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Magnetometer array studies in southeastern Finland on the Baltic shield

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Abstract. Results of two magnetometer array studies on the Baltic shield in southeastern Finland are presented. The first array consisted of 29 Gough-Reitzel type magnetometers recording for about 2 months during autumn 1982. The results indicated two nearly perpendicular anomalous current concentrations crossing the array. The other operation, in 1983, with denser magnetometer spacing, revealed more detailed information about these anomalies.

Magnetograms, induction vectors, hypothetical event maps and profile data are presented to show the spatial behavior of the magnetic field variations, and to locate the anomalies. The east-west striking Mikkeli anomaly is thought to be continuous across the whole array. Two-dimensional modelling of one profile found this anomaly at a depth of 12 km. The Outokumpu anomaly is interpreted to lie at a greater depth than the Mikkeli anomaly, separating the very resistive Archaean eastern Finland from the less resistive Svecofennian central Finland.

The results are compared with electromagnetic deep soundings around Lake Ladoga in the Soviet Union and with deep seismic soundings in Finland. The Outokumpu anomaly and a discontinuity in the Moho depth appear to be related. The continuation of the Ladoga electric anomaly to Finland is not fully understood on the basis of the present results.

Key words: Magnetometer arrays – Conductivity anomalies – Crustal structures – Baltic shield

Introduction

The electrical structure of the earth's crust in central and southern Finland was studied with six magnetometer arrays during 1981–1984. These studies, together with magnetotelluric soundings and some controlled source measurements, formed part of an electromagnetic deep structure research project organized by the University of Oulu (Hjelt et al. 1985). Two of the six magnetometer arrays covered south-eastern Finland. This paper describes the results of these two operations, presenting anomalous zones and relating them to deep electromagnetic sounding data around Lake Ladoga, deep seismic results, and to some tectonic features, are presented.

The first of the two arrays in south-eastern Finland was operated in the autumn of 1982. Twenty-nine modified Gough-Reitzel magnetometers, on loan from the University of Münster (Küppers and Post, 1981), formed three lines 50 km apart, running northeast from the coast of the Gulf of Finland for about 300 km. This array was numbered IV and the three lines, shown on Fig. 1, were labelled G, H and I. Nearly parallel to these lines, in the same region, is the Baltic deep seismic sounding profile measured in August 1982 (Luosto et al. 1984a). Southeast of this array, in the Soviet Union, Rokityansky et al. (1979) have traced an electric anomaly under Lake Ladoga to the Finnish-Soviet border.

The preliminary results of array IV were available in early 1983, and were published together with data from three previous arrays by Pajunpää (1983, 1984). Two zones of intense concentration of induced currents were observed; the first, running north-south across the array, was named the Outokumpu anomaly and the other, running nearly east-west, was named the Mikkeli anomaly.

The other array in this region, numbered V, was designed to cover some interesting regions with a denser spacing. It was divided into two parts, with 15 magnetometers on the western end of the east-west striking anomaly (lines O, P and Q in Fig. 1) and 14 on the I line along the Finnish-Soviet border. The interesting central part of the array IV had to be excluded because it has many lakes and few roads. The station spacing on the lines was 10–30 km, and the array was operated during summer 1983.

The arrays operated for about 2 months, the data being stored on analogue films with a recording interval of 10 s. The amplitude resolution for the field variations is 2–3 nT. Over 90% of all recordings were useful.

Events and data processing

Three events of 2–4 h length from both arrays were digitized and analysed for the intervals listed in Table 1. The arrays were located between latitudes 56° and 58° geomagnetic north. The events were chosen with special care to avoid source field effects on transfer functions, as discussed in a previous paper by Pajunpää (1984). Only the wavenumber estimates for each event are presented in Table 1. The estimates are the average of the mean wavenumbers for 100–500-s periods and the values correspond to spatial wavelengths of 1000–3000 km.

After magnetograms had been drawn, the data for each station and event were processed with a method described

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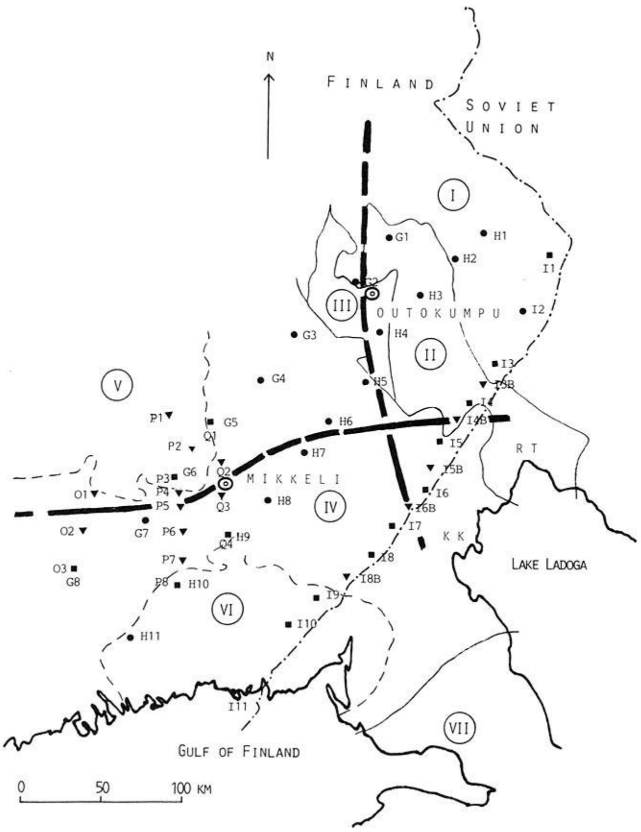

Fig. 1 a. Measured arrays on a map showing the anomalous zones and the main geological units according to Laajoki (1983). *Circles* are stations measured in 1982, *triangles* those measured in 1983 and *squares* are those measured in both operations; *I* Archean basement; *II* karelian schist belt; *III* Outokumpu allochton; *IV* Svecokarelidic supracrustal and plutonic rocks; *V* Central Finland granite area; *VI* Rapakivi rocks; *VII* Paleozoic and younger rocks. **b** Location of the research area on a tectonic map of the Baltic shield (Laajoki, 1983). *3* the Ladoga – Bothnian Bay zone; *5* the Outukumpu allochthon

Table 1. Events

Event number	Date	Time (UT)	Length (h)	Array	Lines	Wavenumber (km^{-1})
5	1982–10–26	1000–1300	3	IV	G,H,I	0.03
6	1982–11–25	0500–0700	2	IV	G,H,I	0.06
13	1982–11–24	1000–1300	3	IV	G,H,I	0.06
15	1983–05–25	0100–0400	3	V	I,O,P,Q	0.02
16	1983–06–18	0400–0800	4	V	I,O,P,Q	0.03
22	1983–07–23	0800–1200	4	V	I,O,P,Q	0.03

by Jones (1981) to obtain smoothed auto- and cross-spectral estimates. Thereafter, all data at each station were combined for the final transfer function estimates. As acceptance criteria and weighting functions firstly, the bias-reduced multiple coherence function (>0.8) between the vertical and the horizontal components (Jones et al. 1983) and, secondly, the product of the spatial wavenumber k and the inductive scale-length C ($kC<0.3$) (Pajunpää, 1984) were used.

Magnetograms

Since the magnetograms of event 5 have been presented by Pajunpää (1984), only those stations showing the maximum amplitudes of the horizontal components are repeated here. The northward component, X, has high amplitudes at stations G7, G4, H6–H7 and I4, while the eastward component, Y, has a maximum at stations G7–G8, H5 and I6.

The magnetograms from line P of event 22 are presented in Fig. 2. Line P crosses and is nearly perpendicular to the Mikkeli anomaly, as shown by the strong increase in the X component at station P4 and the rather flat Y component. The vertical component Z has a clear phase-reversal between P4 and P6, for which data are modelled below.

Induction vectors

Figure 3 shows the reversed real induction vectors at periods of 100, 215, 464 and 1000 s. The corresponding unreversed imaginary induction vectors, with 68% confidence intervals for the transfer function estimates, are shown in Fig. 4. The confidence intervals, which do not necessarily include the possible source-field error, are greatest at 100 and 1000 s and smallest at the mid-periods. This is mainly due to the number of data that were accepted for the different periods. At 100 s the low coherence between vertical and horizontal components and at 1000 s the large inductive scale length, C, with regard to the horizontal scale length, k, reduced the number of accepted data.

The following observations were made about the real induction vectors:

1. There is a clear reversal in the southwest between stations O1–O2, P4–P6 and Q2–Q3.

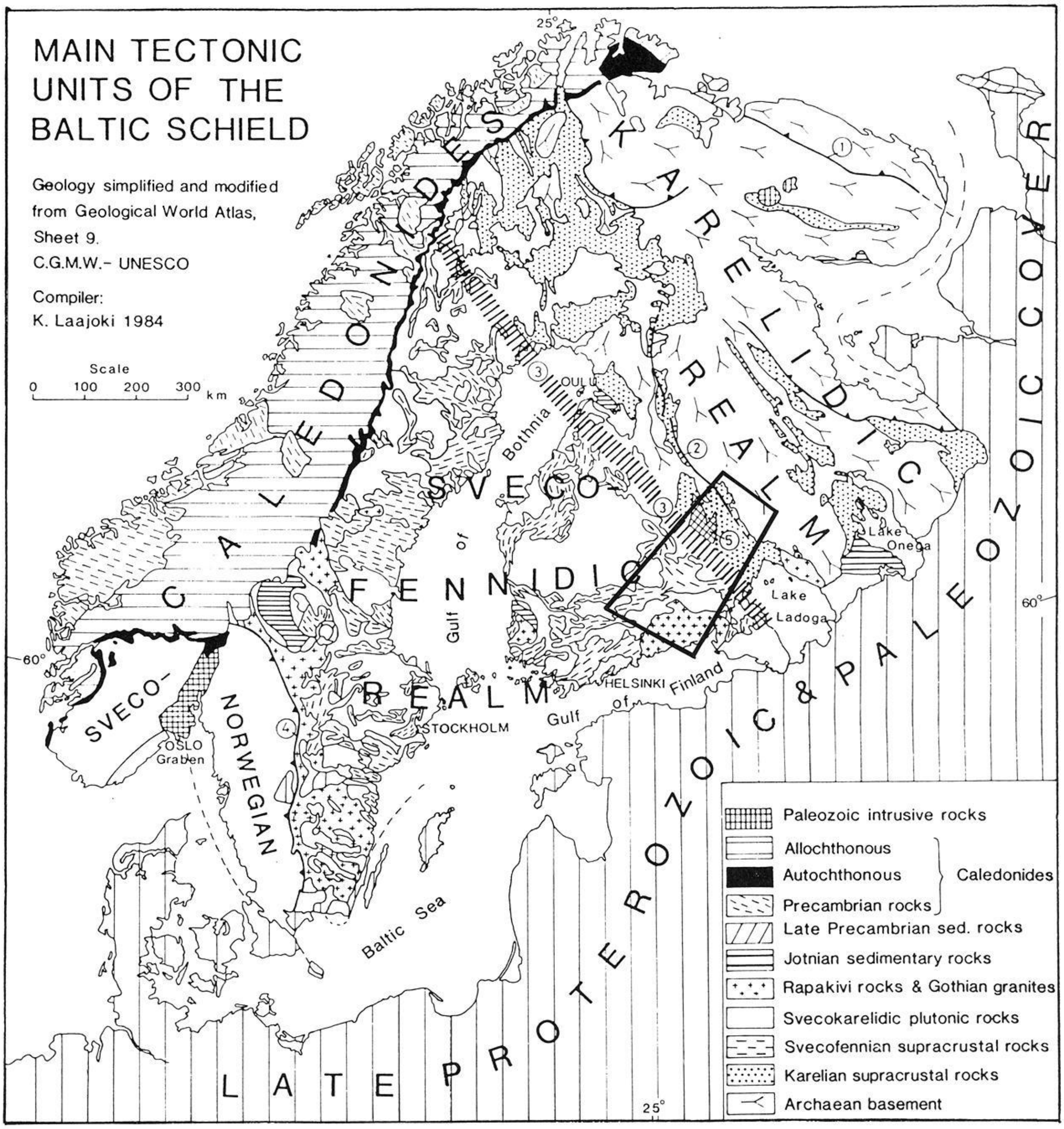

Fig. 1 b

2. The vectors decrease in length towards the coast in the south.

3. There are very large vectors in the northeast.

4. There is a reversal between stations I6–I7 and H4–H6.

5. There is a reduction in the magnitude from I3 to I5 at 100 s and to I6B at 1000 s.

These vectors clearly represent the east-west directed current concentration in the west. The southern and northeastern parts seem to be electrically homogeneous whereas the central part is extremely complex. The shallow Gulf of Finland appears to have no effect at these periods.

The real induction vectors are more reliable than the imaginary ones. However, some observations about the imaginary vectors included:

1. the reversal between P4–P6, both vectors pointing away from the anomaly;

2. the reversal between G1–G2 at 100 s; and

3. the rather short length of all the imaginary vectors compared to the real ones.

The last point may indicate that the currents are mainly not shallow and that the conductivity contrasts are very high.

Hypothetical event maps

Following the method of Bailey et al. (1974) of presenting transfer function data for specific polarizations, hypothetical event maps were computed for two periods, 100 and 1000 s, and for two polarizations. Figure 5 shows the real part and Fig. 6 the imaginary part of the hypothetical vertical field for the polarizations shown on the figures.

The most striking feature in the real-part maps is the strong gradient in the west for the southward inducing field.

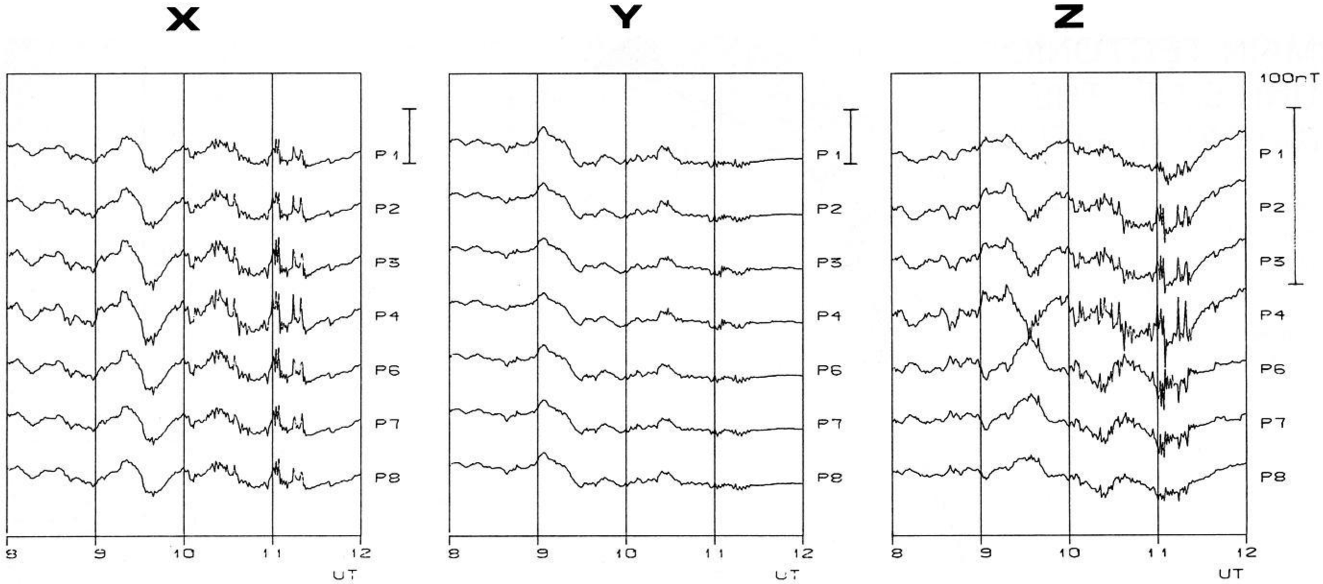

Fig. 2. Magnetograms of a substorm at 0800–1200 UT on July 23, 1983, for the P line

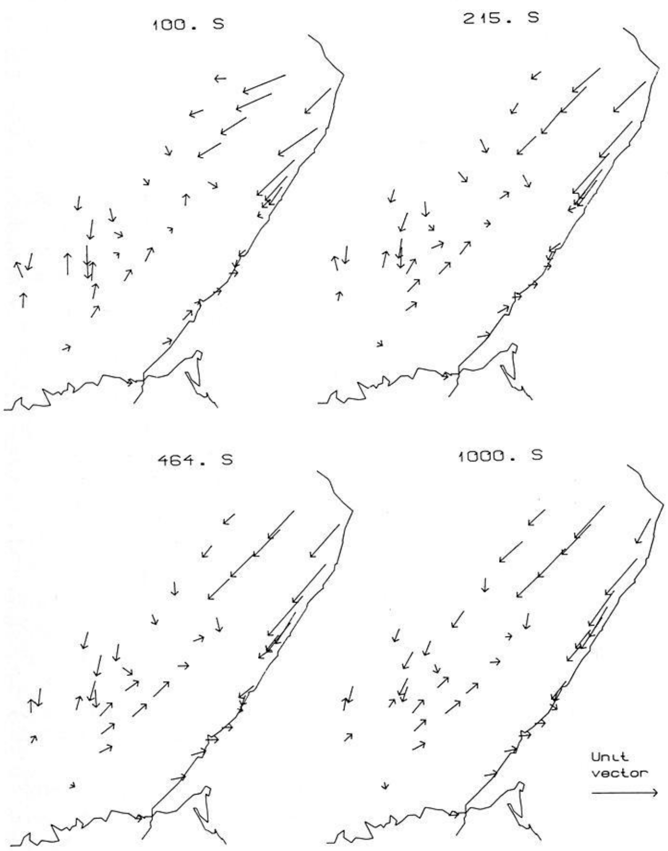

Fig. 3. Reversed real induction vectors

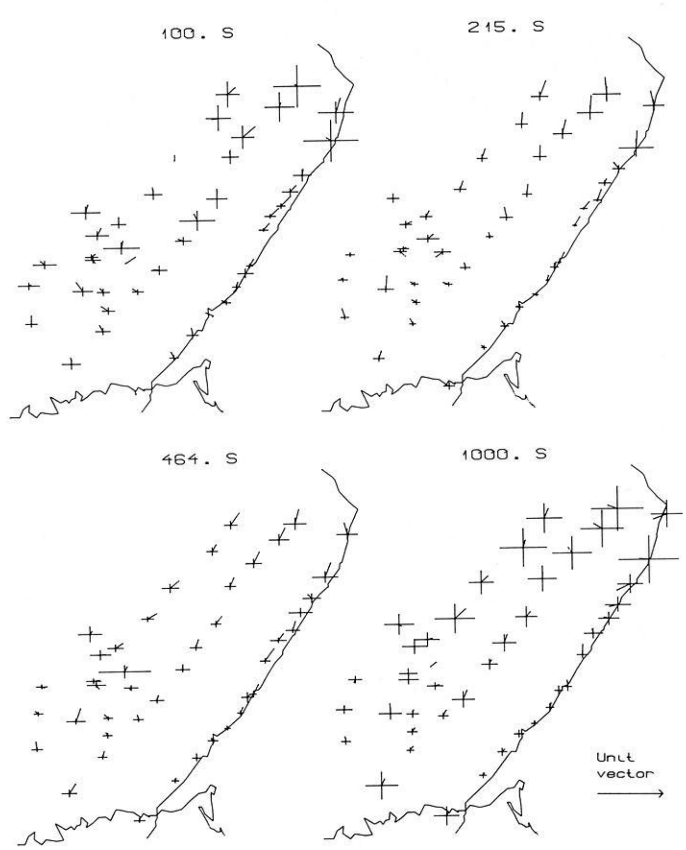

Fig. 4. Unreversed imaginary induction vectors with 68% confidence intervals

The anomaly seems to be very narrow and continues in the west of the array, but in the east it seems to turn northeast and diverge somewhat. Between H5 and H6 a strong gradient can be observed again, and then the two periods behave differently on line I; at 100 s, the stronger gradient is between I3 and I5 and at 1000 s between I6 and I7. For the westward inducing field, the western anomaly is observed only at 1000 s. A large gradient is observed in the northeast at 100 s, while at 1000 s, again, the gradient seems stronger around I6.

The imaginary maps for the southward polarization give only a weak indication of the anomaly in the southwest.

At 1000 s there is some anomalous behavior around I3–I4 and at 100 s between G2 and H3. The westward polarization indicates the anomaly between G2 and H3 more clearly at 100 s but it cannot be seen at 1000 s. Obviously this mainly north-south current concentration, which has a clear out-of-phase response, is very shallow.

Profile data on the I line

The I line appears to have a very complex magnetic field response. To give a more precise idea of the induced currents on this line, Figs. 7 and 8 show the behaviour of the transfer functions and of the horizontal field amplitude as north-south and east-west projections of this line. The horizontal field has been normalized by the mean value of the corresponding component at stations I1, I3 and I10 for the X-component and at I3 and I10 for the Y component.

Although neither of the directions agrees with the I-line direction, these projections show some interesting features. There is a very high transfer function amplitude in the north-east. The X-component in the north-south projection has a very high amplitude at the station I4B, with a rather broad maximum, its half-width being some 50 km. Almost nothing is seen of the Y component, showing that the current flows in the east-west direction. The large half-width of the anomaly is probably not directly related to the depth of the current; rather, it implies that the current flow itself is wide. This explanation is preferable because the field decreases sharply towards longer periods. The maximum response is at about 200 s.

The maximum anomaly in the Y component is at station I6B, some 50 km southwest of I4B. Here, also, the X component has a low anomaly, with about the same frequency response as the Y component, revealing that the mainly north-south directed current also has an east-west component. The maximum response of this anomaly is at about 500 s and clearly lasts for longer periods than the other anomaly.

Two-dimensional modelling on the P line

The hypothetical event maps in Fig. 5 show that the Mikkeli anomaly is a narrow zone striking west from the P line. In the east it turns northeast and obviously diverges, indicating that on the P line, where the best data are available, the current flow is not purely two-dimensional. Obviously, the anomalous field is increased in the north and decreased in the south due to the geometry. However, a two-dimensional model was constructed to estimate the depth of the anomaly. The model is shown on Fig. 9 together with measured and calculated transfer function data. The finite difference method was used, with a program written by Brewitt-Taylor and Weaver (Brewitt-Taylor and Weaver, 1976; Weaver and Brewitt-Taylor, 1978).

The model consists of a good conducting (0.5 ohm m) body at a depth of 12 km, with an area of 5×5 km^2 and total areal conductivity of 5×10^7 Sm. At the surface there is another good conducting (2 ohm m) body, representing the schists and especially affecting the imaginary part of the field. The resistivity of the host rock is 10000 ohm m down to 50 km and 200 ohm m below that. This one-dimensional structure is rather arbitrary and the data cannot resolve it. To the south of the anomaly a low-resistive layer (80 ohm m) is used to explain the asymmetry of the anomaly, although this layer may not be obvious because the asymmetry of the anomaly can be explained also by the three-dimensionality of the anomaly. However, it coincides with a low-velocity layer under the Rapakivi area observed in the deep seismic sounding on the Baltic profile (Luosto et al. 1984a). It was very difficult to find a model that would explain the asymmetric behavior satisfactorily at all periods from 100 to 1000 s. However, it was always necessary to have the good conducting body at a depth of 10 or 12 km. That depth and the total conductivity of the body are the main and most reliable results of this modelling.

Results and discussion

The two main anomalous zones in the research area are (Fig. 1):

1. the east-west striking Mikkeli anomaly and
2. the north-south striking Outokumpu anomaly.

The Mikkeli anomaly lay below about 10 km on the P line, with a maximum response on both the P and I lines at about 200 s. The total longitudinal conductivity of the two-dimensional model is 5×10^7 Sm. In the western part the Mikkeli anomaly is rather narrow, but in the east it is probably wider – some 10–20 km. Although the anomaly cannot be located as sharply on the H line as on the I and P lines, it seems to be continuous across the whole region.

On the geological map the Mikkeli anomaly is located mainly below the Svecofennian schist area. However, close to the Finnish-Soviet border it is clearly overlain by plutonic granites, while in the east it seems to lie below the Karelian schist belt. This anomaly cannot be explained by surface formations such as schist zones. Golod et al. (1983) have presented a map of the electrical conductance of the crust in Soviet Karelia, which shows, among other anomalies, a southeast-northwest striking zone of anomalous conductance exceeding 200 S. This zone meets the Finnish-Soviet border close to the same place as the Mikkeli anomaly, although its direction is rather different. Recent magnetometer array studies in southwestern Finland show that the Mikkeli anomaly continues far to the west along the schist belt, following the southern edge of the central Finland granite area.

The main tectonic outlines do not agree with the Mikkeli anomaly. The Ladoga-Bothnian Bay zone cuts the Mikkeli anomaly and the other tectonic lines are mainly north-south. However, some features coming from the northwest e.g. the Suvasvesi fault, end at a front close to the anomaly (T. Koistinen, 1985 personal communication).

The Outokumpu anomaly gives a maximum response at 500 s, and using the empirical data collected by Rokityansky (1982, fig. 106, p. 296), a total conductivity of about 10^8 Sm is obtained. Application of Biot-Sawart law and a line-current assumption for the Outokumpu anomaly to the data at 500 s on Fig. 8 gives depth estimates for the line current of 15–23 km, using seven stations from I5 to I9. Moreover, the currents are located between I6B and I7, with a horizontal scatter of less than 8 km. This means that the currents are very concentrated but, as the chosen east-west direction is not necessarily strictly perpendicular to the anomaly, the depth estimates can be regarded only as approximations. However, this result together with the frequency dependence indicates that the Outokumpu anom-

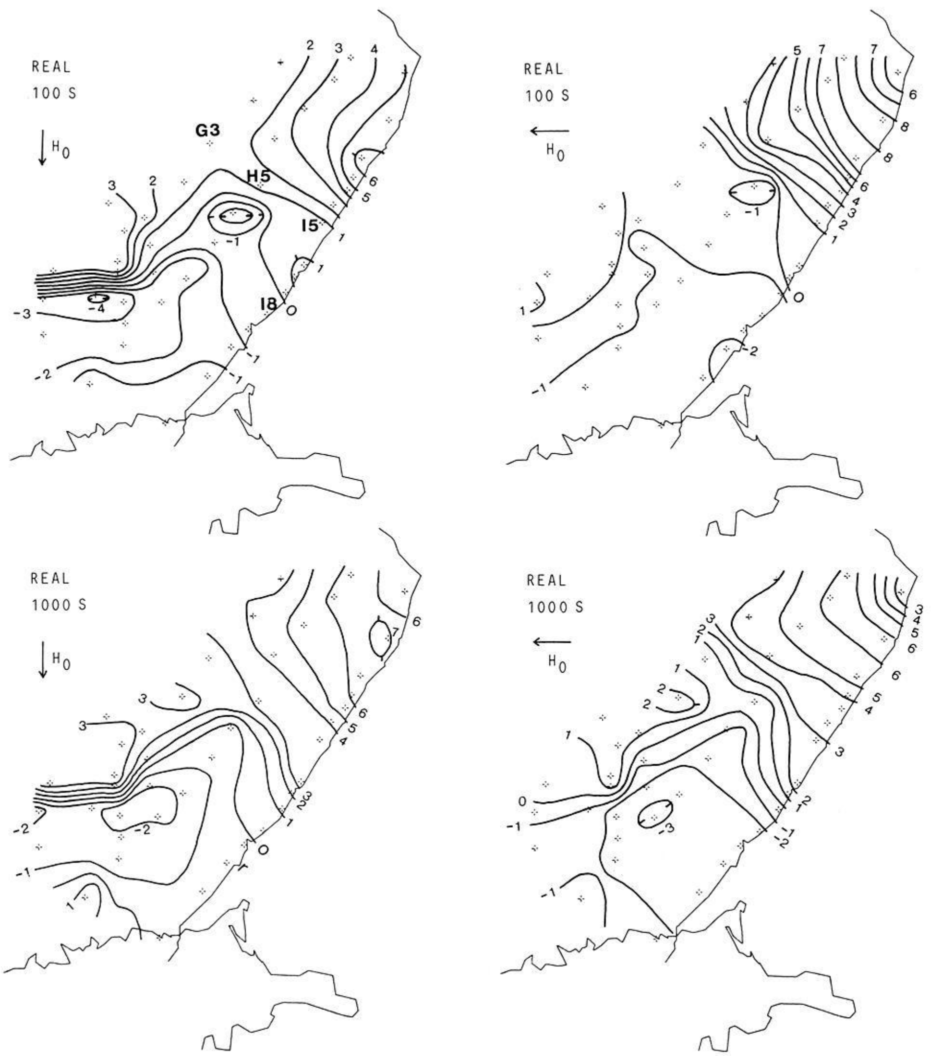

Fig. 5. Hypothetical event contour maps of the in-phase vertical field (× 10) generated by a unified, linearly polarized, horizontal field directed southward (left column) and westward (right column)

aly has a deeper origin than the Mikkeli anomaly. On the H line the Outokumpu anomaly can be located quite accurately close to station H6. North of this the currents seem to diverge to the northwest and the anomaly becomes a conductivity boundary. A new, shallow current concentration is observed in the Kainuu schist belt (Pajunpää, 1984). Under the Outokumpu allochthon the anomaly is shaded by a large number of shallow graphitic schist dykes that respond only to short-period variations and to the imaginary part of the Z-field as seen on Fig. 6.

Pajunpää (1984) showed that the Outokumpu anomaly continues as a conductivity boundary for about 200 km north of the Outokumpu allochthon. The Archaean basement and also the Karelian schist belt east of the anomaly are very highly resistive. West of this conductivity boundary the average resistivity of the crust is lower, and there are probably conductive layers, at least locally, as presented by Jones et al. (1983). In the north the conductivity boundary seems to fit with the Archaean Kuhmo schist belt. If the Outokumpu anomaly has the same origin in the south as in the north, the tectonic line of the Kuhmo schist belt must continue southward under the younger Karelian schists and Svecofennian formations. Nevertheless, there are large faults in the Ladoga-Bothnian Bay zone which clearly cut the Outokumpu anomaly but cannot be found in the available current data, although the anomaly (if it is connected with the Kuhmo schist belt) should be older than the faults.

Deep seismic soundings along the Baltic profile give interesting material for comparison. Preliminary results for this profile published by Luosto et al. (1984a) show that in the central part of the profile the Moho is more than 50 km deep. In the southwest and the northeast the crust is clearly thinner. The deepening of the Moho takes place slightly north or northeast of station G1 (see Fig. 1) and the Moho is clearly less than 50 km in the northeast. Some 200 km north of this station, Yliniemi (1985 personal communication) has reported an increase in crustal thickness of more than 10 km from east to west, near the Kuhmo schist belt and the northern part of the Outokumpu anomaly. Seismic results from the Sveka profile in central Finland (Luosto et al. 1984b) give a Moho depth of more than 50 km for the central and northern part of the profile. If the electrical conductivity boundary of the Outokumpu anomaly and the thickening of the crust are related to each other at the two places, the seismic boundary may coincide with the conductivity boundary.

Rokityansky (1983) has reviewed results of the electromagnetic soundings on the Baltic shield, including magnetic variation (MV) and magnetotelluric (MT) studies of the

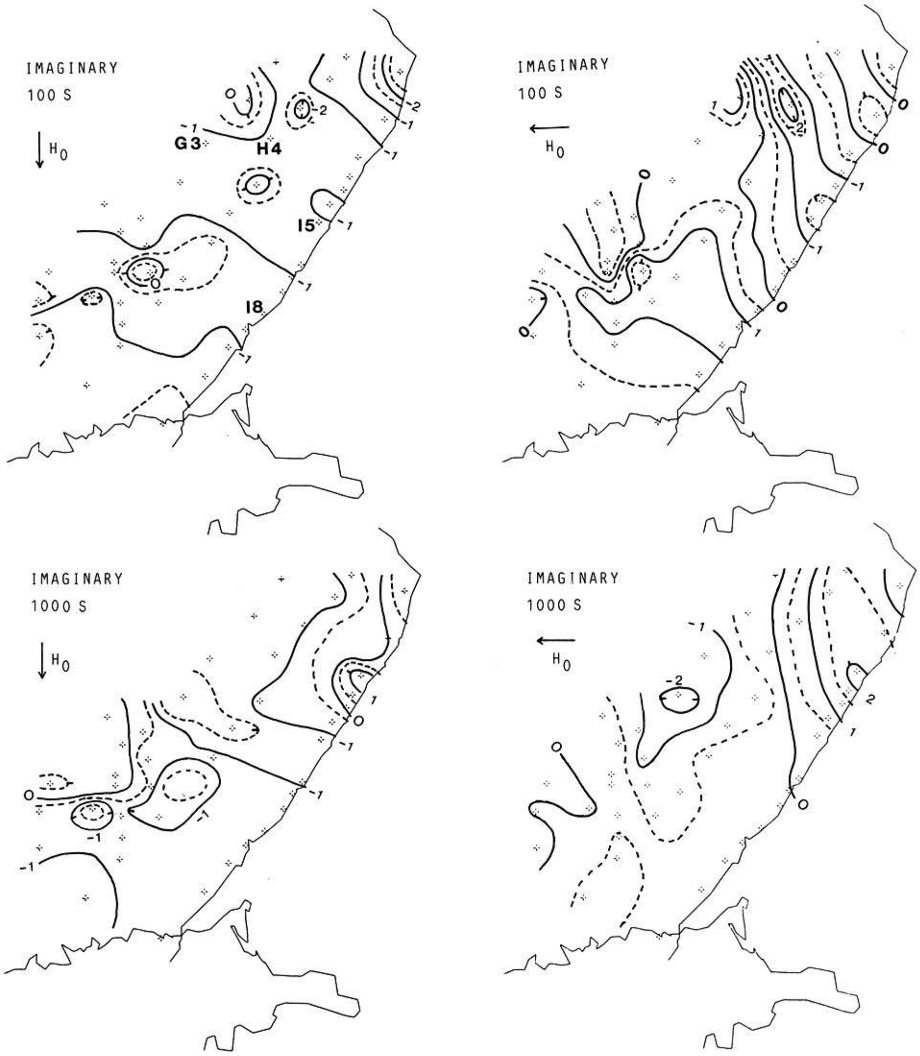

Fig. 6. Hypothetical event contour maps of the out-of-phase vertical field (×10)

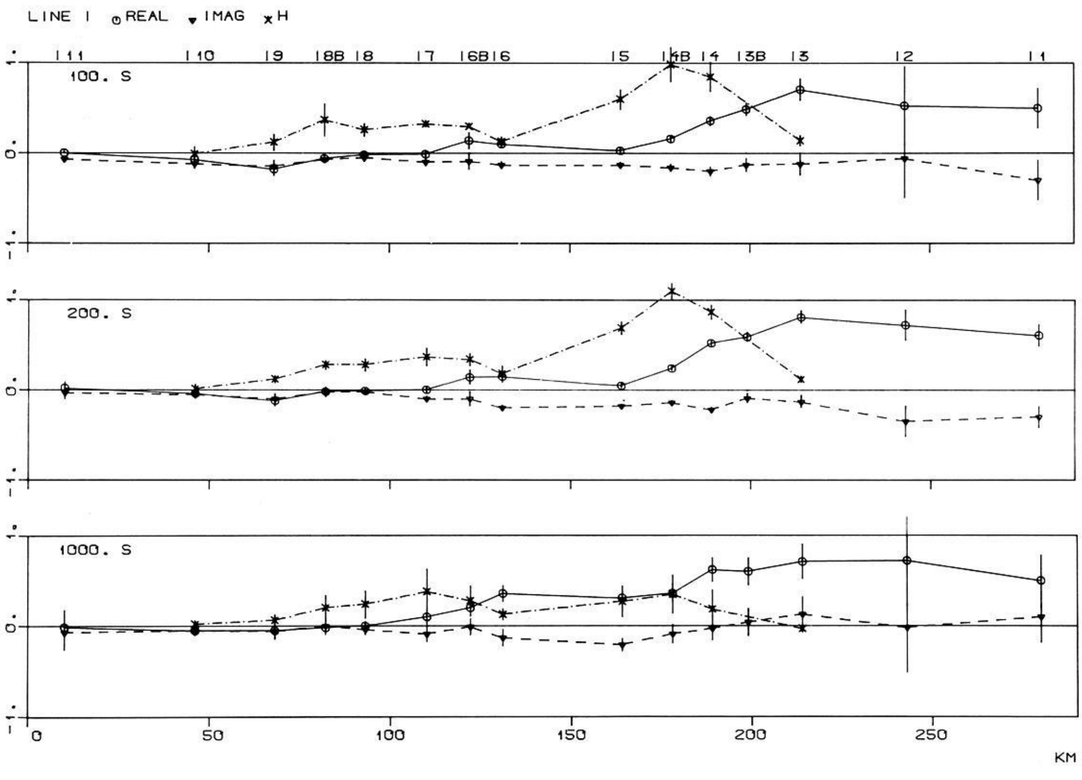

Fig. 7. North-south projection of the data on the I line. The *solid curve* with *circles* is the real part and the *dashed curve* with *triangles* the imaginary part of the transfer function with 68% confidence intervals. The *dashed-dotted curve* with *crosses* is the normalized amplitude of the horizontal north-south component with standard deviation

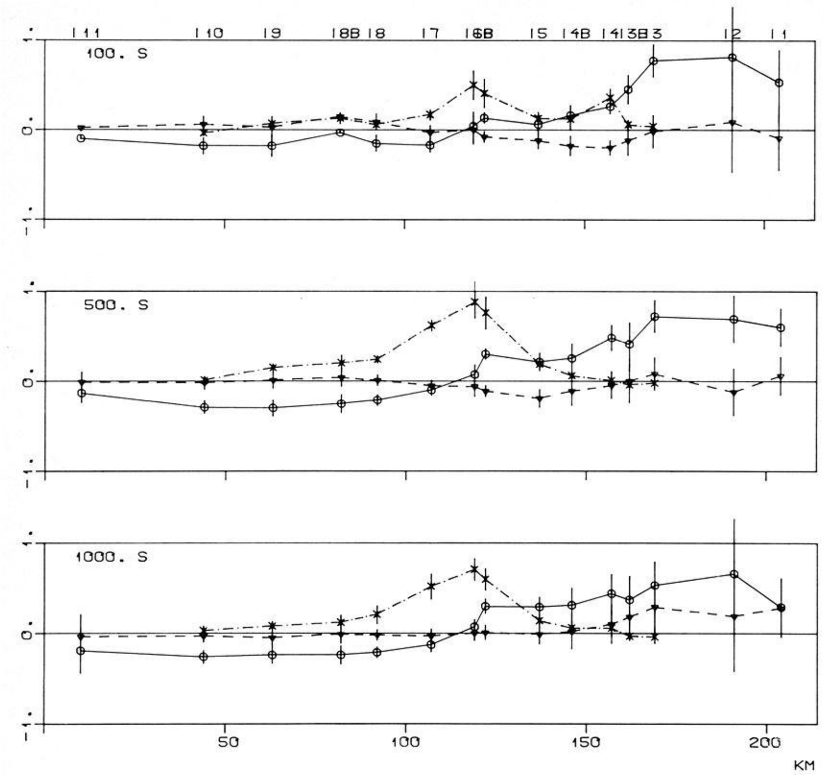

Fig. 8. East-west projection of the data on the I line. The curves are as shown in Fig. 7 except that east-west components are shown

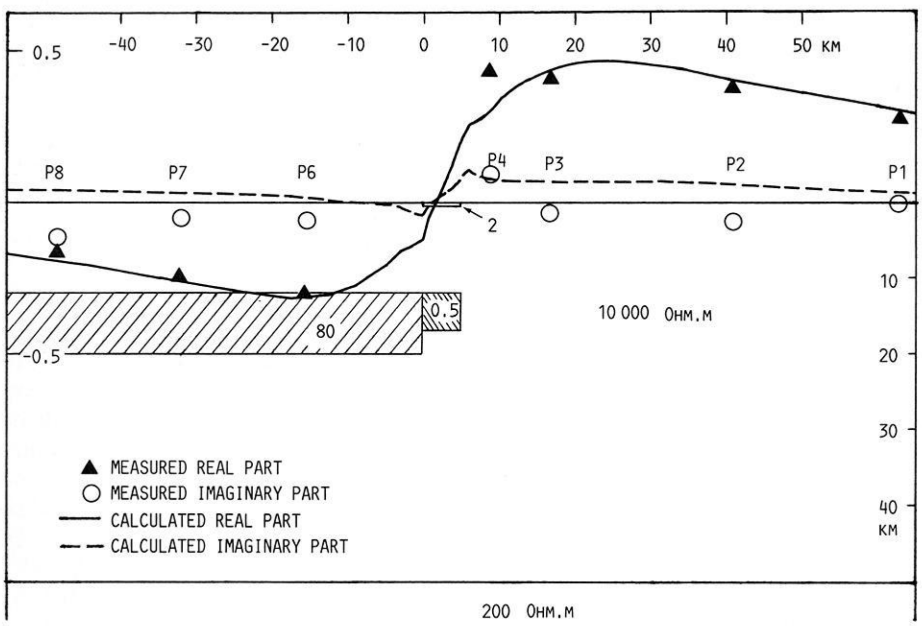

Fig. 9. Geoelectric two-dimensional model for the P line

Ladoga anomaly observed by Rokityansky et al. (1979). This anomaly runs under Lake Ladoga in a northeast-southwest direction to reach the Finnish-Soviet border. Its depth has been determined from MT studies at about 10 km and total conductivity from MV studies is 2×10^8 Sm. The depth is therefore very close to that observed for the Mikkeli anomaly. However, it is rather difficult to connect the Ladoga anomaly with either the Mikkeli or the Outokumpu anomaly.

Rokityansky (1983) also reported a high normalized north-south component (1.8–1.9) at periods of 5–90 minutes at station KK, near the area where the Outokumpu anomaly meets the Finnish-Soviet border (see Fig. 1). However, the normalized east-west component at the station KK is also as high as 1.5. This result is in agreement with the Outokumpu anomaly, if it is assumed that the Outokumpu anomaly turns to the southeast and joins the Ladoga anomaly. At station RT in the northernmost corner of Lake Ladoga the normalized X component is 1.4 at periods of 5–30 minutes and the Y component is only 1.1–1.05. This result agrees with the east-west directed Mikkeli anomaly.

Rokityansky (1983) assumed that the Ladoga anomaly and the Storavan anomaly (Jones 1981) in northern Sweden are parts of a unified Transscandinavian anomaly. The results presented here and by Pajunpää (1984) do not support this thesis.

The data produced by the two magnetometer arrays do not allow a detailed study of the depth, width and uniformity of the observed anomalies. Therefore, magnetotelluric or some other deep electrical soundings are needed across and over the anomalous zones, particularly to determine the depth and accurate location of the Outokumpu anomaly and the related conductivity boundary. Moreover, the proposed crossing structure of the two anomalies should be studied.

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References

Bailey, R.C., Edwards, R.N., Garland, G.D., Kurtz, R., Pitcher, D.: Electrical conductivity studies over a tectonically active area in eastern Canada. J. Geomagn. Geoelectr. **26**, 125–146, 1974

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

Golod, M.I., Klabukov, B.N., Grishin, A.S. Vasin, N.D.: The geoelectric model of central Karelia. In: The development of the deep geoelectric model of the Baltic shield, Part 2, Hjelt, S.E., ed., pp 180–204. Proc. 1st Project Symp., Oulu, 15–18.11.1983, Dept. of Geophysics, Univ. of Oulu, Report No. **8**, 1983

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

Jones, A.G.: Geomagnetic induction studies in Scandinavia – II Geomagnetic depth sounding, induction vectors and coast effects. 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

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

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, Hjelt, S.E., ed., pp 233–244. Proc. 1st Project Symp., Oulu, 15–18.11.1983, Dept. of Geophysics, Univ. of Oulu, Report No. 8, 1983

Luosto, U., Ilmola, V.-M., Zverev, S.M., Kosminskaya, I.P., Sharov, N.V., Korhonen, H.: Results from the DSS study on the Baltic profile in SE Finland. Paper read at the XIX General Assembly of the European Seismological commission, Moscow, 1.–6. Oct. 1984a

Luosto, U., Lanne, E., Korhonen, H., Guterch, A., Grad, M., Materzok, R., Perchuc E.: Deep structure of the Earth's crust on the SVEKA profile in central Finland. Ann. Geophys. **2**, 559–570, 1984b

Pajunpää, K.: Magnetometer array studies in central and southeastern Finland. In: The development of the deep geoelectric model of the Baltic shield, Part 2, Hjelt, S.E., ed. pp 245–262. Proc. 1st Project Symp., Oulu, 15–18.11.1983. Dept. of Geophysics. Univ. of Oulu, Report No. 8, 1983

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

Rokityansky, I.I., Vasin, N.D., Golod, M.I., Novitsky, G.P., Rokityanskaya, D.A., Sokolov, S.Ja.: Electric conductivity anomalies in the south of Karelia (in Russian). Geophys. Commun. Kiev **89**, 36–39, 1979

Rokityansky, I.I.: Geoelectromagnetic investigation of the Earth's crust and mantle. Springer: Berlin-Heidelberg-New York, pp 381, 1982

Rokityansky, I.I.: Geoelectromagnetic studies of the Baltic and Ukrainian shield: Review of some results. In: The development of the deep geoelectric model of the Baltic shield, Part 2, Hjelt, S.E., ed., pp 110–150. Proc. 1st Project Symp. Oulu, 15–18.11.1983, Dept. of Geophysics, Univ. of Oulu, Report No. 8, 1983

Weaver, J.T., Brewitt-Taylor, C.R.: Improved boundary conditions for the numerical solution of E-polarization problems in geomagnetic induction. Geophys. J.R. Astron. Soc **54**, 309–317, 1978

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