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Deep electromagnetic studies of the Baltic Shield

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Abstract. The first systematic collection of magnetotelluric, magnetovariational and frequency sounding results for the Baltic Shield is presented. The great variations in data processing and interpretation methodology make it difficult to present any unified summary of the existing results.

Conductive regions in the crust occur in all parts of the shield; sometimes in connection with schist zones, variations in bedrock structure and composition, and sometimes as apparent conductive layering in the depth range 15–25 km. The extent of this layer, as well as the conductive layer at asthenospheric depths in the northern parts of the shield, cannot yet be established.

The usefulness of combining electromagnetic and other geophysical data is indicated by the example from central Finland, where deep seismic sounding results seem to be able to explain long-period anisotropies of magnetotelluric sounding curves.

Key words: Baltic Shield – Induction studies – Crustal conductive structure – Conductive asthenosphere – Geoelectric models – Magnetotellurics – Magnetometer arrays – Frequency sounding

Introduction

The tectonic structure of the Baltic Shield has recently been outlined by Berthelsen (1983) (Fig. 1). This model forms a framework for the measurements on the northern segment of the European Geotraverse (EGT) project. By simplifying the model, it can be stated that the age of the rocks on the shield increases in going from SW to NE. Thus the oldest rocks have been found on the Kola peninsula.

Three tectonic features are important for electromagnetic (EM) deep studies; namely, the Kola suture (no. 1 in Fig. 1), the granulite arch (its boundary is given as no. 2 in Fig. 1) and the fossil plate boundary (no. 3 in Fig. 1). Although the structural connection of the latter feature across the Bothnian Bay is unclear, the structure on the Finnish side is the target of great geological interest because of its importance in mineral prospecting. It is often referred to as the Ladoga-Bothnian Bay zone (LBBZ), but its deep structure has not been studied geophysically until very recently.

Other recent descriptions relevant to the geology of the Baltic Shield can be found in Gáal (1981), Salop (1983) and Simonen (1980).

The purpose of this paper is to collect a table of available data of deep EM studies on the Baltic Shield. Mainly published material only is included, but for the central (Finnish) part of the shield some data are mentioned, which are in the stage of processing or interpretation. The collected data sets form a first attempt towards the construction of a unified geoelectrical model of the shield, to specify the common features, and to divide the shield into electrically similar regions. Electrical models for the crustal part as such have a value in enlightening structural geological problems but also as a correction when aiming at the electrical properties of deeper parts of the Earth (as in the international ELAS-project, where the asthenosphere is the main target).

Since EM data have been processed and interpreted using a large variety of points of view from the start, it is not possible at this stage to make any unified summary of the results. Some relevant points are, however, discussed in more detail. The present great activity of EM studies in all parts of the shield will definitely improve the geoelectrical models in the very near future.

The collected data has been summarized in Table 1, where the shield has been, for convenience, divided geographically into eastern, central (= Finland) and western parts. The information given comprises the method used, the number of measuring points reported, the period range of measurements and the depth of conductive layers. Some comments and appropriate references have been added. The list of references is also subdivided areally into Finland, Karelia, Kola and Sweden. The IMS work (cf. next section) has been referenced separately.

Astenospheric models

During 1976–1979 the structure of the Earth's magnetosphere was studied through great international efforts. The International Magnetospheric Study program (IMS) made, among others, use of 37 Gough-Reitzel magnetometers operating in northern Scandinavia. Data from these stations together with observatory records, in places completed by telluric registrations, have been extensively analysed also for purposes of studying the internal structure of the Earth. Some important results on the electrical properties of the deep lithosphere have been obtained (Jones 1980–1983, in several papers; Küppers et al. 1979; Lange, 1979).

Jones analysed the data thoroughly for various effects and aspects of data analysis. By careful selection of events

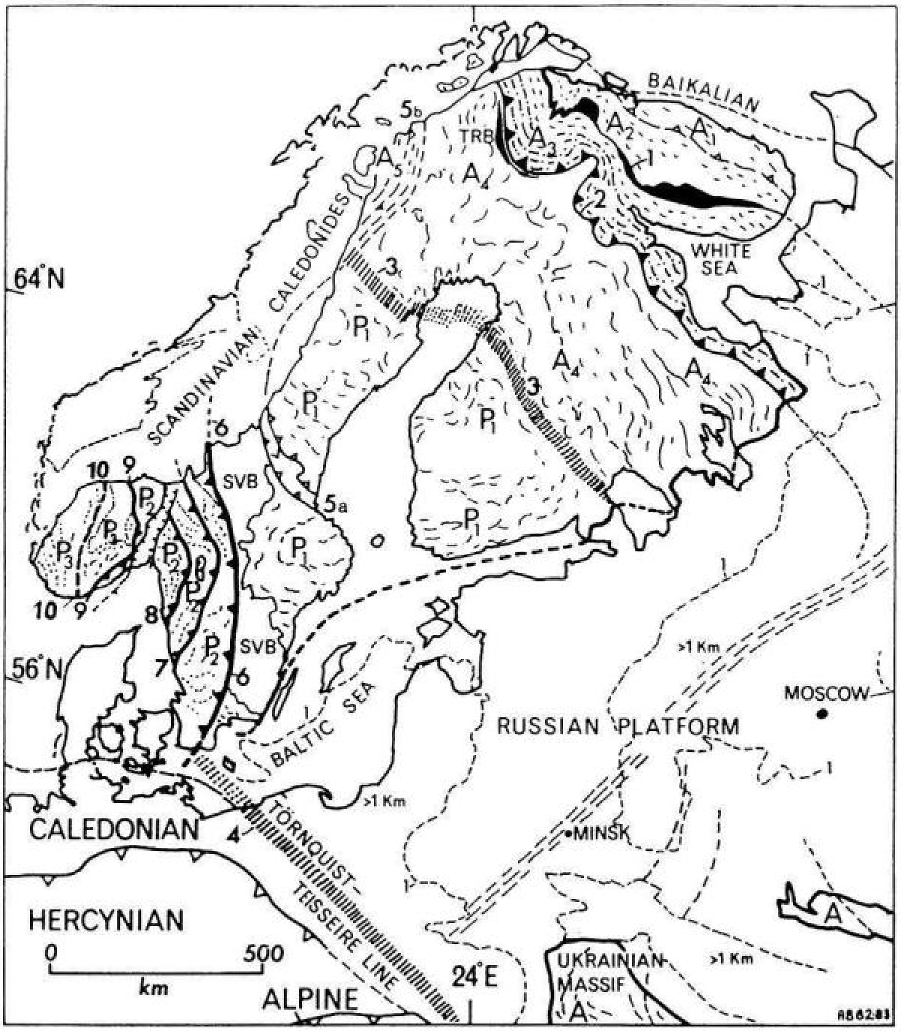

Fig. 1. Tectonic division of the Baltic Shield according to Berthelsen (1983). A_1–A_5, tectonic units of the Archean "nucleus"; P_1–P_3, Proterozoic crustal age provinces; 1–10, main structural features (1 = the Kola suture, 2 = the boundary of the Granulite belt, 3 = a fossil plate boundary)

and by using the averaging horizontal spatial gradient technique (HSG) for a set of nine magnetometers around Kiruna in northern Sweden, he concluded that the conductive ocean (the so called coast effect) did not influence the analysis of these stations to any relevant degree. The data seemed to fit the Weidelt criteria indicating a layered structure of the Earth in this area, although the westernmost chain of magnetometers was outside the shield proper in the Caledonides.

By using old high-frequency audiomagnetotelluric (AMT) data from Kiruna (Westerlund, 1972) and seismic results for the average depth to the Moho, Jones was able to extend the rather narrow band of the original magnetovariational (MV) data to lead to a better model of the resistivity versus depth in these regions. Similarly, he fixed his models for stations KEV and NAT (cf. Fig. 2) using some of the parameters of the Kiruna (KIR) model.

A summary of the models is presented in Fig. 3, where the existence of an asthenospheric conductive layer is evident, according to Jones, for the three northernmost regions KEV, KIR and NAT. The depth to the conductor decreases from west to east. (See Fig. 2 for the hatched areas showing the regions covered by the magnetometers for each data set.) No crustal conducting layers can be seen in the models. The limits of the depth to the conducting layers obtained from Monte-Carlo inversion are indicated in the comment column of Table 1. Jones does not state source field distortions of his results.

In the central part of the shield, at station SAU, magnetotelluric sounding (MTS) data again indicate a definite one-dimensionality of the Earth. The presence of a crustal conductive layer is clear (Fig. 3). Its horizontal extent can not be estimated. The presence of an asthenospheric conductor is most uncertain at SAU and can not, in any case, be closer to the surface than 150 km (Jones et al., 1983).

By combining one-dimensional (1D) inversions of observatory data with some soundings in the region of the data set G and AMT data from the Archean part of the profile AB (Fig. 6), a normal resistivity curve was constructed by Kaikkonen et al. (1983). This model is believed by the authors to be valid at least for the old Archean basement, although data from various parts of the shield are distorted by crustal inhomogeneities. The MTS data from KUK (cf. Fig. 6) fit the generalized normal curve of resistivity versus depth very well.

Geoelectric models for the eastern part of the shield

The eastern part of the shield has been the target of extensive electromagnetic and other conductivity measurements since the early 1970s. The first MTS curves were presented from the Kola peninsula (Vladimirov, 1971; Kovtun, 1976).

Table 1

	Location	Method	N	T(s)	H_{cond}(km) from ρ_{min}	Comments	Reference
Data set Eastern Baltic Shield (subsets K, G and R)							
K I	Profile from Rybachy Island to S	MHD, FS	14	0.1–10		Regional crustal inhomogeneities	Velikhov et al., 1982 Gorbunov et al. 1982 Krasnobayeva et al., 1983
K II	Profile to E from Rybachy Island	MHD, FS	11	0.1–10			Gorbunov et al., 1982
	Profile to E from Rybachy Island	MTS	11	1–1500	50–70, 350–500	Crustal inhomogenities Krasnobayeva "normal" curve	Krasnobayeva et al., 1981, 1982
KIII	Profile across Pechenga complex	MHD, FS	23	0.1–10		Regional variations	Gorbunov et al. 1979, 1982
	Profile across Pechenga complex	MTS	5	1–400	Equivalent crustal conductor 10–14 km thick	Local conductive structure of the Pechenga complex	Pavlovsky et al., 1978 Zhamaletdinov, 1980
KIV	Profile across Imandra-Varzuga zone	MTS	1?	25–150		Local galvanic distortions	Zhamaletdinov et al., 1979
	Profile across Imandra-Varzuga zone	MVP	10	20–60		Local crustal conductive anomaly	Zhamaletdinov et al., 1979
KV	Profile from II to the N coast Kola peninsula	FS	8	0.1–10		Negligible coast effect	Krasnobayeva et al. 1981, 1982
	Various points	MTS	7	5–1,000		Large variations, crustal conductors	Zhamaletdinov et al., 1976; Kovtun 1976
	Lovozero	MTS	1	0.1–1,000	0–10...15 several 100		Zhamaletdinov et al., 1976; Kovtun 1976
	N. Karelia	MTS	5	20–500	150–200, 350–400		Golod et al., 1980
G	Tuulos-Kemi (BALTIC)	MTS	13	10–1,000	W50, C110, E60		Vasin, 1979 (personal comm.)
	Tuulos-Kemi	MTP	60	20–40			Vasin, 1979 (personal comm.)
G	C. Karelia	MTS	21	20–7,000	150–200, 60–90 in the west	From ρ_{EW}	Rokityansky et al., 1983 Golod et al., 1983
R	Ladoga	MVP				Horizontal position of Lake Ladoga conductivity anomaly	Rokityansky et al., 1981
	Ladoga	MTS	4	5–10			Rokityansky et al., 1981
		Numerical					Kaikkonen, 1983
Data set Central Baltic Shield (Finland)							
J2	Kevo	MVS/HSG	5+4	30–4,000	110–120	Asthenosphere, cf. curve KEV, Fig. 3	Jones 1982b, 1984
	Sodankylä	MTS	1	5–100	15–20 (ρ_{NS})	From observatory data	Pernu 1973
J3	Sauvamäki	MVS/HSG	3	100–3,000	–	Bad quality, no interpretation	Jones 1984
J3	Sauvamäki	MTS	1	100–3,000 I/3,000–1/8	22.5 (mean), >150	Crustal conductive layer (15.5–29),[a] asthenosphere uncertain (153...248)[b]	Jones et al., 1983
	Oulu region	IMS		100–3,000		Anomalous region, qualitative result	Lange, 1979; Küppers et al., 1979
	Oulu region	MVS					Pajunpää, 1984
	Oulu region	MTS	6	2–3,600		Crustal conductor $\rho<1\ \Omega$m (preliminary)	Zhang et al., 1983
A–B	Profile SVEKA	MTS	5	100–	4–34	cf. Fig. 7, crustal inhomogeneity	Ádám et al., 1982

[a] ranges of acceptable depth (in km)

Table 1. (continued)

	Location	Method	N	T(s)	H_{cond}(km) from ρ_{min}	Comments	Reference
	Profile SVEKA	AMTS	64	1/3,700–1/8		2D model of crust, cf. Fig. 7	Kaikkonen et al., 1983
	Profile SVEKA	MTS	5	100–		Preliminary	Korja, 1983
KUK	Profile SVEKA	MTS	2	100–3,000		Fits "normal" curve, cf. Fig. 3	Korja, 1983
	Profile BALTIC	MTS	9	0.1–10, 2–3,600		Measured July-83	Under analysis
	67°–70° N	MHD, FS	2.4	0.1–10		Crustal conductor	Heikka et al., 1983; Velikhov et al., 1983
	60°–67° N	MVS	4 × 30	60–			Pajunpää, 1984; Pajunpää et al., 1984
	Nurmijärvi	MTS	4				Pirjola, 1983
		Numerical					Kaikkonen, 1983
Data set Western Baltic Shield							
J1	Kiruna	MVS/HSG	9	100–9,000	160 (mean)	Asthenosphere (148–180)[a], cf. curve KIR, Fig. 3	Jones, 1980
J1	Nattavaara	MTS	1	100–2,500	210 (mean)	Asthenosphere (170–244)[a], cf. curve NAT, Fig. 3	Jones et al., 1983
J1	Kiruna	AMTS	2	0.0001–100			Westerlund, 1972
	FENNOLORA	MTS	10	–1,000		Crustal conductors (preliminary)	Rasmussen et al., 1983

[a] ranges of acceptable depth (in km)

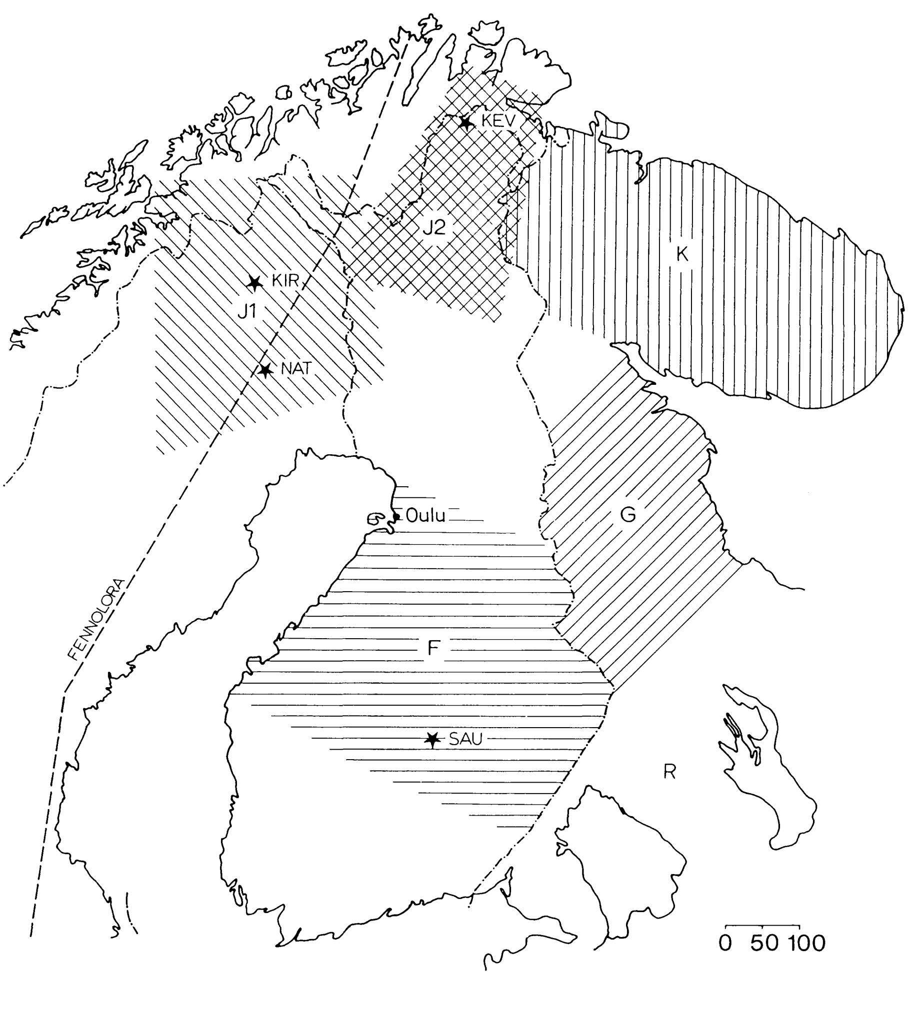

Fig. 2. Main areas with existing deep EM data on the Baltic shield. J1, J2 = IMS magnetometer arrays; K = MTS and FS (MHDS) data on the Kola peninsula; G = MTS data of central Karelia; R = MTS and MV data in the Ladoga-Onega region; F = AMT, MTS and MV array data in central Finland; FENNOLORA = MTS data along DSS profile. KEV = Kevo, KIR = Kiruna, NAT = Nattavaara, SAU = Sauvamäki (Hankasalmi)

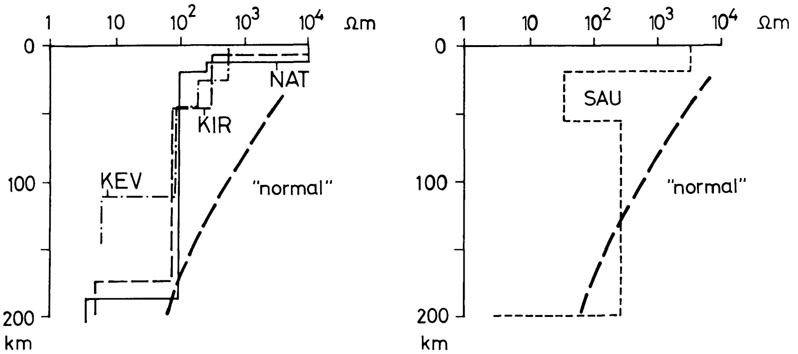

Fig. 3. Selected resistivity-versus-depth models on various parts of the Baltic Shield. For locations, see Fig. 2. KEV = MVS/HSG-model (Jones, 1982b; Jones et al, 1983); KIR = MVS model (Jones 1980; Jones et al., 1983); NAT = MTS model (Jones et al., 1983); SAU = MTS model (Jones et al., 1983); "normal" = generalized model for the old Archean part of the shield (Kaikkonen et al., 1983)

The great variations between various sounding curves indicated a possible electrical complexity of the Earth's crust. Later work has confirmed this.

Kola

MTS, mostly from the northernmost part, the so-called Murmansk block of the Kola peninsula, have been analysed by Krasnobayeva et al. (1981, 1982). The long period parts of the curves were joined asymptotically and the authors believe this procedure minimizes crustal distortions of the sounding curves. The justification of this procedure is not clear and it is not possible to understand on what grounds the asymptote of Krasnobayeva et al. differs from the asymptote of the normal curves for the East European platform (Vanyan et al. 1977, 1980) and for the old Archean part of the Baltic Shield (Kaikkonen et al., 1983). Problems of ionospheric source effects have not been indicated in the works of Krasnobayeva et al.

Recently frequency soundings (FS) using a powerful magnetohydrodynamic generator (MHD) have completed the picture of the geoelectric structure of the Kola peninsula. In MHD soundings (MHDS, described ao. by Gorbunov et al. , 1979; Velikhov et al., 1982; Krasnobayeva et al., 1983; Heikka et al., 1983) a pulse source field is created. The generator, located at the Rybachy Island on the northern shore of the Kola peninsula, feeds a current pulse of up to 10–20 kA or several subsequent pulses of 0.5–1.2 kA via a 7-km-long cable into the Barents sea. The current tends to flow around the island, thus both magnetic and electric dipole fields are created. Telluric fields and associated secondary magnetic fields have been measured at distances of 350–500 km from the source. The main part of the Kola peninsula has thus been studied. Signals have also been well recorded in northern Finland (Heikka et al., 1983; Velikhov et al., 1983), where the tectonically important granulite arch can easily be traversed by FS profiles using this source.

A map of equal telluric and magnetic fields portrays the geoelectric structure of the upper crust horizontally, but no vertical structural model for the area has yet been published. Conductivity calculations clearly divide the Kola peninsula into blocks of different resistivities. The conductivity blocks correlate well with the geological units of the area (Fig. 5). The Murmansk block is the most resistive one and the ore-critical Pechenga and Imandra-Varzuga zones have the lowest resistivities. A number of more detailed profiles and studies have been conducted in the surroundings of these formations (Vasin et al., 1981; Zhamaletdinov et al., 1979; Gorbunov et al., 1979; Pavlovsky et al. 1982).

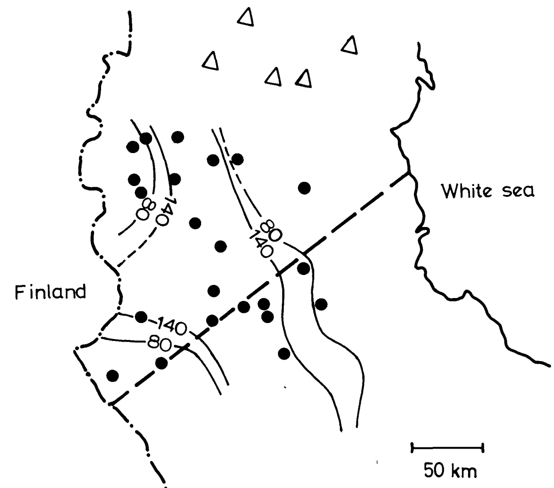

Fig. 4. MT sounding points of data set G. Isolines of apparent depths of conductors are given in km. (Golod et al., 1983). *Dashed line:* part of the DSS profile BALTIC (existing MT points not shown); *full circles:* MTS (Golod et al., 1983); *triangles:* MTS (Golod et al., 1980)

It does not seem possible to establish the presence of a uniform crustal layer for the Kola peninsula from the existing results; also, no indications of asthenospheric conductors are available. The number of existing conductivity measurements have made it possible to construct a reasonably valid conductivity-times-thickness (S-value) map for the peninsula and other parts of the eastern Baltic Shield. Such a map has been used (by extrapolating it through geological analogy to the central and western parts of the shield) as input for modelling telluric distortions on the whole Baltic Shield (Kaikkonen, 1983).

Karelia

In the central Karelian part of the shield the geology has a clear and widespread NS trend. This led Golod et al. (1983) to analyse directly the EW apparent resistivity curves of MTS. The authors believe these curves approximate conditions well and thus give reliable estimates of conductor depths. Despite extensive crustal distortions of the MTS curves, they seem to indicate the presence of a common conductor in the upper mantle. Golod et al. have summarized these results and constructed a map of the depth to the conducting layer, which has been redrawn in Fig. 4. Similar results have been reported from MTS work along the deep seismic sounding (DSS) profile BALTIC running

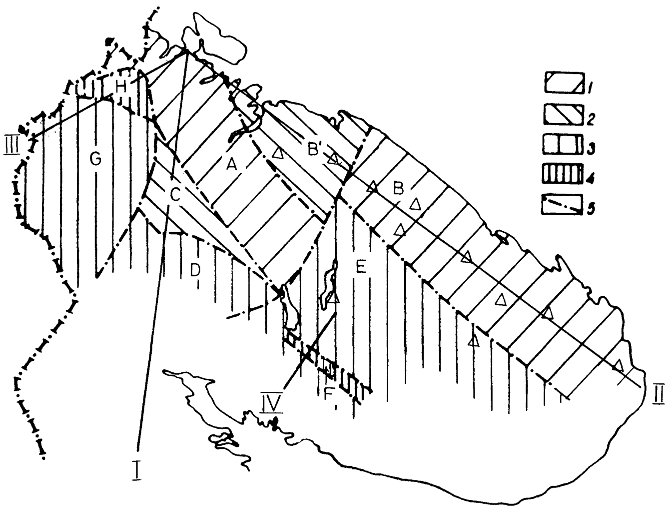

Fig. 5. Division of the custal rocks of the Kola peninsula as given by electrical resistivities obtained from MHDS results (Velikhov et al., 1982). I–V, MHDS profiles. Resistivities in Ωm: 1–10^5, 2–10^4, 3–10^3, 4–<100. 5 – blockboundaries; A – Central Kola, B, B′ – Murmansk, C – Notozero, D – Monchegorsk, E – Keiv suite, F – Imandra-Varzuga, H – Pechenga blocks. *Triangles:* location of MTS points (Krasnobayeva et al. 1981, 1982)

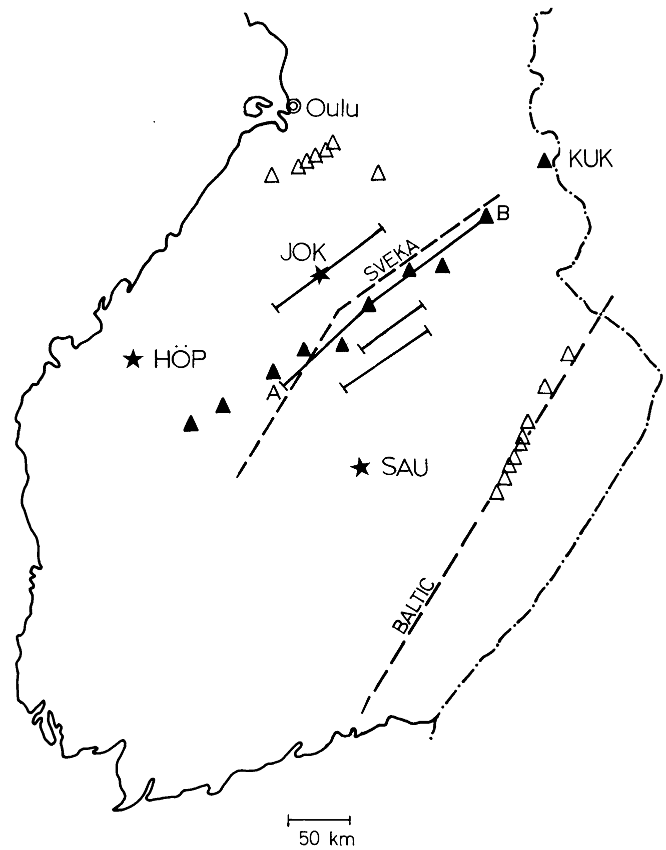

Fig. 6. Deep EM data in Finland (data set F). *Solid triangles*: MTS points (Ádám et al. 1982, Korja 1983). *Open triangles*: MTS points under analysis. *Stars*: MV stations of data set J3 (IMS/Jones, 1983). A⊢——⊣B: main scalar AMT profile (cf. Fig. 7). ⊢—⊣: additional AMT profiles. ----: DSS profiles, SVEKA and BALTIC

from Kemi to Tuulos in Soviet Karelia (Vasin, personal communication).

A conductivity map of the upper crust, based on DC soundings, has also been published for the region of data set G (Golod et al., 1980; Rokityansky et al., 1983). The map correlates well with the geological picture of the corresponding area. In southern parts of Karelia, MTS curves from the west and northwest shores of Lake Onega indicate widespread good conductors, which can be explained by rocks of shungite existing as reasonably thick layers in this area. Magnetometer profiling data from several locations around Lake Ladoga point towards a linear crustal conductivity anomaly trending SE-NW below the lake (Rokityansky et al., 1981; Vagin et al., 1982). Depths in the upper crust are obtained from MTS measurements. The conductivity anomaly continues on the NW shore of Lake Ladoga (Rokityansky et al., 1981) and also on the Finnish part of the Baltic Shield (Pajunpää, 1984).

Central part of the Baltic Shield

In Finland, in the central part of the shield, deep EM studies started systematically in 1980 under the framework of the ELAS project. The first measurements consisted of AMT and MT soundings across the LBBZ followed later by extensive MV array studies, further MTS work and recently MHDS in the northernmost parts of Finland.

The MV arrays were located on both sides of the LBBZ; the northern shores of the Bothnian Bay are under study at present. The first analysis of the data (Pajunpää, 1984; Pajunpää et al., 1984) confirms the existence of the Oulu conductivity anomaly noted by Küppers et al. (1979) in an early work on IMS data. The anomaly can not be explained by the Jothnian Muhos sandstone formation or the NW-SE trending Kiiminki-Utajärvi schist zone alone. Preliminary results of a MTS profile across the anomaly (Zhang et al., 1983) suggest low resistivities typical of graphitic schist zones even at depths of 10 km.

Another distinct MV conductivity anomaly is situated in the eastern parts of Finland, approximately in the middle of the Finnish continuation of the BALTIC DSS profile (cf. Fig. 6). A part of the anomaly is evidently a continuation of the Ladoga anomaly, but there seems to be strong evidence for a more complex conductivity stucture (Pajunpää et al., 1984). Some less pronounced MV anomalies have been noted, which can be explained by regional variations of rock conductivities and the presence of graphitic schist zones.

The MTS profile of 1980 (AB in Fig. 6) consisted originally of 5 MTS points and 64 scalar AMTS points. In addition, the AMT parts of the deep sounding curves are averages of results at several points around each MTS station. Directional anisotropy was measured in the field by rotating the direction of the scalar AMT sounding measurements. The results have been thoroughly discussed by Adám et al. (1982) and Kaikkonen et al (1984). The AMT data suggest clearly the central part of the profile to be better conducting than the surroundings. This central part coincides with what is usually referred to as the LBBZ. Because of the high frequencies used in AMTS the result is valid for the first upper kilometers of the crust.

The apparent depths of middle and lower crust conductors at the two northernmost MTS points 2 and 3 (cf. middle part of Fig. 7) can be explained by inductive effects of nearby schist zones. They thus do not refer to real con-

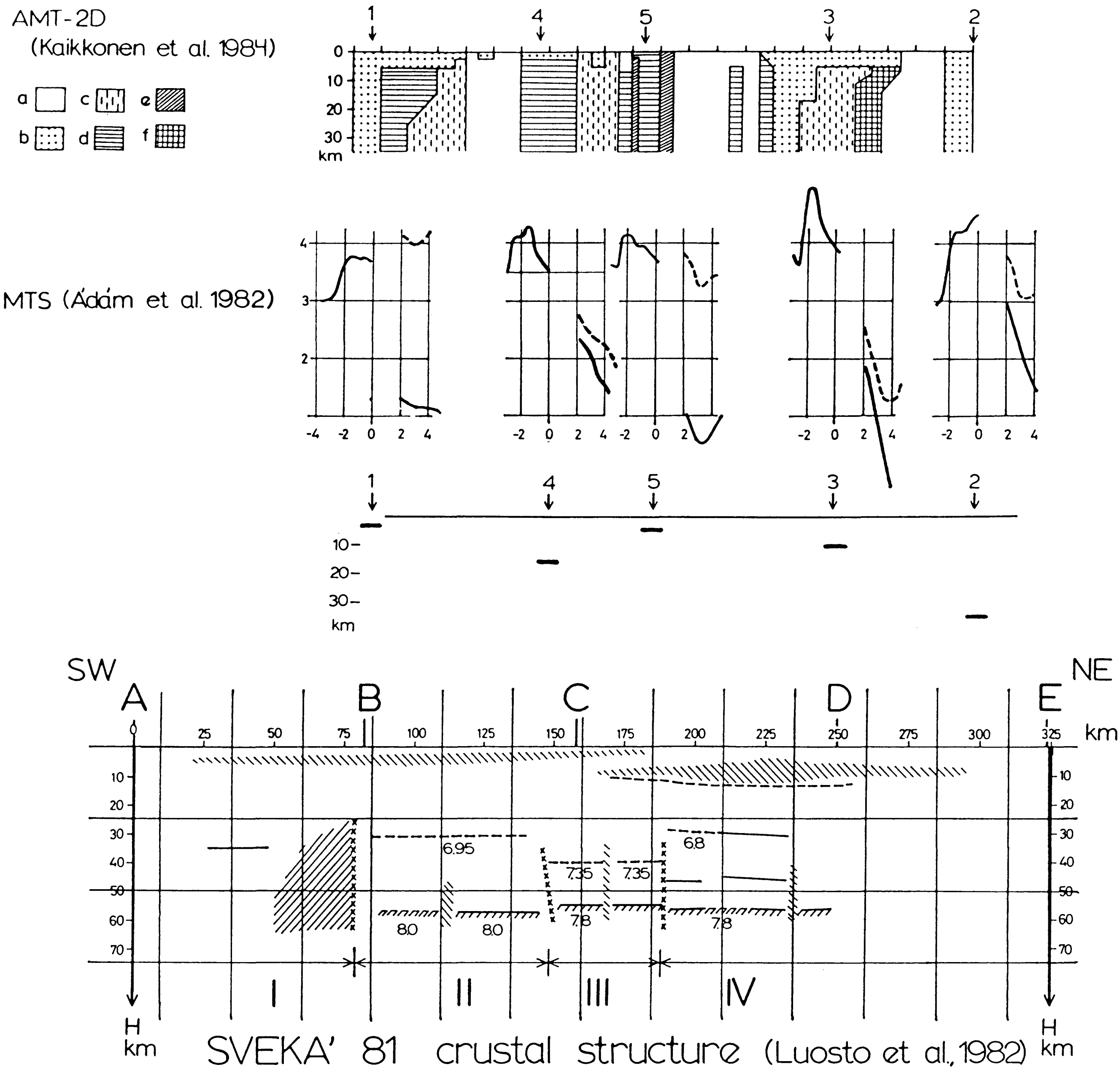

Fig. 7. Seismic (DSS) and electric (MTS) cross-sections along the profile SVEKA. *Upper part*: 2D inversion of scalar AMT data. A – 200,000, b – 15,000–20,000, c – 5,000, d – 1,000, e – 500, f – 100 Ωm *Central part*: MTS curves 1–5 for rotated ρ_{min} *(full line)* and ρ_{max} *(dashed)*. AMT parts of the curves are regional averages around the sounding points. Bars indicate position of apparent conductive layer from 1D inversion of ρ_{min}. *Lower part*: DSS section. A–E: shot points. I–IV: seismically different crustal blocks, \\\\\\\\ LVL (low velocity layer), ////// shadow zone, ////// Moho, × × × × faults and other vertical boundaries

ductive horizontal layers. The results at points 4 and 5 are difficult to explain due to complex geology. At point 1 the minimum and maximum apparent resistivities differ by some three decades at longer periods. Since the AMT data show an extraordinarily good electrical isotropy of the upper crust, the long-period anisotropy means a distinct conductivity anisotropy in the middle or the lower crust. Such an anisotropy could be of structural type and the deep fault, seen as seismic shadowing (bottom part of Fig. 7), could be the cause of it.

Some of the newer MTS points on the same profile will shed more light on the deep structure of the SVEKA profile and the LBBZ, although measurements in the period range 0.1–1000 s are necessary for further detailed analysis. The electrical complexity of the deep crust along SVEKA is also evident from the 2D model obtained from the scalar AMT profile data (Fig. 7, upper part).

The regional divison of the AMT profile into three different conductivity regions is statistically very clear (Kaikkonen et al., 1984). A broader conductivity exists on a parallel AMT profile to the north, while southern parallel profiles do not show so clear-cut conductivity patterns.

In summary, the data seem to indicate that the LBBZ is not electrically homogeneous along its length. Additional profiles across the zone will be needed for a more complete structural picture. In addition to seismic data along

SVEKA, preliminary spectral analysis of both gravity and aeromagnetic data of the surrounding regions have been conducted by Ruotoistenmäki (1983). A surprisingly great number of the gravity and magnetic source concentrations seem to have counterparts in the seismic and EM vertical cross-sections along SVEKA.

Similarly MV, MTS and DSS measurements have been performed along the parallel BALTIC profile, but the results are not yet available for interpretations or for comparative analysis.

Western part of the Baltic Shield

The IMS array data and the Nattavaara MTS results have already been discussed above. During the summer of 1983, the EM group of Uppsala University started MTS work along the FENNOLORA DSS profile and at selected profiles on the southern edges of the Baltic Shield. The very preliminary results along FENNOLORA (Rasmussen et al., 1983) seem to indicate the presence of crustal conductors at several places along the profile. The work is continuing and it will be completed by MV array studies in the framework of the EGT project.

Conclusions

The first attempt to collect a systematic data set of deep EM measurements on the Baltic Shield has shown the complexity of the electrical structure of the crust. Although some indications of conducting layers at asthenospheric depths exist, the horizontal extent of such a layer cannot be estimated at present. Conducting schist zones, variations in bedrock structure and composition, deep faults and fractures as well as source effects in the northern parts of the Baltic Shield make a reliable localization and summarizing mapping of crustal conducting layers difficult. Some soundings can be explained by a crustal conductive layer in the depth range of 15–25 km, but it is impossible to state anything about the horizontal extent of such layers. It is essential that further measurements are conducted actively in all parts of the shield in order to improve the geoelectrical model of the crust as such, and also in order to maximize the possibilities of studying the deeper parts of the Earth.

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