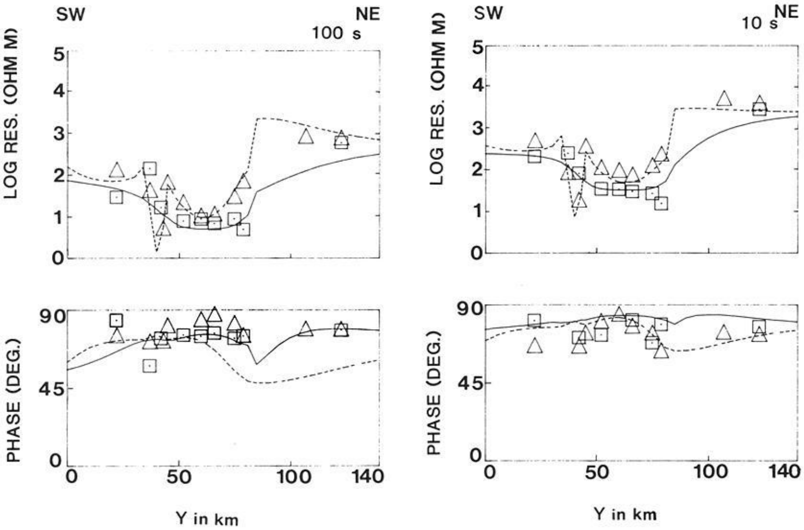


Fig. 7. The 2D model data fitted to measured data along profile OULU I. *Squares* represent the data measured in NS direction, *triangles* in EW direction, the *solid line* represents the model response in NS direction (*E*-polarization) and *dashed line* in EW direction (*H*-polarization). Both apparent resistivity and phase curves are shown at two periods, 10 s and 100 s

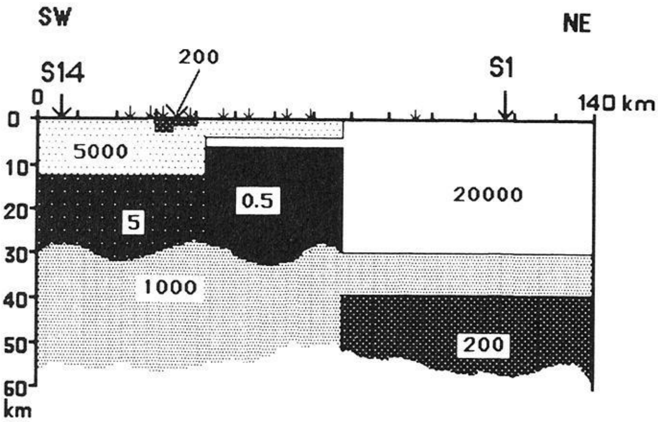


Fig. 8. The final 2D model from OULU I. The model corresponds to the data fit shown in Fig. 6. *Numbers* are the resistivities in ohm m

model. However, at 100 s both methods give about the same northeastern border for the anomaly. The MT method does not give any variations inside the conductive block.

Discussion

In this paper we have presented results from an electromagnetic study over the Oulu conductivity anomaly. The anomaly was located by MV measurements and thereafter studied by MT to obtain depths and conductivities. The anomalous body, with a very low resistivity of 0.5 ohm m, was found at a depth of 4–7 km. The thickness of the body proved to be unresolvable. To the west of the anomaly there was found to be a low-resistive crustal layer from a depth of 14 km probably down to 25–30 km. In the eastern part, no conductive crustal layer seems to exist.

A heat flow measurement from the borehole of Liminka (Järvimäki and Puranen, 1979) gave a heat flow value of 43.8 m W/m^2. No glacial corrections have been performed for these values. According to Parasnis (1975), a glacial correction increased a heat flow value by 10%–20% in Sweden, which would also apply in Finland. The borehole lies 5 km north of MT sites 5 and 6 on the Muhos formation. Using this heat flow value, the 2D model of profile OULU I and the procedure described by Shankland and Ander (1983), data were transformed into log (conductivity) versus 1/temperature scale. Data from low-conductivity layers are in good agreement with the data from LCLs (low conductivity layers) of stable zones (Shankland and Ander, 1983, Fig. 6), while logσ versus 1/T values from those very conductive layers (0.5 and 5 ohm m) are anomalous – they stand even above the limit of "wet" granite with 1%–2% water. If the 10%–20% glacial correction is taken into account, it increases temperature and decreases 1/T which means that logσ versus 1/T values from 0.5 and 5 ohm m layers come closer to the limit of "wet" granite.

The liquids in the porous rocks have been mentioned as possible highly conducting material in the upper crust, for example on the Skellefte field in northern Sweden (Pedersen et al., 1985). In the Oulu anomaly the liquids could originate from the mantle during tectonic movements when the Svecofennian crust overthrusted the Archean realm. On the other hand, the superdeep well at Kola in the Soviet Union has revealed a zone of hydraulic disaggregation of metamorphic rock accompanied by microfracturing at a depth of 4,500–9,000 m (Kozlovsky, 1984). In that zone, numerous flows of highly mineralized water, "water of crystallization", were found. This kind of thick Archean brine zone could also help in explaining the origin of the Oulu anomaly, although, at least in the western part, the thickness of the conductive body seems to be much larger than the "water zone" in Kola. Also, as stated above, to explain this anomaly by free water in rocks (assuming rocks to be granites) the water content must be very large. If the same situation, that free water increases conductivity, is also valid for other rocks, the anomaly could be explained by more conductive rocks than granite added to the effect of fluids in rocks. The lack of the conducting material in the uppermost few kilometres could be explained by the younger igneous rocks above the thrust zone.

Acknowledgements. This work was performed under the research projects "Deep EM research in Finland" (055), "The deep geoelectric model of the Baltic Shield" (111) and "Geoelectrical studies of the crust and upper mantle in the Baltic Shield" (04/111) all financed by the Academy of Finland with additional support from the University of Oulu and the University of Uppsala. The authors wish to return many thanks to Prof. S.E. Hjelt, the leader of the project, for the support and advice along the course of this work as well as to Prof. L.B. Pedersen for much advice and for the loan of the MT stations. The magnetometers were on loan from the University of Münster with the kind help of Prof. Untiedt. Dr. Alan Jones gave us useful comments and very kind help in SVD analysis. Our best thanks to him. The authors are also very grateful to Dr. R.G. Roberts, T. Rasmussen, K. Koivukoski, P. Kääntee, J. Heikka and H. Juntti for help during the field work and for useful discussions. Thanks to Prof. K. Laajoki and Lic. T. Pernu are also deserved for their useful comments and discussions.

References

Berthelsen, A.: The tectonic division of the Baltic Shield. Proceedings of the First Workshop on the European Geotraverse (EGT), the Northern Segment. European Science Foundation, 13–22, 1984

Brewitt-Taylor, C.R., Weaver, T.J.: On the finite difference solution of two dimensional induction problems. Geophys. J.R. Astron. Soc. **47**, 375–396, 1976

Fowler, D.F., Kotick, B.J., Elliott, R.D.: Polarization analysis of natural and artifically induced geomagnetic micropulsations. J. Geophys. Res. **12**, 2871–2883, 1967

Gamble, T.D., Goubau, W.M., Clarke, J.: Magnetotellurics with a remote magnetic reference. Geophysics **44**, 53–68, 1979

Hjelt, S.E., Kaikkonen, P., Pajunpää, K., Korja, T., Heikka, J.: Electromagnetic studies of the Baltic Shield in Finland. Ann. Geophys. 1985 (in press)

Jepsen, J.B., Pedersen, L.B.: Evaluation of tensor AMT measurement system. Laboratory of Geophysics, Aarhus Univ. Geoskrifter **15**, 1981

Johanssen, H.K.: A man/computer interpretation system for resistivity soundings over a horizontally stratified Earth. Geophys. Prosp. **25**, 667–691, 1977

Jones, A.G.: Geomagnetic induction studies in Scandinavia II. Geomagnetic depth sounding, induction vectors and coast-effect. J. Geophys. **50**, 23–36, 1981

Jones, A.G., Olafsdottir, B., Tiikkainen, J.: Geomagnetic induction studies in Scandinavia III. Magnetotelluric observations. J. Geophys. **54**, 35–50, 1983

Järvimäki, P., Puranen, M.: Heat flow measurements in Finland. In: Terrestial heat flow in Europe, V. Cermak and L. Rybach, eds.: pp , Berlin Heidelberg New York, Springer-Verlag 1979

Kozlovsky, Ye.A.: The world's deepest well. Scientific American, December 1984, 106–112, 1984

Küppers, F., Post, H.: A second generation Gough-Reitzel magnetometer. J. Geomagn. Geoelectr. **33**, 225–237, 1981

Küppers, F., Untiedt, J., Baumjohann, W., Lange, K., Jones, A.G.: A two-dimensional magnetometer array for ground-based observations of auroral zone electric currents during the International Magnetospheric Study (IMS). J. Geophys. **46**, 429–450, 1979

Laajoki, K.: The main tectonic features of the Baltic Shield in Finland. In: The development of the deep geoelectric model of the Baltic Shield, Part 2. Proceedings of the 1st project symposium, Oulu 15–18 November 1983, S.E. Hjelt, ed.: pp. 233–244. Dept. of Geophysics, Univ. of Oulu, Report No. 8., 1984

Lange, K.: Inductionseffekte in Nordskandinavien – untersucht am Beispiel zweier ostwärts fliessender polarer Elektrojets. Dipl. thesis, Universität zu Münster, 160 pp, 1979

Pajunpää, K.: Magnetometer array studies in Finland – determination of single station transfer functions. J. Geophys. **55**, 153–160, 1984

Pajunpää, K., Heikka, J., Korja, T.: Magnetometer array studies in Finland. J. Geomagn. Geoelectr. **35**, 543–553, 1983

Parasnis, D.S.: Temperature phenomena and heat flow estimates in two Precambrian ore-bearing areas in North Sweden. Geophys. J.R. Astron. Soc. **43**, 531–554, 1975

Park, S.K.: Distortion of magnetotelluric sounding curves by three dimensional structures. Geophysics **50**, 785–797, 1985

Pedersen, L.B., Svennekjär, M.: Extremal bias coupling in magnetotellurics. Geophysics **49**, 1984

Pedersen, L.B., Rasmussen, T., Roberts, R.G., Zhang, P.: Remote reference magnetotellurics at Uppsala University. Paper presented at the XV Scandinavian Geophysicist Meeting (NOFTIG), Espoo, Finland, 15–17 January 1985

Pernu, T.: Studying of soil and bedrock structures with DC-resistivity measurements especially in Finnish conditions (in Finnish). Lis. thesis, Univ. of Oulu, 99 pp. 1979

Roberts, R., Zhang, P., Pedersen, L.B.: Remote reference magnetotelluric measurements (0.1–10 s) across the mylonite shear zone in southern Sweden. In: The development of the deep geoelectric model of the Baltic shield, Part 2. Proceedings of the 1st symposium of project no. 13 between the Academy of Finland and the Soviet Academy of Sciences, Oulu, 15–18 November 1983, S.E. Hjelt, ed.: pp. 328–339, Dept. of Geophysics, Univ. of Oulu, Report no. 8, 1984

Rokityansky, I.I.: Geoelectromagnetic investigation of the Earth's crust and mantle. New York: Springer-Verlag 1982

Shankland, T.J., Ander, M.E.: Electrical inductivity, temperatures and fluids in the lower crust. J. Geophys. Res. **88**, 9475–9484, 1983

Simonen, A.: Precambrian in Finland. Geological Survey of Finland, Bull. **304**, 1980

Received April 22, 1985; Revised version September 9, 1985
Accepted September 9, 1985