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The Electrical Structure of the Lithosphere and Asthenosphere beneath the Fennoscandian Shield

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The electrical structure of the crust and upper mantle beneath three regions of Scandinavia has been delineated by the magnetotelluric (MT) and the horizontal spatial gradient (HSG) techniques. The analyses were applied to data recorded by the Scandinavian IMS magnetometer array complimented by telluric observations.

Models compatible with the response functions observed in northern Sweden and northeastern Norway/northern Finland are distinctive by exhibiting: (i) a negligibly small resistivity contrast across the seismic Moho; and (ii) the unequivocal existence of an electrical asthenosphere beneath both regions. In definite contrast, the response function observed in southern Finland demands a highly conducting layer (of resistivity around 10 – 50 Ωm) in the lower crust, and an order of magnitude increase in resistivity on entering the mantle. This increase is at a depth compatible with the known seismic Moho for the region.

It is not possible to make a quantitative estimate of the depth to the electrical asthenosphere beneath southern Finland, due to lack of long period information, but a qualitative measure indicates that the asthenosphere depth increases with increasing distance towards the centre of the north European craton.

1. Introduction

The lithospheric and asthenospheric structure of shield regions is of paramount importance for determining the tectonic processes that gave rise to their generation. With this knowledge, the geotectonicist could build physical models of the processes that are, at present, occuring, and accordingly present a viable mantle convection model of the earth. One physical parameter that is very sensitive to variations in certain other parameters, with which it has a strong affinity, is electrical conductivity. Many workers believe that a conductivity-depth profile of the mantle, at a certain location, can be directly translated into a mantle

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geotherm for that location, using laboratory data of the conductivity-temperature relationship of samples of pure minerals, or assemblages, thought to be representative of the dominant mantle constituents (for example, OLDENBURG, 1981). Such an exercise is, however, frought with inherent problems (see, for example, DUBA, 1976), and its validity has been called into question. TOZER (1979) is of the opinion that variations in electrical conductivity are more strongly correlated to variations in effective viscosity, rather than temperature, with the inference (TOZER 1981) that the rôle of meteoric water is of extreme importance. Notwithstanding these apparent dissensions, it is without question that geomagnetic induction studies over various tectonic regimes can radically constrain mantle models proposed by workers in other geophysical fields. With these considerations in mind, the recent ELAS (for ELectrical ASthenosphere) project attempted to focus the attention of the geomagnetic induction community on the detection and delineation of a possible local maximum in electrical conductivity in the upper mantle. Such a maximum may exists without corresponding viscosity or seismic velocity minima, if the somewhat speculative carbon theory of DUBA and SHANKLAND (1982) is true. However, the converse is not possible - any minima in effective viscosity or seismic velocity, due to the effects of partial melting and/or water content, must have a corresponding counterpart as a maximum in the mantle conductivity profile.

In this work, the results pertinent to ELAS are collated from the various induction studies carried out by the author and co-workers utilising data from the IMS (International Magnetospheric Study) magnetometer array in Scandinavia, of 36 modified Gough-Reitzel variometers (KÜPPERS and POST, 1981; KÜPPERS *et al.*, 1979) and 6 digital fluxgate magnetometers (MAURER and THEILE, 1978), and data from telluric field observations at two locations (JONES *et al.*, 1983). The derived response functions from three regions of Scandinavia - northern Sweden, northeastern Norway/northern Finland, and southern Finland - certainly display differing characteristics. Also, they are all markedly dissimilar to the "generalized" response curve, constructed by VANYAN *et al.* (1977), of the regional data from the East European Platform. The differences for northern Sweden and northeastern Norway/northern Finland from the "typical" shield response is that beneath both there must be a highly conducting zone in the upper mantle, at depths of around 100 – 200 km, to satisfy the observations. In contrast, for southern Finland there must be a highly conducting lower crustal layer, which is not present beneath the other regions. This vindicates the previous comments by KÜPPERS *et al.* (1979) in their explanation of the observed stronger attenuation of the vertical magnetic field component at short periods (i.e., 100 – 1000 s period) is southern Finland (south of Oulu) than in northern Finland.

The observations made will be described briefly in the following section, and the transfer functions estimated from the data sets will be illustrated, both in terms of the variation of the depth of the eddy current flow with period and their "Bostick" transformations. Section 3 will present the best-fitting models (found by Monte-Carlo random searches), together with the more objective D^+

and H^+ models, acceptable to the response functions. A discussion of these models follows (Section 4), and finaly conclusions will be drawn concerning the efficacy of geomagnetic induction studies and the lithospheric/asthenospheric structure beneath Fennoscandia.

2. Observations and Response Functions

Full details of the various instrumentation used, and their deployment, will not be given here - the interested reader is referred to KÜPPERS and POST (1981), KÜPPERS *et al.* (1979), MAURER and THEILE (1978), and JONES *et al.* (1983). Briefly, data from the magnetometers were recorded with a temporal resolution of 10 s, with the exception of one located in southern Finland on 20 s (HOP, see map in KÜPPERS *et al.*, 1979). The telluric field observations were also made with a resolution of 10 s. However, a timing discrepancy of 20 s between the magnetic and the telluric data was unacceptable (this would result in a phase error of 72° at 100 s period), and hence an objective scheme for detecting and reducing any such discrepancy was devised and employed on the MT data by JONES *et al.* (1983).

Two different induction methods were used to derive estimates of the geomagnetic response of the earth: (1) the horizontal spatial gradient (HSG) technique of BERDICHEVSKY *et al.* (1969) and SCHMUCKER (1970); and (2) the more ubiquitous magnetotelluric (MT) method. The HSG technique was employed on three groups of stations centred on Kiruna (KIR, see Fig. 1), Kevo (KEV) and near Sauvamäki (SAU) — the details are reported in full elsewhere (JONES 1980, 1982a, 1982b). Magnetotelluric observations were made at Nattavarra (NAT) and Sauvamäki (SAU-MT) and are described in JONES *et al.* (1983). The two response functions KIR and NAT are believed to be characteristic of northern Sweden, KEV is thought to describe northeastern Norway/northern Finland, and SAU-HSG and SAU-MT are considered representative of southern Finland.

The response functions themselves will not be illustrated herein with any error information included - this can be found in the appropriate references cited above. Also, both of the MT responses, NAT and SAU-MT, are considered to be $1D$, and thus only the off-diagonal tensor element of the MT impedance tensor in which the author places the most confidence is considered.

Illustrated in Fig. 2 are part of the estimated response functions from the five analyses. They are displayed in terms of the real part, g, of Schmucker's *Inductive Response Function*, $C(\omega)$. This function has the units of length, and the real part can be considered as the depth of the maximum eddy current flow, or the depth of the "centre of gravity" of the in-phase induced current system (WEIDELT, 1972; SCHMUCKER and WEIDELT, 1975). Also illustrated in Fig. 2 is the function for the East European Platform, i.e., $\hat{g}_{EEP}$, calculated from the "generalized" curve of VANYAN *et al.* (1977), as described in JONES (1982b). Several points are worthy of note:

(i) The estimated responses fall into four distinct "groups", which correspond

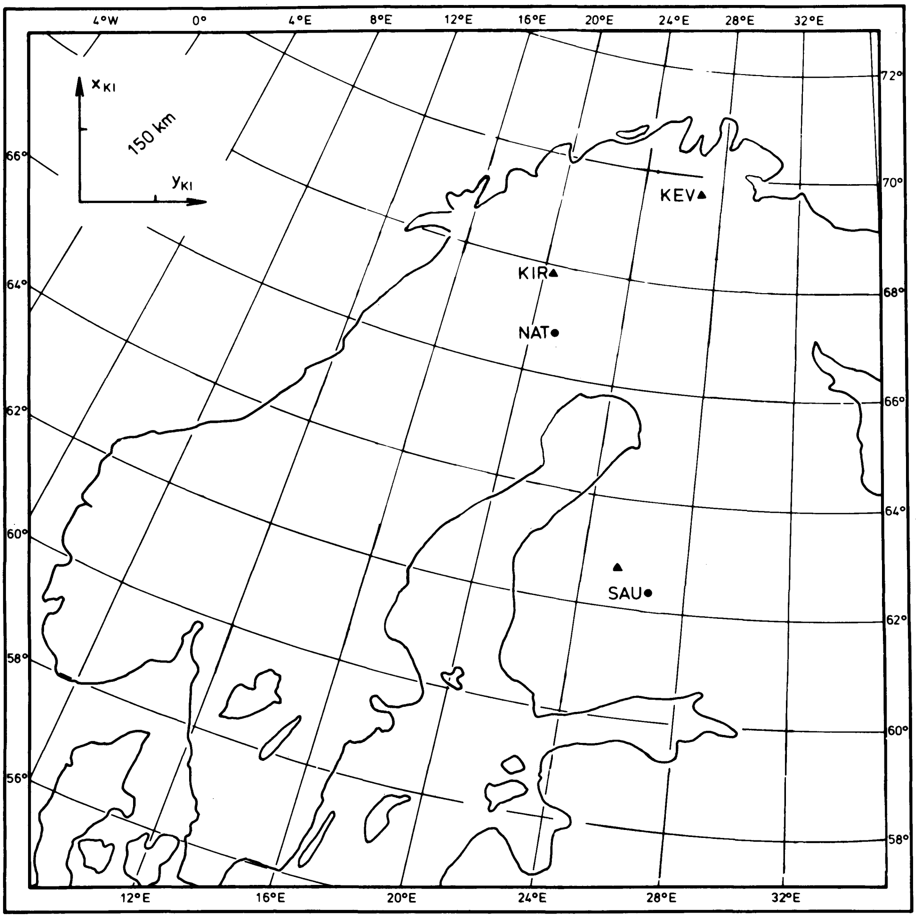

Fig. 1. Map showing the locations of the five induction studies reported in the text. The *triangles* indicate the HSG sites, whilst the *circles* depict the MT ones.

exactly to a geographical grouping: Group 1, northern Sweden response, displayed by $\hat{g}_{KIR}$ and $\hat{g}_{NAT}$; Group 2, northeastern Norway/northern Finland response of $\hat{g}_{KEV}$; Group 3, southern Finland response of $\hat{g}_{SAU-MT}$ and $\hat{g}_{SAU-HSG}$; and Group 4, the East European Platform response, $\hat{g}_{EEP}$.

(ii) Response function $\hat{g}_{KEV}$ is very alike $\hat{g}_{KIR}$ and $\hat{g}_{NAT}$ at the shorter periods, i.e. < 1000 s, but differs from them at the longer periods. This indicates that the crustal/uppermost mantle structure beneath both regions is similar, but that the depth to a conducting zone in the upper mantle is less beneath KEV than beneath KIR and NAT.

(iii) $\hat{g}_{SAU-HSG}$ and $\hat{g}_{SAU-MT}$ are dissimilar to the other responses throughout the whole period range. This suggests that both the crust and mantle structure

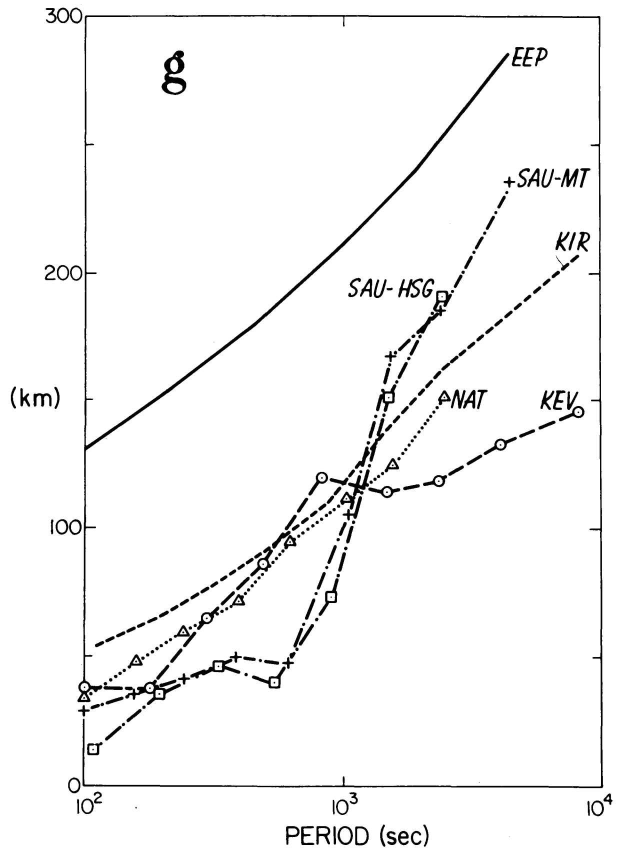

Fig. 2. Comparison of the real part of $\hat{C}(\omega)$ for the five analyses and for the East European Platform (EEP) response.

are different beneath southern Finland that beneath northern Scandinavia.
(iv) in both regions where there has been both HSG and MT studies, the estimated response functions are very compatible - compare $\hat{g}_{KIR}$ with $\hat{g}_{NAT}$, and $\hat{g}_{SAU-HSG}$ with $\hat{g}_{SAU-MT}$. This, in itself, is rather remarkable considering that: (a) the HSG data were analysed in a different manner from the MT data; (b) the HSG technique demands a highly non-uniform source for reliable estimation of the spatial gradients whilst MT requires either a uniform source or one that varies in a linear manner with horizontal distance (DMITRIEV and BERDICHEVSKY, 1979; SCHMUCKER, 1980); (c) the HSG data were all winter time events of high activity, whilst the MT data were summer time events of moderate activity; and (d) any residual timing discrepancy between the telluric and magnetic data would have resulted in a large phase error, and hence an inaccurate estimate of g from the ρ_a and Φ estimates.

(v) the depth of the "centre of gravity" of the in-phase induced current system in the upper mantle, at 3000 s say, becomes progressively deeper as one traverses Scandinavia from north to south, from KEV - KIR/NAT - SAU - EEP, i.e., as one approaches the centre of the North European Craton.
(vi) distortion of the telluric field, by current channelling effects, does not affect the HSG responses, only the MT ones. Hence, the similitudes of the HSG and MT responses infer that there are no appreciable, or detectable, telluric distortion effects at NAT and SAU. Thus, no DC-type distortion removal factor, of the form discussed by LARSEN (1977) and RICHARDS *et al.* (1982), need be applied to the MT apparent resistivity response curves.

That such independent estimations should produce highly compatible responses vindicates the HSG analysis, and subsequent interpretation, of data from the KIR region. It is apparent that any effects due to the high ferromagnetic mineral content in the crustal rocks at Kiruna were removed by smoothing the magnetic fields.

To ascertain if the ocean-continent boundary, and/or possible mantle conductivity variations between the oceanic mantle and the continental mantle, could give rise to two-dimensionality in the response function observed at KIR, numerical modelling was undertaken. Two possible *2D* geoelectric models for northwestern Scandinavia, taken along a profile running NW/SE from KIR towards the coast (as profile AA' in Fig. 12 of JONES 1981a), were studied. Model a (see Fig. 3) is for the case where the structure is the same beneath the Norwegian Sea as beneath the northwestern edge of the Fennoscandian shield. Model b is perhaps more geophysically plausible in that beneath the ocean the crust is thinner (absence of sialic layer) and the depth to the asthenosphere is less. The theoretical MT response functions that would be observed at KIR, at periods of 200 s, 1000 s, and 3600 s (1 hour), for both the E and H polarizations, and for both models, are indicated in Fig. 3. As can be seen from the illustration, it is not possible at KIR to detect any differences, to within the standard errors, between the *1D* best-fitting model and either of the *2D* models, in the period range of observation. Possible *3D* effects due to the irregular coastline were studied by JONES and WEAVER (1981). They showed that, for the profile of interest here, *2D* and 3D thin sheet models gave virtually identical responses.

That $\hat{g}_{\text{SAU}-\text{HSG}}$ should be so much like $\hat{g}_{\text{SAU}-\text{MT}}$ confirms the confidence placed by the author in the former (JONES, 1982b). The two longest period estimates of $\hat{g}_{\text{SAU}-\text{MT}}$ in Fig. 2 are the preliminary estimates quoted in JONES (1982b), which did not, however, pass the very strict acceptance criteria applied to the MT data in the more rigorous full analysis (see JONES *et al.*, 1983). The SAU-HSG data will not be used further as the imaginary part of $\hat{C}_{\text{SAU}-\text{HSG}}$, i.e., $\hat{h}_{\text{SAU}-\text{HSG}}$ is not considered well estimated.

First-approximations of the conductivity-depth distributions were gained from the estimated response functions for KIR, KEV, NAT, SAU-MT and EEP by using the Bostick transformation (BOSTICK, 1977; see also WEIDELT *et al.*, 1980; JONES, 1983). For the HSG responses, there was sufficient confidence in the

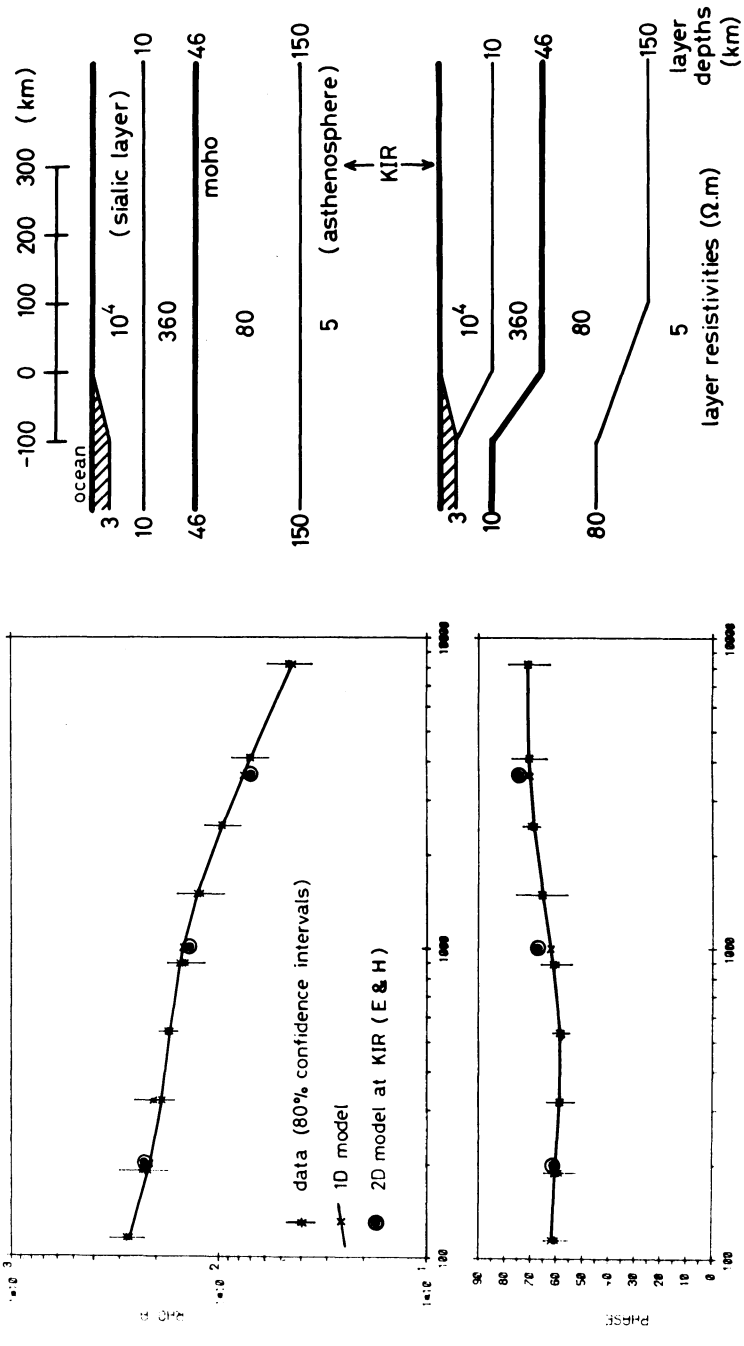

FIG. 3. The theoretical *2D* models, shown on the right, compared to the data observed at KIR and the best-fitting *1D* model to it. The upper model is for a lithosphere that is the same beneath the oceans as beneath the continent, the lower model is for a thinning crust and shallowing asthenosphere beneath the ocean. The *full line* is the theoretical *1D* response for a model given by the geoelectrical structure directly below KIR in the *2D* models. The *dots* are the *2D* responses for both models and for both polarisations of the source field. The *stars* are the responses observed, with 80% confdence limits shown.

phase information that the "Bostick" resistivities were considered best estimated from the expression given in Weidelt *et al.* (1980), which utilises the "approximate phase" determination of Weidelt (1972). In contrast, for the MT responses, and the EEP "generalized curve", more confidence was placed in the gradients of the apparent resistivity curves than in the phases - due to the aforementioned problem with relative timing - and therefore the conventional expression was employed for determining the Bostick resistivity. Figure 4 illustrates the Bostick inversions of the responses considered here (note: SAU refers to SAU-MT).

These approximate inversions also suggest various points mentioned above: (i) beneath KEV there is a conducting zone beginning at around 120 km depth; (ii) KIR and NAT are very compatible and indicate a conducting zone beginning at around 170 - 200 km depth; (iii) beneath SAU there is a conducting lower crust, and at long periods there is the indication that the SAU structure approaches that beneath EEP; and (iv) the EEP response is radically different from all of the others - note that for 10^3 s period all the Scandinavian responses are around 125 km depth, whilst the EEP response is at a depth of 250 km.

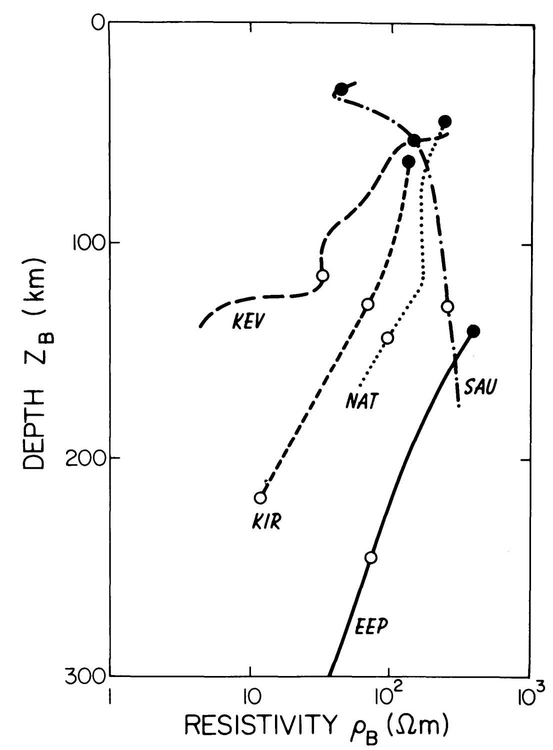

Fig. 4. The "Bostick" inversions of the response functions. The solid circles are the responses at 100s, whilst the open circles are those at 1000s.

3. Models

Acceptable $1D$ geoelectric models were discovered from the response functions by the Monte-Carlo random search procedure of JONES and HUTTON (1979). Although the Monte-Carlo approach is known to be impractical if the dimension of the search space is large, i.e., if the number of model parameters is large, for a small number of parameters its advantage of not having to assume linearity gives it superiority over other available methods which necessitate linearizing the inversion problem (PARKER, 1983). The ranges of the acceptable model parameters will not be shown here – they are to be found in the other referenced publications – only the best-fitting models discovered will be considered. For the Monte-Carlo searchs, the "best" – defined as the models that minimise AMPDIF and PHADIF as defined in JONES and HUTTON (1979) – 4-layer models are illustrated in Fig. 5. These models were discovered with the *a priori* informa-

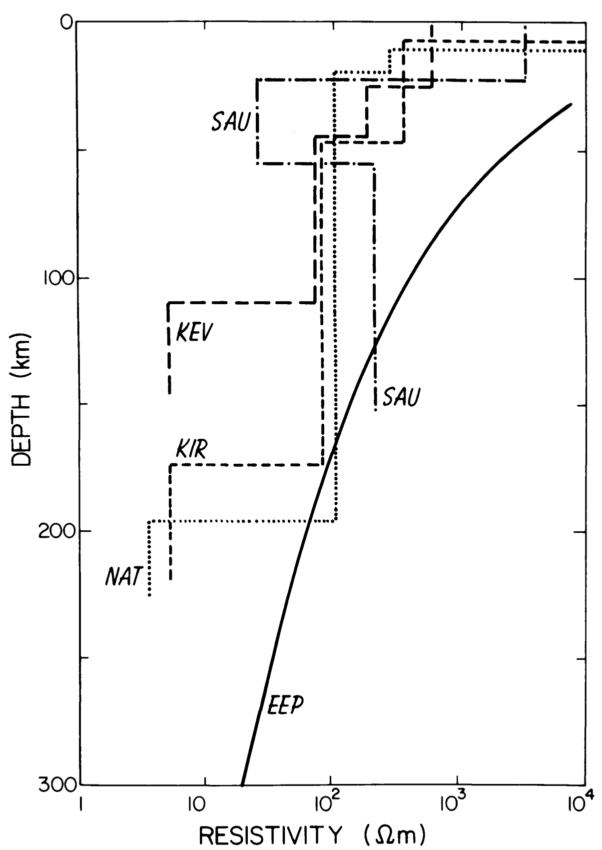

Fig. 5. The "best-fitting" 4-layer models to the response functions, with the interpreted EEP model of VANYAN *et al.* (1977).

tion, or "problem constants", of: KIR; ρ_1 = 10^4 Ωm (from AMT data of WESTERLUND, 1972) and d_2 = 46 km (depth to Moho from BUNGUM *et al.*, 1980): KEV; d_2 = 46 km (depth to Moho), ρ_3 = 80Ωm and ρ_4 = 5Ωm (same mantle resistivities assumed beneath KEV as found under KIR): NAT; ρ_1 = 10^4 Ωm (same upper crust assumed beneath NAT as KIR): and SAU; ρ_1 = 3000Ωm (from AMT measurements conducted by JONES *et al.*, 1983). Also shown in Fig. 5 is the interpretation by VANYAN *et al.* (1977) of the "generalized" EEP response.

The inclusion of a forced layer boundary at 46 km for the KIR and KEV responses was undertaken to discover if geoelectric boundaries at the known Moho depths were permissable. This was certainly discovered to be the case. However, for all three northern Scandinavian responses, KIR, KEV and NAT, 3-layer models could be found that satisfied the data equally well. For SAU, because of insufficient long period information (longer periods are required at SAU for probing the mantle than at the other locations due to the existence of the highly conducting lower crustal layer), below 150 km any resistivity between 1 - 200Ωm is acceptable.

In order to ascertain whether the *a priori* constraints given above had any diverse effect by restricting the model space too dramatically, independent assessments and inversions of the responses were undertaken employing PARKER'S (1980, 1983) schemes. Table 1 lists, for each response, the X^2 misfit for the D^+ models, together with the X^2 statistic to be able to reject the hypothesis that the data originate from a 1D earth at the 90% level of confidence (note: a standard error of 10% was assumed for the EEP response). The models are given in Table 2, and the upper 250 km of them are illustrated in Fig. 6. The X^2 misfits infer that all responses can be interpreted in a 1D manner. The KEV response is acceptable after the data at 190 s and 900 s are rejected from the analysis (these points were smoothed for the Monte-Carlo inversion). The H^+ models were then sought which were just acceptable to the X^2 statistic. These H^+ models are then those with the largest possible values for the layer parameters,

Table 1. The misfit of the response functions to the D^+ models listed in Table 2, and the minimum misfit to be able to reject the hypothesis that the data are from a 1D earth, at the 90% level of confidence.

Response	Number of degrees of freedom	X^2 misfit of D^+ model	Minimum X^2 statistic at 90% confidence level
EEP	22	0.0036	30.81
KEV	16	126.5	23.54
KEV*	12	12.65	18.55
KIR	18	3.91	25.99
NAT	16	3.62	23.54
SAU	14	9.67	21.06

KEV* is the KEV response without the two anomalous, and physically unacceptable, $\hat{g}_{KEV}$ values at 190 s and 900 s (see Fig. 2).

Table 2. The D^+ models for the response functions of interest in this work.

Site	Depth (km)	Conductance (S)
EEP	52.5	33
	137	362
	210	1160
	283	2780
	359	5280
	434	8310
	543	15600
KEV	0	178
	90.1	4130
	133	97300
	138	∞
KIR	0	56
	62.3	660
	143	1750
	203	13400
	314	71600
NAT	45.4	687
	157	1940
	249	34300
	291	∞
SAU	12.4	224
	47.6	1000
	245	∞

and are therefore the least delta-like. These modles are shown in Fig. 7. It can be seen that the H^+ models reproduce very faithfully all the pertinent characteristics of the "best-fitting" models illustrated in Fig. 5.

4. Discussion

Various points are significant about the models presented in the previous section. For the lower crust, there does not appear to be a substantial variation in electrical conductivity across the Moho seismic boundary beneath northern Scandinavia. As mentioned previously, 3-layer geoelectric models can be found that satisfy the observed responses at KIR, NAT and KEV. These models would then geophysically represent the upper crust, the lower crust and uppermost mantle, and the highly conducting asthenosphere. Note that all models for northern Scandinavia display an electrical resistivity in the range 100 – 300Ωm for the lower crust, thus classifying them as Type II according to JONES (1981b). Beneath SAU however, there is radically different lower crustal layer. This layer is highly con-

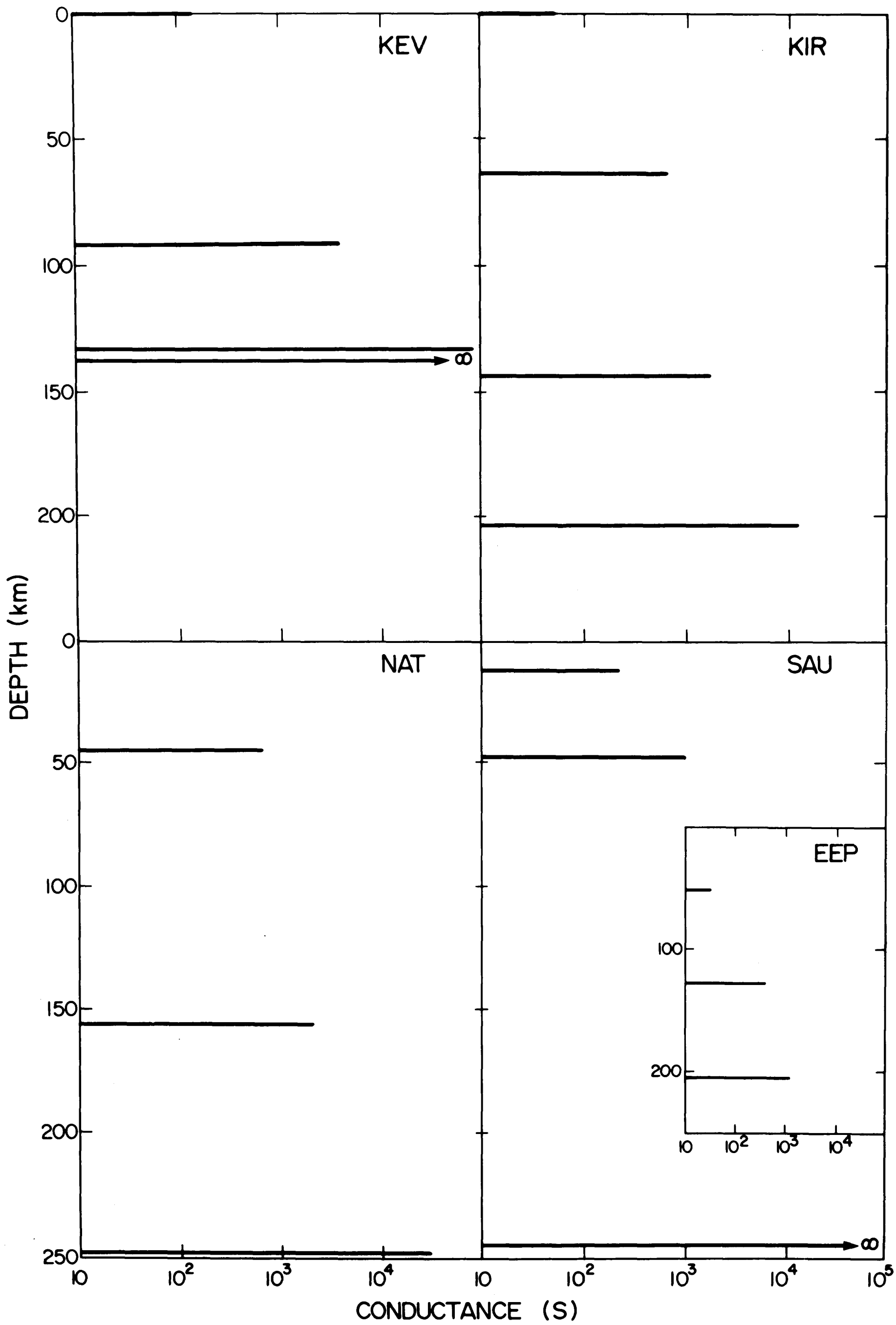

Fig. 6. The D^+ models for the response funcitons discussed herein. The misfits to the data are listed in Table 1.

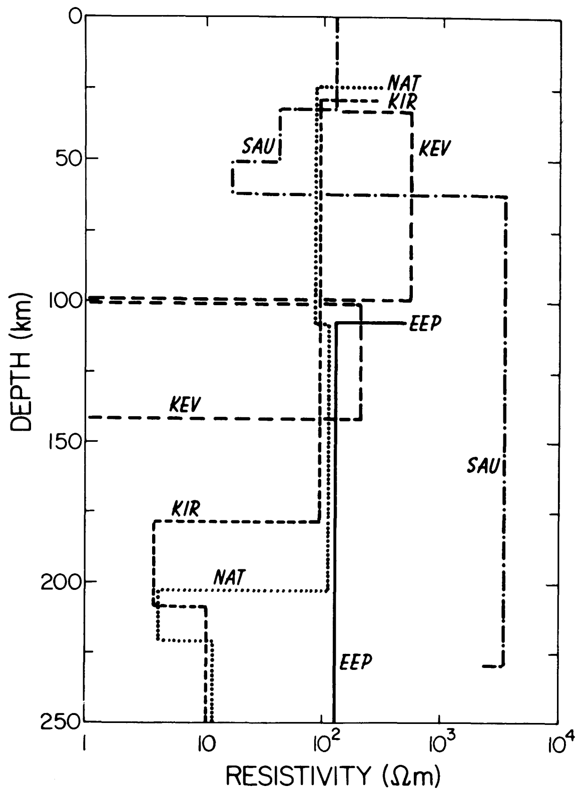

Fig. 7. The H^+ models derived by inverting the response functions with a layer parameter such that the X^2 misfit was the maximum permissable, i.e., these are the least delta-like acceptable models.

ducting, of resistivity in the range 10 – 50Ωm (Type III, JONES, 1981b), and is very difficult to explain without recourse to such speculative theories as graphitization or serpentinization. This highly conducting layer provides for a very large contrast in resistivity between it and the underlying layer. According to BUNGUM *et al.* (1980), the Moho beneath southern Finland is at a depth of between 45 – 49 km (see their Table 3). This depth correlates quite well with the transition zone of 62 km in Parker's H^+ inversion (see Fig. 7), and the average depth of 42 km in the Monte-Carlo inversion (JONES *et al.*, 1983). Hence, southern Finland may be one of the few locations where the seismic Moho transition corresponds to an electrical transition zone.

For the upper mantle, the resistivity beneath KEV, KIR and NAT appears to be very similar (this value was fixed in the Monte-Carlo search for the KEV response, but no such restriction was applied in Parker's H^+ inversion), but beneath SAU there is the indication that the upper mantle is more resistive, but not exceptionally so.

The most pertinent results for the ELAS project, however, are the requirements of a highly conducting zone within 200 km of the surface beneath all three northern Scandinavian stations. This zone appears to be closer to the surface beneath northeastern Norway/northern Finland (KEV) than beneath northern Sweden (KIR and NAT). Independent evidence for a transition to a conducting zone at around 100 km depth beneath KEV comes from the formal interpretation of MT data recorded at Lovozero on the Kola peninsular by VLADIMIROV (1976). A transition from 600Ωm to 80 Ωm at a depth of around 105 km was interpreted. The resistivity of the conducting zone is somewhat higher than the KEV value, but Vladimirov's longest period at which he had estimates was about 200 s (see his Fig. 1), and hence this model parameter is not well resolved. Also, MT work in the early 1960's by OELSNER (1965) on West Spitzbergen was interpreted as indicating the presence of a highly conducting zone, of resistivity 1Ωm, beginning at a depth of 115 km.

For northern Sweden, the correlation of the acceptable geolectric models with the seismic ones has been discussed in detail by JONES (1982a). Three different groups have proposed the existence of a seismic low velocity zone beneath Sweden to explain their observations (CASSELL and FUCHS, 1979; NOLET, 1977; GIVEN and HELMBERGER, 1980) – all at very comparible depths to the proposed highly conducting electrical zone. There is the indication, from the best-fitting models, that the asthenosphere is slightly deeper beneath NAT than beneath KIR (such a $2D$ effect would not seriously affect the $1D$ interpretation). However, models can be found in which this does not have to be true. The H^+ models also infer than the asthenosphere deepens and thins as one moves progressively towards the centre of the stable craton. Beneath KIR, the H^+ model indicates a highly conducting zone beginning at a depth of 178.5 km of resistivity 3.8Ωm and thickness 30 km. This implies a conductivity-thickness product of some 8000 S, which is a "well-developed" asthenosphere by VANYAN *et al.*'s (1977) criterion (a depth integrated conductivity greater than 1000 S). Beneath NAT, the zone is at a depth of 203 km, of 4.1Ωm and 18 km thickness, i.e., 4500 S integrated conductivity. For SAU, the earlier (JONES, 1982b) interpretation of the MT data (see Fig. 2), showing a shallower depth at 3000 s for $\hat{g}_{SAU}$ than for g_{EEP}, of an asthenosphere at 250 km is not confirmed by the inversion of the MT response function derived from a more rigourous analysis of the data.

5. Conclusions

In this paper, the results of various induction studies have been collated. These studies have shown conclusively that geomagnetic induction techniques are quite capable of giving estimated response functions with sufficient accuracy to be able to delineate the electrical asthenosphere and its variations with lateral position. The two methods employed, MT and HSG, gave surprisingly very compatible response functions. This effectively eradicates any aspersions concerning the possibility of telluric distortion effects on the MT responses, or of significant magnetic field distortion by the iron ore deposit at Kiruna.

The results show that beneath northern Scandinavia there must exist a highly conducting zone (i.e., resistivity less than 10Ωm) within 200 km of the surface. Such a zone must be deeper than 150 km beneath SAU, and is interpreted as existing at a depth of 300 km beneath the centre of the East European Platform from the model of VANYAN *et al.* (1977). Two other analyses, one on the Kola peninsular and one on West Spitzbergen, postulate the existence of a conducting zone at around 100 km depth. Thus, the distinct impression given by these studies is that the depth to this zone increases with increasing lateral distance towards the centre of the north European craton. This theory gains weight from the observations of ÁDÁM *et al.* (1983) on the Karelian megablock. They report that the Niblett inversion (which is exactly the same as the Bostick inversion, see JONES, 1983) of their data shows a continuous decrease of resistivity with depth with a form very similar to that of the EEP curve illustrated in Fig. 4.

The other result of importance is the requirement of a conducting lower crust beneath southern Finland. This zone explains the previously observed stronger attenuation of the vertical magnetic field component at locations south of the Svecokarelian fault compared to that observed to the north of it (KÜPPERS *et al.*, 1979). It could also explain the observations by PAJUNPÄÄ *et al.* (1983) of differences between western and north-eastern stations of their magnetometer array which straddled the Svecokarelian fault.

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