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Electrical Conductivity Beneath Iceland – Constraints Imposed by Magnetotelluric Results on Temperature, Partial Melt, Crust- and Mantle Structure

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Abstract. Magnetotelluric results from 38 sites in North Iceland yield a detailed spatial distribution of conductivity versus depth. A high-conductivity layer, about 10 Ωm, marking the transition between crust and upper mantle is detected throughout the surveyed area, its depth increases from 10 km within the zones of present tectonic activity to 20–30 km at a 50–100 km distance from the rift axis. The high conductivity layer indicates some basaltic melt fraction at temperatures around 1,000 °C. The calculated average crustal temperature gradients are 100–150 °C/km at the rift axis and 50–70 °C/km at about 100 km distance. Below this anomalous zone, down to 150 km depth, the conductivity decreases to 100 Ωm due to the ultrabasic chemical composition of the upper mantle and a possible decrease of melt content with increasing depth. The temperature gradient within the upper mantle cannot be more than a few °C/km. However, a highly conducting asthenosphere exists below 150 km depth.

The following petrological model for Iceland is suggested: Diapiric updoming of the asthenosphere leads to partial fusion of parent ultrabasic mantle material, resulting in segregation and upward migration of basaltic melt. Lower density, lower viscosity and higher mobility relative to the solid phase causes the melt to rise faster than the ultrabasic material. This melt fraction then forms the basaltic crust of Iceland which is thickening away from the ridge axis with increasing age.

Key words: Iceland – Magnetotellurics – High-conductivity layer – Temperature – Partial melt – Petrological model

Introduction

Correlation between electrical conductivity and temperature offers a unique chance to infer the temperature distribution in the Earth's interior from magnetotelluric data. Therefore, the magnetotelluric method is applicable to quantitative geodynamic modeling of the Icelandic rift zone.

In 1977 and 1980 magnetoelluric surveys in North and East Iceland were realized in a joint effort of the University of Munich, Germany, and the National Energy Authority, Iceland. A total of 38 magnetotelluric sites were occupied as shown on the simplified geological map (Fig. 1), partially preceded by geological investigations and shallow resistivity soundings. High-energy source fields at the high geomagnetic latitude of Iceland and the absence of technical noise made short recording times possible and high-quality data were obtained.

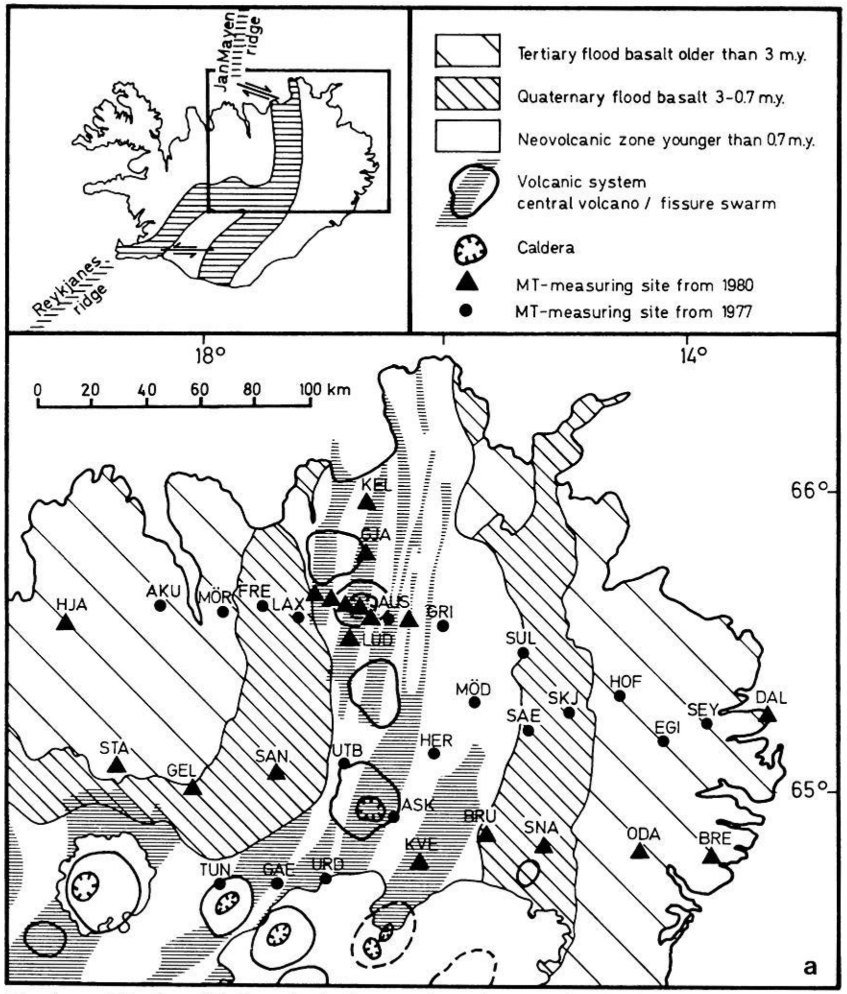
Mobile magnetotelluric equipment comprising 2-component electric-field amplifiers, 3-component flux-gate mangetometers, 3-component induction-coil magnetometers for shorter periods (6 s–1 h), and digital tape recorders were employed. In addition a line of 6 Askania variographs combined with long period electric field recorders (1 h–1 d) worked simultaneously at six sites during the 1977 survey. For more detailed information on the experiments and the geology, the reader is referred to Beblo and Björnsson (1978), and Beblo and Björnsson (1980), where first results and interpretations along with a description of data analysis and numerical modeling are presented.

Magentotelluric Results, Resistivity Models and Interpretation

Source Field Geometry and Geomagnetic Depth Sounding

According to Haak (1978), an inhomogeneous source field causes the MT response to be different from the zero-wavenumber response only if the skin depth is on the order of the spatial dimensions of the source. The longest periods used for our magnetotelluric modeling were 1,000 s corresponding to a skin-depth of about 50–100 km. This is small compared with the 400–500 km half-width of the polar electrojet, therefore the influence of its inhomogeneity is small enough to be negligible. However, complicated source fields during auroral substorms may have the same spatial dimensions as our profile of the Askania variographs (about 200 km).

Wolfgram (1980) concluded that the disturbed-time magnetic variations in the period range 200 s to a few h were dominated by the source-field geometry. The long-period magnetic data could not be used for geomagnetic



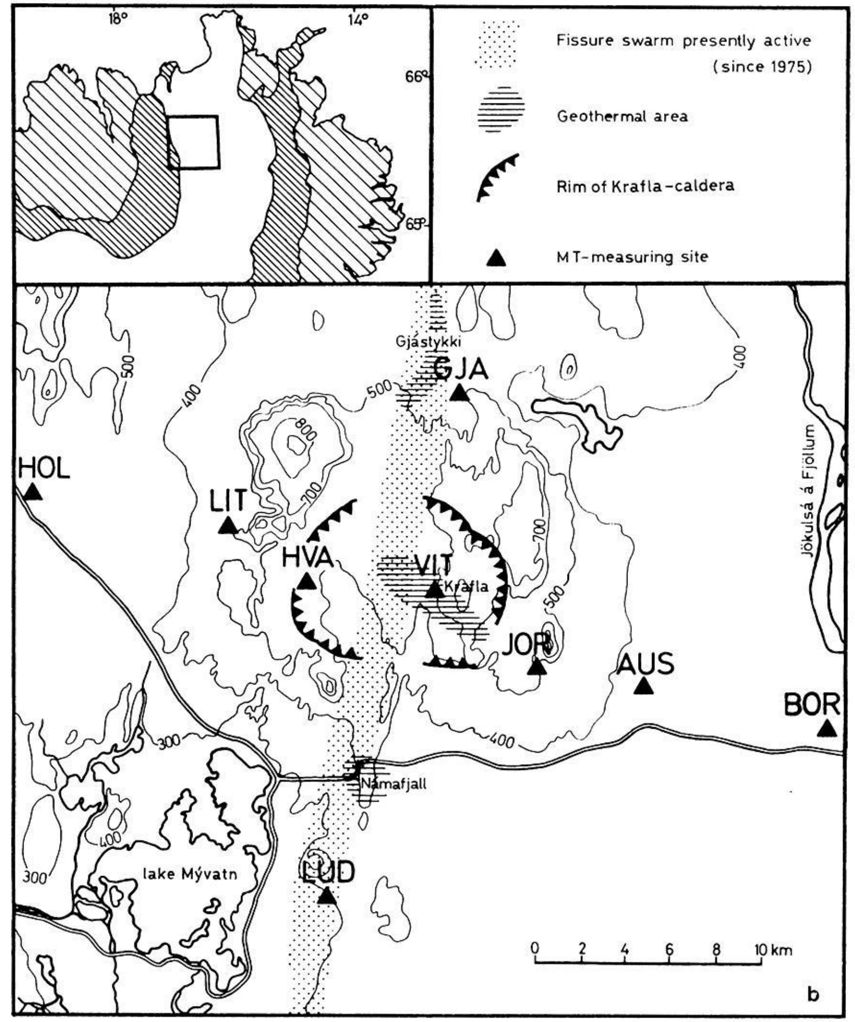


Fig. 1 a and b. Simplified geological map of northeast Iceland, showing locations of magenetotelluric measuring sites depth sounding because they contained too few variations with a vertical magnetic field component free of source effects. However, it was possible, on the basis of these data, to exclude a very pronounced, two-dimensional conductivity anomaly beneath Iceland at greater depth, that would caused transfer functions between vertical and horizontal magnetic variations to be larger than 0,1.

Interpretation of the Magnetotelluric Data

Using electric (E) and magnetic (B) fields recorded simultaneously one can determine a complex transfer function, the tensor $z\ (i,j) = E(i)/B(j)$. The elements of z depend on the conductivity distribution and on the orientation of the measuring coordinate system. As a first step in data processing the "preference direction" of the electric field was determined as the angle of coordinate rotation at which the two orthogonal electric field components are least coherent. The preference direction indicates lateral variations of the electric conductivity near to the measuring site. For a laterally uniform distribution of the conductivity (one-dimensional case) no preference direction exists. In the case of considerable variations of the conductivity in one horizontal direction (two-dimensional case) the electric field will be strongly polarized giving a well determined preference direction (Kemmerle 1977).

Within the Tertiary flood basalt areas the computed preference direction of the electric field indicates horizontal variations of the conductivity at crustal depths, whereas the preference direction disappears within the Quaternary flood basalt areas and within the Neovolcanic zone. For depths greater than 5 km these areas show approximately a one-dimensional conductivity distribution, i.e. a variation of conductivity with depth only.

Shallow resistivity soundings (Björnsson, 1976) show conductivities down to 2 km depth within the Tertiary flood basalt area distinctly lower than those below the Neovolcanic zone. This indicates that the Neovolcanic zone can be treated as a conductivity anomaly with a pronounced strike direction.

For a two-dimensional structure it is possible to rotate the coordinate system until one axis is parallel to the strike direction. Two independent systems of equations are then obtained to calculate the apparent resistivity ρ_a and the phase φ from the tensor z. The solutions are:

a) $\rho_{a_{\parallel}} = \frac{\mu_0 T}{2\pi} |z_{\parallel}|^2; \ \varphi_{\parallel} = \arg(z_{\parallel})$ E-Polarisation, TE-mode,

b) $\rho_{a_{\perp}} = \frac{\mu_0 T}{2\pi} |z_{\perp}|^2; \ \varphi_{\perp} = -\arg(z_{\perp})$ B-Polarisation, TM-mode.

In the case of a one-dimensional conductivity distribution both *TE*-mode and *TM*-mode, give identical solutions. This is more or less the case for all sites within the Neovolcanic zone.

Apparent resistivity and phase curves were obtained for all sites; some examples of the 1980 th survey are shown in Fig. 2. Small error bars of the 68% confidence interval reflect the high quality of the data. The scattering increases slightly at periods above 1,000 s because of

a) numerical corrections for the slope of the electronic high-pass filter,

b) lesser degrees of freedom for spectral averages at longer periods, and

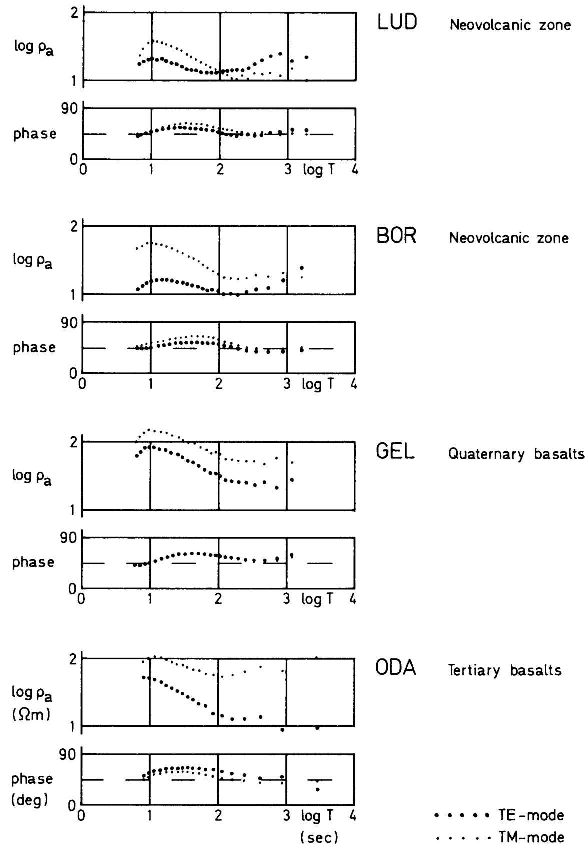


Fig. 2. Examples for apparent resistivities and phase differences, seperated in *TE*-mode ($\rho a_{\parallel}$, $\varphi_{\parallel}$) and *TM*-mode ($\rho a_{\perp}$, $\varphi_{\perp}$). Due to high data quality error bars are too small to be drawn for periods shorter than about 1,000 s. The shift of minimum $\rho a_{\parallel}$ toward longer periods in correspondence to an increase in depth to the highly conducting layer with increasing distance from the rift axis is clearly seen

c) the spatially inhomogeneous source fields (polar electrojet) being non-stationary.

For a first interpretation of the data, models of one-dimensional conductivity distribution versus depth were fitted to the *TE*-mode curve of apparent resistivity and phase at each site using the psi-algorithm of Schmucker (Schmucker, 1974). Due to the continuity of the parallel electric field across the boundaries of the two-dimensional anomaly the *TE*-mode curves are weakly distorted by horizontal near-surface inhomogeneities and reflect mainly the conductivity structure in greater depth.

At all sites the best fit was obtained with three-layer-models of the type: a good conductor for the second layer, poor conductivity below and above.

The results of the numerical modeling were assembled into some east-west sections (Figs. 3a–3d) across the rift axis and a north-south section (Fig. 3e) along it. They clearly show the zone of enhanced electrical conductivity throughout North Iceland dipping from about 10 km to 20–30 km depth with increasing distance from the rift axis. The sites LIT, HVA, and VIT on the rift axis exhibit an extremely shallow conductor (Fig. 3b) at about 5 km depth (Arnason, 1981). These sites are located within the Krafla central volcano where active rifting is taking place.

The results from a seismic refraction measurement near Krafla (Zverev et al., 1980) are superimposed onto the magnetotelluric results in Fig. 3b. Seismic reflecting horizons

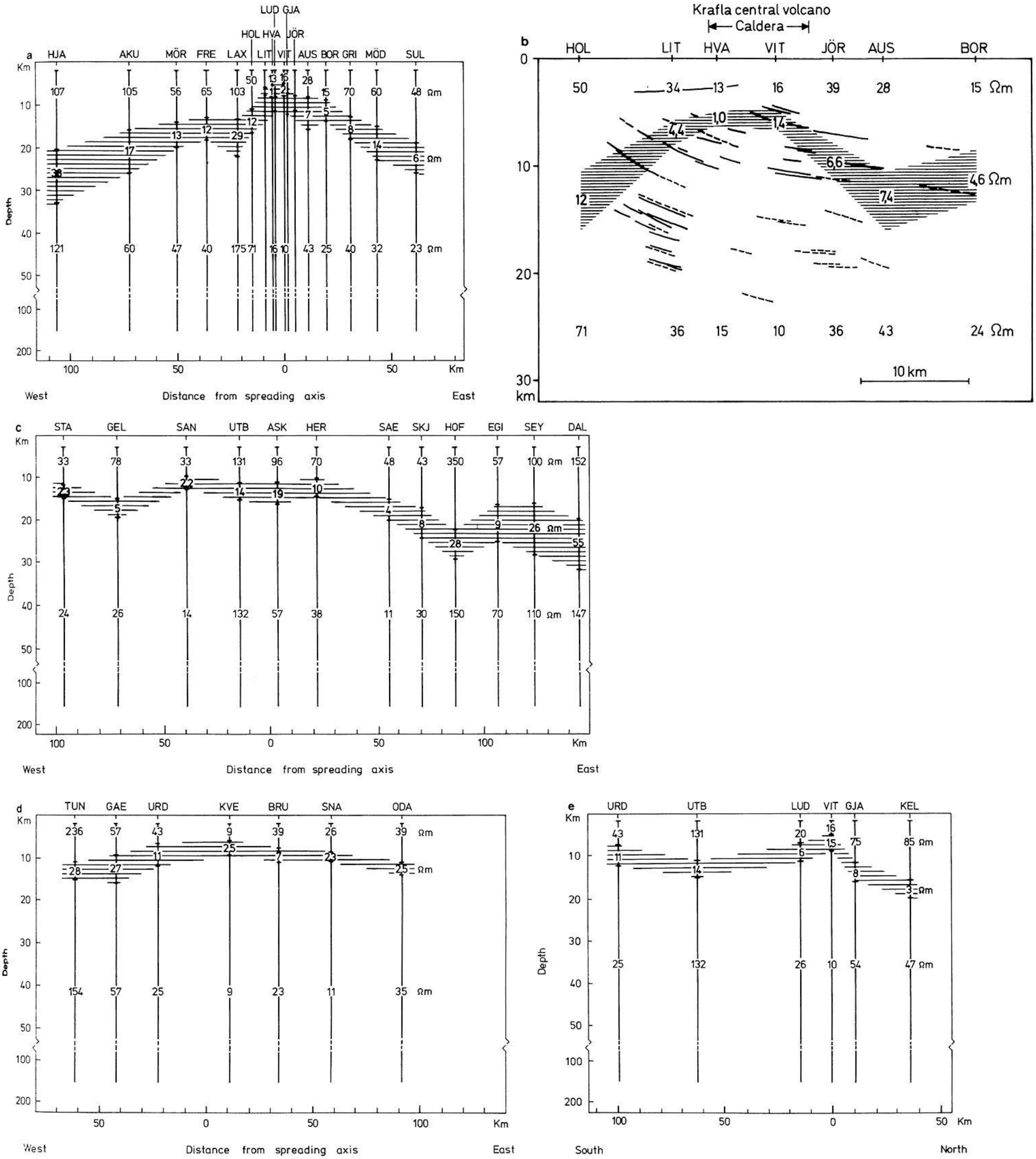


Fig. 3a–e. Models of one-dimensional conductivity distribution at all sites, calculated from apparent resistivities and phases of the *TE*-mode, and assembled into profiles. The hatched areas show a continous high conductivity layer with a mean resistivity of 10–15 Ωm. The numbers indicate resistivities in Ωm. **a, c and d** East-west magnetotelluric cross-sections perpendicular to the strike and centered at the spreading axis showing significant updoming of the high conductivity layer within the Neovolcanic zone. **b** Magnetotelluric cross-section through the currently active Krafla central volcano region (inner part of Fig. 3a) showing extremly high conductivities of 1–5 Ωm (hatched area) at only 5 km depth within the Krafla region. The high conductivity is very likely caused by deep circulating geothermal fluids, high-level melt accumulation and magma chamber below HVA and VIT. A seismic cross-section (Zverev et al., 1980) has been superimposed onto the magentotelluric results. **e** North-south magnetotelluric cross-section along the strike of the rift zone, centered on the Krafla central volcano

are absent below the rift axis at 10–15 km depth suggesting homogeneity in the physical properties at these depths. This seismically homogeneous body is interpreted by Zverev et al. (1980) as being a magma chamber. Microearthquake observations in the Krafla area indicate a confined magma chamber at 3–7 km depth (Einarsson, 1978) below the MT-stations HVA and VIT.

An shallow conductor was also found at the site KVE (Fig. 3d) located in the vicinity of the Kverkfjoell central volcano. The conductivity sections in Fig. 3c and Fig. 3e show an updoming of the conductor at the rift axis and a nearly horizontal position at about 10 km depth within the Neovolcanic zone, which is in agreement with seismic observations which indicate that no continous partially molten layer can be present above 10 km depth within the crust in NE-Iceland (Sanford and Einarsson, 1982).

The subsidence of the good conductor to the north of site KEL in Fig. 3e might be a result of thicker crust within and north of the Tjoernes fracture zone connecting the rift axis to the Kolbeinsey (Iceland-Jan Mayen) ridge.

The Coast Effect

Considerable horizontal changes in electrical conductivity near the coast affect the electromagnetic recordings. Stein (1982) computed and compared numerical modeling results with the two-dimensional distribution of conductivity with the magnetotelluric results of Iceland. The numerical modeling revealed two effects:

a) The coast effect is significantly enhanced if the horizontal gradient of conductivity increases. The influence of the coast effect increases with increasing period of the electromagnetic field variations.

b) Strong lateral gradients of the conductivity distribution, representing a more complicated geological structure, may conceal the coast effect.

Apparent resistivity and phase results at some magnetotelluric sites were chosen for comparison with the coast effect modeling results. The coast effect should be visible within the range SNA-ODA-BRE where BRE is located close to the coast line (cf. Fig. 1). The *TM*-mode fields may be affected when approaching the coast whereas the *TE*-mode fields do not show a coast effect.

In general, the coast effect was found to have less influence than expected. The preference direction of the electric field, the polarisation $p=(Z_{\|}/Z_{\perp})-1$, and the scewness $S=(Z_{xy}-Z_{yx})/(Z_{\|}-Z_{\perp})$ (Reddy et al., 1977) are better indicators for the presence of a coast effect. They indicate an effect at the site ODA and BRE which are nearest to the coast whereas no coast effect is indicated at SNA. On the other hand the Neovolcanic zone as a shallow conductive structure clearly dominates at the sites west of SNA. The northern sites (DAL-SKJ, Fig. 1) are affected by local, shallow contrasts in conductivity; their results could not be explained with the coast effect modeling.

Electrical Conductivity, Temperature, and Petrological Conditions in Crust and Mantle

An importand aim of magnetotelluric investiagtions of subsurface electrical conductivity distribution is to get some knowledge about temperature and petrology in the Earth's interior. The key to this is the change in the electrical conductivity of various rock types with temperature, pressure, oxygen fugacity and other parameters. These parameters have been investigated by several authors, and were complied and interpreted recently by Haak (1980). The usual petrological model for asthenospheric geodynamics (Ringwood, 1969; Waff, 1974) consists of an ultrabasic-peridotitic mantle with solid olivine and liquid basalts.

The average conductivity of basalts is one order of magnitude higher than that of peridotite at the same temperature. Either material is partially molten above 1,000 °C and liquid above 1,400 °C. This relation between electrical conductivity and temperature is valid only for almost dry rocks at depths greater than about 10 km. The conductivity in the uppermost kilometers of the Earth's crust depends mostly on the porosity and permeability of the rock matrix as the amount and chemical condition of the interstitial water.

A Petrological Model for Iceland

The shallow zone of enhanced electrical conductivity as inferred from our magnetotelluric numerical modeling (Fig. 3) is not limited to Northern Iceland since Hermance and Grillot (1970) found a shallow high conductivity layer at a site located within the Neovolcanic zone of Southern Iceland. Recently, Hersir et al. (1982) found a shallow zone of enhanced conductivity in Southern Iceland at a depth increasing with distance from the rift axis. Apparently, the magnetotelluric method does give the same conductivity distribution for North Iceland as it does for South Iceland, which is encouraging for the construction of a petrological model for Iceland.

Iceland's crust is manly build up of flood-basalt layers and basltic intrusions. If the basaltic crust reaches down to the depth of the 10–15 Ωm conductor, temperatures around 1,000 °C must be present. For detailed discussion on this point see Beblo and Björnsson (1980). At this temperature the basalts will already contain some melt fraction. If we assume the basaltic material to extend below the anomalous zone then the increased average resistivity of 100 Ωm at greater depth (Fig. 3) would indicate a decrease in temperature. This would not be in agreement with the geodynamic processes in rifting zones. In a rifting region an upward flow of material is conncected with an upward dragging of isotherms, i.e. an increase in temperature with depth. Consequently, the pronounced change in conductivity is a result of the change in chemical composition below the anomalous layer. We conclude that the material below the zone of enhanced conductivity is of ultrabasic composition, i.e. mantle material. For ultrabasites, a resistivity value of 100 Ωm gives a temperature of 1,000 °C at which partial melting is expected. The melt content is highest in the basaltic high conductivity layer – the base of the crust – and decreases with increasing depth within the upper mantle. These results – indicating a differentiating process in the mantle – are supported by seismic refraction experiments (Gebrande et al., 1980). They concluded a 17–23% melt fraction at depths between about 10–20 km, decreasing with increasing depth. An estimate of the amount of melt fraction from the magentotelluric results is difficult. Waff (1974) showed that two different models may describe the relation between electrical conductivity and melt fraction:

Model 1: Isolated, electrically conducting tubes and pockets of molten basalt are contained in a highly resistant matrix of solid olivine yielding an effective conductivity σ which is approximately that of the solid phase σ_s, where N is the percent melt fraction.

$$\sigma = \frac{1-2N}{1-N}\,\sigma_s.$$

A melt fraction of about 30% is required for a two-fold to three-fold increase of the electrical conductivity.

Model 2: Isolated, electrically resistant olivines are coated with a highly conductive, basaltic melt resulting in an effective conductivity which is approximately that of the liquid phase σ_l, where N is the percent melt fraction.

$$\sigma = \frac{2N}{3}\,\sigma_l.$$

A melt fraction of around 5% is sufficient to increase the effective conductivity by a factor 10 to 100 beyond the conductivity of the solids.

Hermance (1981) and Thayer et al. (1981) discuss the same facts by interpreting their magnetotelluric field observations in Iceland. Melt pillows (model 1) are not likely to be detected by magnetotelluric measurements because they increase the apparent conductivity only slightly. The zones of enhanced conductivity within the asthenosphere are on the other hand explainable with a continuously connected melt over large areas (model 2).

Shankland and Waff (1977) calculated the changes of temperature and melt fraction with varying electrical conductivity for the crust-mantle boundary. The melt fraction decreases with depth and is probably not more than 5% at about 100 km (30 kbar). Shankland and Waff showed that water contents as low as 0.1% H_2O do not significantly increase the melt fraction or, respectively, decrease the temperature.

Long-period (1,000 s–30,000 s) magnetotelluric results obtained by Haak and Damaske (1980) for the sites AUS and FRE (Fig. 1) fit consistently with our results. Their model shows a pronounced second increase in conductivity for the asthenosphere at 150–170 km depth. This deep-seated conductor shows up in the apparent resistivities above 10,000 s. The phase already exceeds 45° above 1,000 s and increases with increasing periods (Fig. 2), a sign of an increase in conductivity at greater depths.

It is interesting to compare the Mid-Atlantic-Ridge conductivity model for Iceland to MT-data measured in the Pacific-Rise crest by Filloux (1981, 1982). In Fig. 4 the conductivity models are shown for site FRE (Iceland) and station 1A (Pacific-Rise) which are at an equivalent distance from the spreading center. In both models the similarity of a pronounced high conductivity layer is evident at the base of the crust. Electrical conductivities for the asthenosphere from 100–200 km depth are also quite similar. In both places a systematic change of conductivity with crustal age seems to be evolved.

In conclusion, the model for the Earth's crust and mantle beneath Iceland based on the subsurface electrical conductivity distribution may be viewed as follows:

Beneath the rift axis diapiric-type motion in the updoming asthenosphere leads to partial fusion of mantle material, resulting in the segregation and upward migration of a basaltic melt. The melt fraction tends to escape due to its lower density, lower viscosity, and higher mobility as compared with the solid phase. Consequently, a chemical differentiation between melt fraction and rock matrix occurs whereby basaltic melt with a high electrical conductivity is "sweated out" from the olivine-ultrabasite-basalt multiphase system of the mantle. The melt fraction rises faster than the remining solid phase and creates a zone of magma accumulation from which Iceland's basaltic crust is generated, thickening away from the ridge with increasing age.

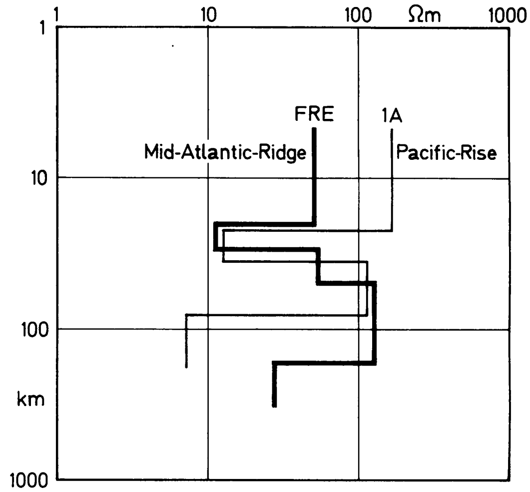


Fig. 4. The Mid-Atlantic-Ridge conductivity model for Iceland (Beblo and Björnsson, 1979, Haak and Damaske, 1980) compared to MT-results in the Pacific-Rise-Crest (Filloux, 1981, 1982). The conductivity models are shown for site FRE (Iceland) and station 1A (Pacific Rise). These sites are at the same distance from the spreading axis. The similarity of a pronounced high conductivity layer at the base of the crust is evident. The electrical conductivity from 100–200 km depth is also quite similar

This model developed from electrical conductivity is consistent with theoretical convection-models for the sub-ocean lithosphere (Bottinga and Allegre, 1976; Bottinga and Steinmetz, 1979). They started from a two-phase system composed of 75% peridotite and 25% basalt with a 1 cm/year drift rate which is in good agreement with assumed drift rates of Iceland. Their final model exhibits a zone enriched with basalt at depths of 15–20 km. The zone of enhanced electrical conductivity beneath Iceland encloses the calculated isotherms 1,000 °C and 1,100 °C entirely.

The Temperature Gradient Beneath Iceland

The MT-results suggest temperatures of 1,000 °C to 1,100 °C for the region of enhanced electrical conductivity. An average value for the temperature gradient in the Icelandic crust can be obtained by dividing these temperatures by the depth to the conductor. The temperature gradients obtained this way reach values as high as 150–180 °C/km at the rift axis and about 60 °C/km at a distance of 100 km (Fig. 5). However, the values at the rift axis scatter considerably. The reason for this is very likely irregular distribution of deep circulating geothermal fluids and magma accumulation in the crust of the active spreading zone. Hydrothermal alteration and circulation of saline geothermal water within the fractured Neovolcanic zone in Iceland may raise the conductivity considerably. Below about 5 km depth most cracks and pores are probably closed. Electrolytic conduction is thus not likely in the depth range greater 5 km, and therefore the high conductivity requires high tempera-

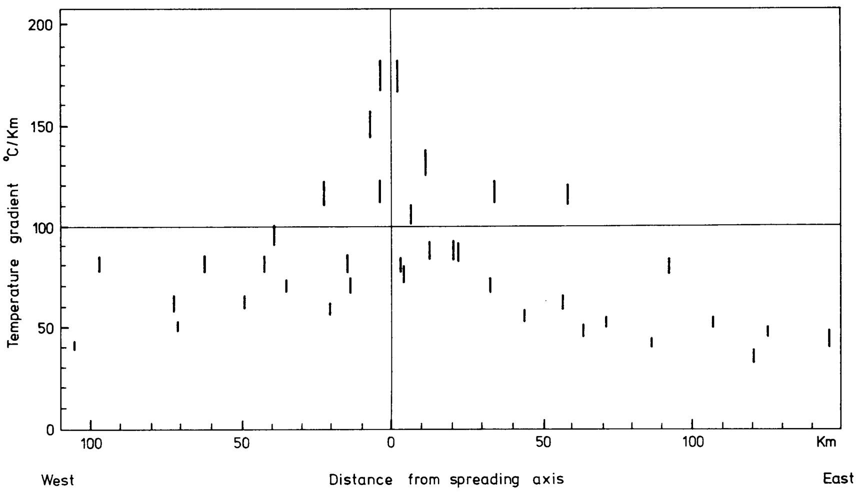


Fig. 5. Thermal gradients for the Icelandic crust, centered on the spreading axis, as inferred from the magnetotelluric results. The vertical bars show the mean temperature gradient at each site assuming a temperature range of 1,000–1,100 °C in the centre of the highly conducting layer

tures caused by magmatic intrusions, dykes or sills and high level magma chambers.

The temperature gradients obtained from magnetotellurics are consistent with borehole temperature measurements from Iceland (Palmason et al. , 1979) as well as from measurements on the Mid-Atlantic Ridge south of Iceland (Bram, 1980).

The conductivity models (Fig. 3) show values of 100 Ωm or even more for the deep layer. In the case of constant increase in temperature with depth the conductivity of ultramafic rocks should be about 10 Ωm, an order of magnitude lower than measured by magnetotellurics. Therefore the temperature gradient must be much lower within the upper mantle than in the crust. According to Shankland and Waff (1977) a theoretical mantle geotherm of 3–4 °C/km may be possible. Hermance and Grillot (1970) as well as Haak and Damaske (1980) inferred mantle geotherms of 2 °C/km from their long-period magnetotelluric results.

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