RELATIONS BETWEEN ELECTRICAL CONDUCTIVITY AND PETROLOGICAL PARAMETERS OF THE CRUST AND UPPER MANTLE

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Abstract. Laboratory data of the electrical conductivity of rocks and minerals pertinent to the deeper crust and upper mantle are summarized. They are discussed in the context of a theory to calculate effective conductivities of materials in the state of partial melt. Most published data have been obtained by too rapid measurements, i.e. without reaching an equilibrium state of the sample. Conductivity measurements on a material similar to the composition of pyrolite are not yet known, their importance is outlined. A global conductivity distribution obtained by electromagnetic induction studies is represented by a few results covering oceanic and continental areas. Till today it seems to be a doubtful venture to deduce the temperature of the upper mantle or even the existence of a partial molten asthenosphere from a global conductivity distribution. On a more local scale the correlation of electrical conductivity with temperature and state of the material seems to be more realistic. This is tentatively shown by two petrological models of the Afar depression in Ethiopia and of the mid-oceanic rift.

1. Introduction

It seems to be a simple question: How does the electrical conductivity of upper mantle material depend on temperature under the conditions of the upper mantle? It also seems to be a common experience that no straight forward answer – if any at all – can be given (Duba, 1976). This one simple question may be split up into several, possibly unanswerable, questions: What does the mantle material consist of, which partial pressures of oxygen and water do exist in the upper mantle, how can one control technically upper mantle conditions in a laboratory, how can one get mantle material, etc. In a recent paper Schock *et al.* (1977) solved the problem of the nature of the mantle material, or its main constituent at least, by referring to Shakespeare (1622). This up to now widely unknown petrologist, in his tragedy Othello, indeed mentioned 'chrysolite' as the material of which the Earth consists. However, reading the corresponding sentence twice one gets the feeling that even Shakespeare doubted such a simple model. Unfortunately, the course of the tragedy prohibited any further discussion of this important item. Fortunately, new laboratory measurements, mathematical and physical model considerations, and new results from the petrology of the upper mantle, during the last decade, may give clues to the answer of that simple question asked primarily.

2. Laboratory Results

Without any doubt, olivine and pyroxene are candidates for the mineral constituents of the mantle material, whilst peridotite and eclogite are candidates for the rock constituents. This was the reason for measuring the electrical conductivity of these materials as a function of temperature in a great number of experiments. I do not want to repeat the excellent review given by Duba (1976) about the primarily diverging laboratory curves and about

Geophysical Surveys (4) (1980)57-69. 0046-5763/80/0041-0057$01.95.

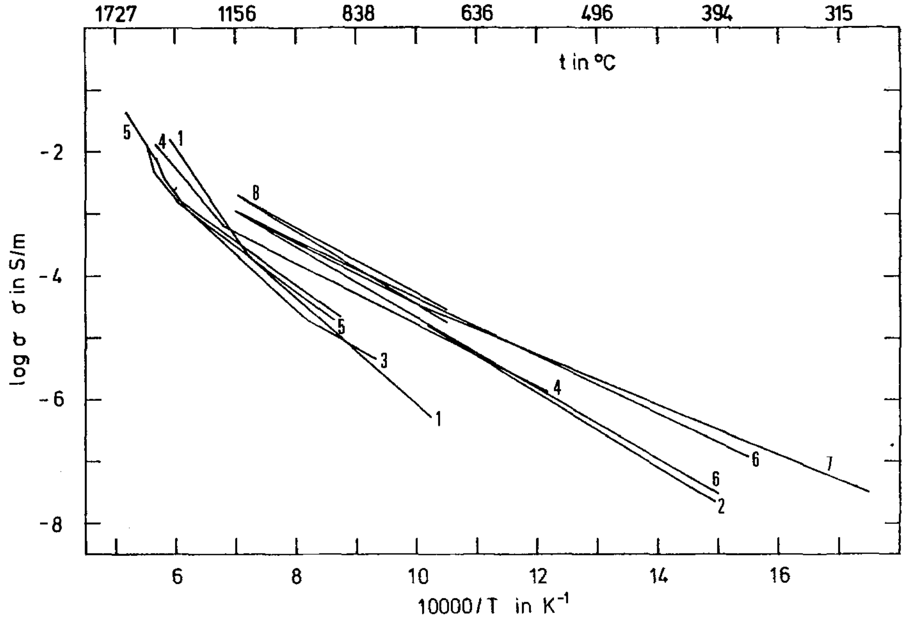

Fig. 1. The electrical conductivity of selected olivine single crystals and polycrystalline olivines of natural consistence. The selection is restricted to the least conductive samples, since noncontrolled conditions during the experiments tend to increase the conductivity (electrical isolation, oxydizing, cracks, etc.) The higher conductivity results which are not presented here may be influenced by the experimental conditions. It should be kept in mind that the presented conductivities indicate a lower limit of the conductivity of olivines. (1) Hughes 1953; (2) Duba 1972; (3) Duba, Nicholls 1973; (4) Duba *et al.*, 1974; (5) Duba *et al.*, 1974; (6) Red Sea peridot in Ni/NiO, Haak (1980); (7) Brazilian peridot in Ni/NiO, Haak (1980); (8) Polycrystalline olivine, Schock, *et al.*, 1977.

the methods to reduce the spread and to measure one, reproducible curve. In Figure 1, I selected some of the most resistive laboratory curves for olivine, which represent the electrical conductivities under those conditions of temperature and oxygen-fugacity as are suggested to be relevant for the upper mantle. The curves 6 and 7 have been measured at the upper limit of the olivine stability field, by using a Ni/NiO buffer. Schock *et al.* (1977) investigated whether the polycrystalline structure of the sample could enhance the conductivity as is generally believed. The results of their measurements are included in Figure 1 as the two bifurcating lines no. 8. Taking into account the non-buffered atmosphere during the experiment this result clearly points to equal 'resistive' curves such as they are known for single crystals, in contradiction to the general belief. This result does not, of course, exclude the conductivity enhancing effect of the 'dirty' grain boundaries of a polycrystalline structure (Shankland and Waff, 1977). These low conductivities of olivine, though reproducible and oxygen-fugacity controlled, were very reluctantly accepted, since all comparisons with the electrical conductivities of the upper mantle which have been determined by electromagnetic induction studies have yielded temperatures that are simply too high and which are not compatible with the known petrology at these depths.

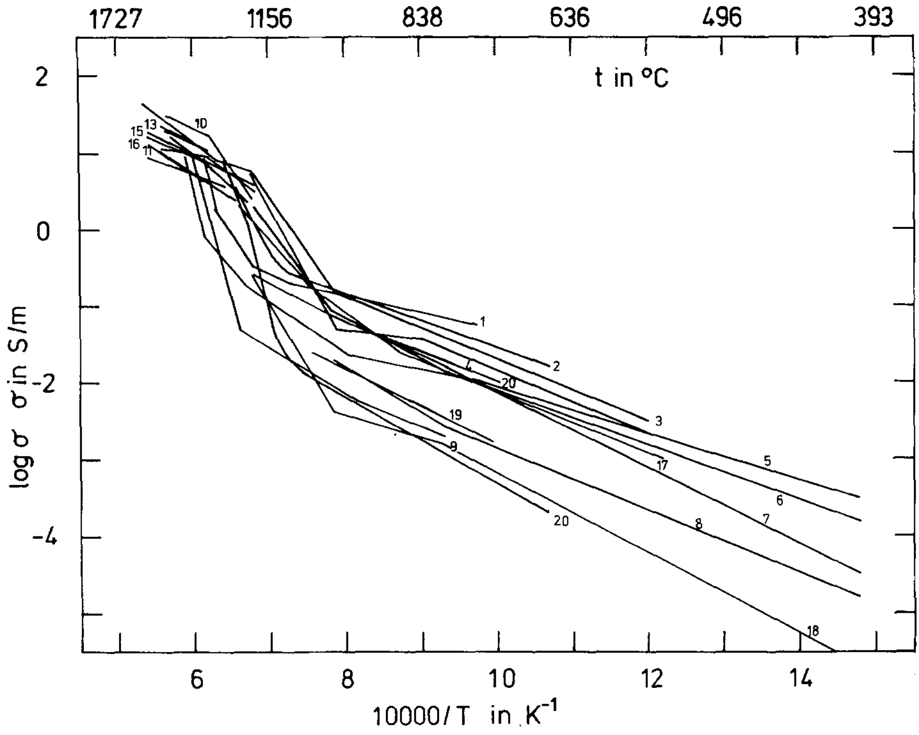

Fig. 2. The electrical conductivity of natural and synthetic basalts of various consistency. A representative average of all basalts curves should give more weight to the lower conducting curves than to the higher ones, since too rapid cooling rates yield too high conductivities of not equilibrated basalt. (1) Olivine tholeiites (Khitarov *et al.*, 1970); (2) (Presnall *et al.*, 1972); (3) Nephelinite; (4) basanit, (Rai, Manghnani, 1978a); (5) Rift basalts; (6) Island basalts (Indian ocean); (7), (8) Alkaline basalt (Bondarenko and Galdin, 1972); (9) Al-tholeiite (Khitarov et al., 1970); (10) Tholeiite (Rai and Maghnani, 1978a); (11), (13), (15), (16) Basaltic melts (Waff and Weill, 1975); (14) Alkali basalt (Rai and Maghnani, 1978a); (17) (Watanabe, 1970); (18) Olivine basalt (Bondarenko and Galdin, 1972); (19) with QMF buffer (CO_2/CO); (20) pure CO_2 buffer (Duba, 1976).

The second, but minor candidate for a main constituent of the mantle material, namely basalt as the low pressure equivalent of eclogite, has also been investigated extensively, see Figure 2. It should be emphasized that the conductivities of basalt in the solid state depend on oxygen fugacity (Duba *et al.* 1975), and, furthermore, that the conductivities depend on time near the solidus temperature due to slow equilibrium processes of the order of magnitude of several days up to months (Presnall *et al.* 1972; Duba *et al.* 1975). Finally, the electrical conductivity of molten basalt does not depend on oxygen fugacity (Waff and Weill, 1975). Most of the curves presented in Figure 2 were measured in air or some inert atmosphere, however not under conditions of fugacity relevant for the upper mantle. If one compares curve no. 19 measured with a fugacity close to that of a quartz-fayalite-magnetite buffer, yielding thus corresponding low oxygen-fugacities, one may infer that the results are indeed representative for the conductivities of basalt. The temperature at which the conductivities begin to increase strongly may be somewhat uncertain since extremely low heating rates of the order of days would probably shift the beginning of the steep rise to somewhat lower temperatures.

At the present state of knowledge, the reliable results seem to be the conductivity of the solid state olivine and the conductivity of basaltic melt. These two facts serve as the two 'columns' on which a theory has been built up to calculate an effective conductivity for various compositions and conditions of the upper mantle (Honkura, 1975; Waff, 1974; Shankland and Waff, 1974, 1977). The basic idea is to calculate the effective conductivity of a material consisting of two components with different conductivities. The one component is a solid state matrix of olivine, the other a basaltic melt. A more simplified but still effective formulation of the resulting conductivity as a function of the conductivities of olivine, basalt and melt fraction has already been given by Maxwell (1892). Two different models must be distinguished: In Model 1, well-conducting melt bubbles are isolated in a poorly conducting olivine matrix, in Model 2 poorly-conducting crystals are completely surrounded by a well-conducting melt. The essential idea is to incorporate experimental results from the petrology of the process of melting under various conditions. Model 2 seems to be the better approximation with respect to the melting process on a microscopic scale. Even at a low degree of melting the melt spreads rapidly to surround the residual crystals, while isolated melt pockets have not been observed (Green and Liebermann, 1976, p. 73). On the other hand, at a high degree of melting, magma is squeezed out and segregates in isolated magma chambers. With respect to the limited resolution of electromagnetic induction studies, Model 1 must be favoured now. However, the problem is still ambiguous, since, e.g. in Model 2 a high effective conductivity may be due to either a high temperature and a low melt fraction or to a low temperature and a high melt fraction. This problem concerning the amount of melt at a given temperature has been investigated extensively by many petrologists (e.g. see Wyllie (1971), Ringwood (1975), Scarfe *et al.* (1972)). In addition, the important influences of time, water content and pressure can now be taken into account. Many petrologists argue that for various reasons 0.1% water has to be present in the mantle. The effect of time on melting has clearly been demonstrated by Scarfe *et al.* (1972). They investigated the melting of a garnet peridotite, a rock most probably originating from the upper mantle. A solidus temperature of this rock 1225° C ± 20° was measured after keeping at each run the temperature constant for at least 4 days. Then four samples of the same rock were heated up to 1250° C to observe melting as function of time: After 1 h, Sample 1 displayed just traces of melt, after 1 day Sample 2 yielded 10% melt, after 4 days Sample 3 yielded 15% melt and finally after 7 days Sample 4 displayed 16% melt. This slow process of melting must be taken into account when measuring the electrical conductivities of such ultraframic rocks. Rai and Manghnani (1978a) measured indeed the electrical conductivity of the same specimen, at a heating rate of 300 K/h. Their results will be discussed later on. Shankland and Waff (1977, Figures 6 and 8) used the resulting relations between melt fraction, temperature and pressure to calculate the effective conductivity of a material consisting of solid olivines and basaltic melt.

The question is whether such an artificial material is in any relation to the real material of the earth's mantle. Only a few natural minerals and rock types are discussed by the petrologists as the possible constituents of the mantle material. One can therefore compare the electrical conductivities of these materials so far measured with the conductivities calculated by Shankland and Waff (1977). Unfortunately, the authors presenting the laboratory results for the electrical conductivity do not always use the same words for the same material as defined by the petrologists, e.g. in the 'conductivity' literature the word olivine is used in two senses: in the first (correct) sense, olivine is a solid solution of the two minerals forsterite (Mg_2SiO_4) and fayalite (Fe_2SiO_4). It is generally accepted that the olivine in the mantle consists of 10% fayalite and 90% forsterite. In the second, incorrect, sense, the word olivine is used to designate minerals consisting of more minerals than just olivine (e.g. orthopyroxene). They seem to be identical with peridots, a single crystal even of gem quality. Peridotite, however, is a rock containing more than 50% olivine. Olivinites (e.g. Bondarenko and Fel'dmann, 1973) do not seem to be identical with olivine as described above. Rather, they may be identical with peridotites or with dunites, which are rocks containing 90% olivine, probably originating from the upper mantle.

Eclogite may be thought of as a basalt under high pressure, it probably forms part of the lower crust and the upper mantle. At a still greater depth, a rock compound of olivine and orthopyroxene, called harzburgite, is believed to exist, underlain by lherzolite, a composition of olivine, orthopyroxene and clinopyroxene. Since the latter mineral melts first one can imagine that the harzburgite layer is the residual material derived from lherzolite by repeated heating and partial melting. In this sense lherzolite itself could be the residual material of a still more primitive mantle material. Ringwood (1976) 'invented' such a mantle material, which he calls pyrolite. Bottinga and Allegre (1976) remarked that this word pyrolite is exclusively used by Australian petrologists and by geophysicists. Though there may exist some controversial ideas about the mantle material among the petrologists, the concept of pyrolite is persuasively simple: Heating pyrolite yields 3 parts olivine (in the second sense) and 1 part basalt. Therefore one can define the upper mantle material mentioned above according to Green and Liebermann (1976): (a) harzburgite – pyrolite – (20-30)% basalt, (b) lherzolite = pyrolite – 10% basalt. A number of investigations of the petrological and physical properties of the pyrolite seem to confirm that it can be regarded as a good approximation to the mantle material. With the experimental data for pyrolite Green and Liebermann (1976) deduced a seismic velocity distribution for the upper mantle which agrees very well with the velocity distribution as obtained from seismic field experiments. Laboratory measurements on the electrical conductivity for pyrolite are not yet known. However, one should get at least an idea about the conductivity of pyrolite by measuring the conductivity of ultramafic rocks as presented in Figure 3. Obviously, the question is now, whether these laboratory curves are representative for the electrical conductivity of the real upper mantle material. Another question is whether a method such as that of Shankland and Waff (1977) yields conductivities comparable to those resulting from measurements. Quite generally, two temperature regions may be distinguished according to the slopes of the conductivity curves. In the low temperature region the activation energy[1] is less than 1 eV, in the high temperature region the acti-

[1] The activation energy A is defined by $\sigma(T) = \sigma_0 \exp(-A/kT)$, with $\sigma(T)$ = electrical conductivity at absolute temperature T, σ_0 = constant factor, k = Boltzmann constant.

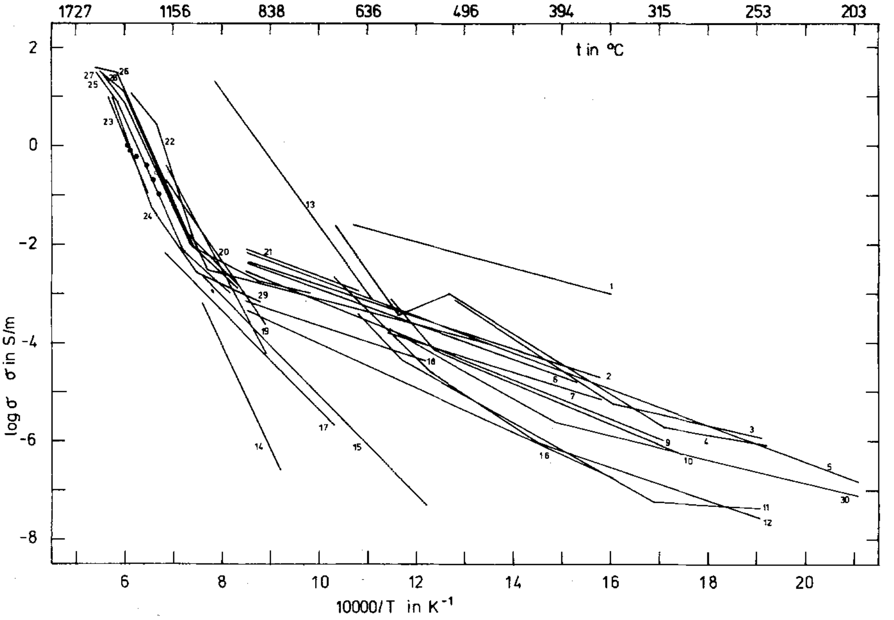

Fig. 3. Electrical conductivity of ultramafic material. A prominent feature of this material is the steep rise of the conductivity function with 'activation energies' between 2 and 4 eV, a somewhat enigmatic result (c.f. text.) (1), (2), (5), (6), (7), (9), (16), (18), (21) eclogites (Lastovickova, 1976); (3), (11) peridotites; (4) dunites; (10), (12) olivinites (Dvořak, 1973); (13) olivinite + peridotite (Bondarenko and Fel'dmann, 1973); (14), (15) peridotite (Parkhomenko, from Bondarenko and Fel'dmann, 1973) + plagioclase peridotite (Bondarenko and Fel'dmann, 1973); (17) dunite (Bondarenko and Fel' dmann, 1973); (19) pyrope spinel dunite; (20) pyrope peridotite (Bondarenko and Fel'dmann, 1973); (22) garnet websterite; (24) spinel lherzolite; (25) garnet peridotite; (26) garnet lherzolite; (27) garnet peridotite; (28) eclogite (Rai and Maghnani, 1978b).

vation energy is formally calculated to be between 2 and 4 eV. The 6 black dots represent the conductivities calculated by Shankland and Waff (1977, Figure 8, curve SPH), which are based on the melting experiment described. The measured conductivity of the same specimen, a garnet peridotite, is presented by curve 25. Since the 3 lower dots lie on the curve itself and the deviation of the 3 upper dots is not large, the calculated and the measured conductivities seem to be in good agreement. Actually the question arises, why do they agree? The steep slope of the curve in the high temperature region can be interpreted by an increasing amount of melt. This interpretation seems to be reasonable, since all the measurements shown here have been made under quite different oxygen fugacities and the conductivity curves do not diverge – in contrast to what we know from the conductivities of olivines. Since Waff and Weill (1975) demonstrated that the conductivity of the melt does not depend on oxygen fugacity, one could think the steep slope is indeed best interpreted by melting. But this is impossible: Scarfe et al. (1972) observe the solidus temperature to be at 1225°C and they need at least 4 days to obtain the state of equilibrium. The lowermost dot marks the solidus temperature which obviously does not coincide with the beginning of the steep slope. It is unimaginable that the rocks begin to melt at lower temperatures: the heating rate during the conductivity measurements was 300 K/h, whereas the heating rate in the experiment of Scarfe *et al.* was much slower needing at least 1 h to detect a trace of melt and 1 day to get 2/3 of the melt fraction in equilibrium state. Though the measurements are made on a specimen of the same rock, the results are not yet comparable, since the experimental conditions have been too different.

Notwithstanding the still missing proof of the validity of the method proposed by Shankland and Waff (1977) (on the same rock under the same experimental conditions), this method gives at present the only possibility to determine the electrical conductivity of the upper mantle material in the laboratory. E.g. till now it is impossible to measure the electrical conductivity of a rock containing 0.1% water at upper mantle temperatures. The determination of its melting-temperature relations seems to be a feasible venture.

3. Global Field Studies

Some selected results from electromagnetic induction methods are presented in Figure 4. Banks (1972) and Schmucker (1974) evaluated data obtained in continental areas. However, Bank's curve is mainly based on D_{st}-variations and is therefore uncertain for depths less than 400 km (Schmucker, 1974). Schmucker's curve is based on S_q- and D_{st}-variations thus holding for the whole depth range as indicated. At 500 km in Schmucker's curve a merely 'mathematical' step appears which can be replaced by a continuously decreasing resistivity function. A comparison of the conductivities obtained by Schmucker with the conductivities of the olivine single crystals in Figure 1 yields temperatures as high as 1400–1600°C. Even higher temperatures would be inferred from the conductivities below Hawaii obtained by Larsen (1975). It is open to question whether this conductivity curve is representative for the oceanic upper mantle or for an anomalous mantle. The conductivity of depths more than 100 km determined by Poehls and Von Herzen (1976) in the Atlantic Ocean seem to be more compatible with the conductivity obtained by Schmucker (1974) for the same depth in continental areas.

The desirable estimation of the temperatures on the basis of the Shankland-Waff-models incorporating the effect of pressure and the presence of a reasonable amount of water is (because of their conductivity range) beyond the scope of the present discussion. A comparison of the conductivity of the ultraframic rocks in Figure 3 with Schmucker's conductivities gives 'reasonable' temperatures between 1000 and 1200°C down to a depth of 400 km. Still, it is not certain whether these experimental conductivities are reliable values since these measurements are not performed under the corresponding pressures and water fugacities of the upper mantle.

At present, it seems to be impossible to deduce objectively 'reasonable' temperatures for the mantle. Two possibilities exist to 'modify' the present knowledge in order to get 'reasonable' temperatures. The first possibility refers to the uncertainties of petrology, leading to 'dirty' grain-boundaries (Shankland and Waff, 1977) which enhances the effective conductivity of an olivine matrix, respectively lowering the temperatures. The second

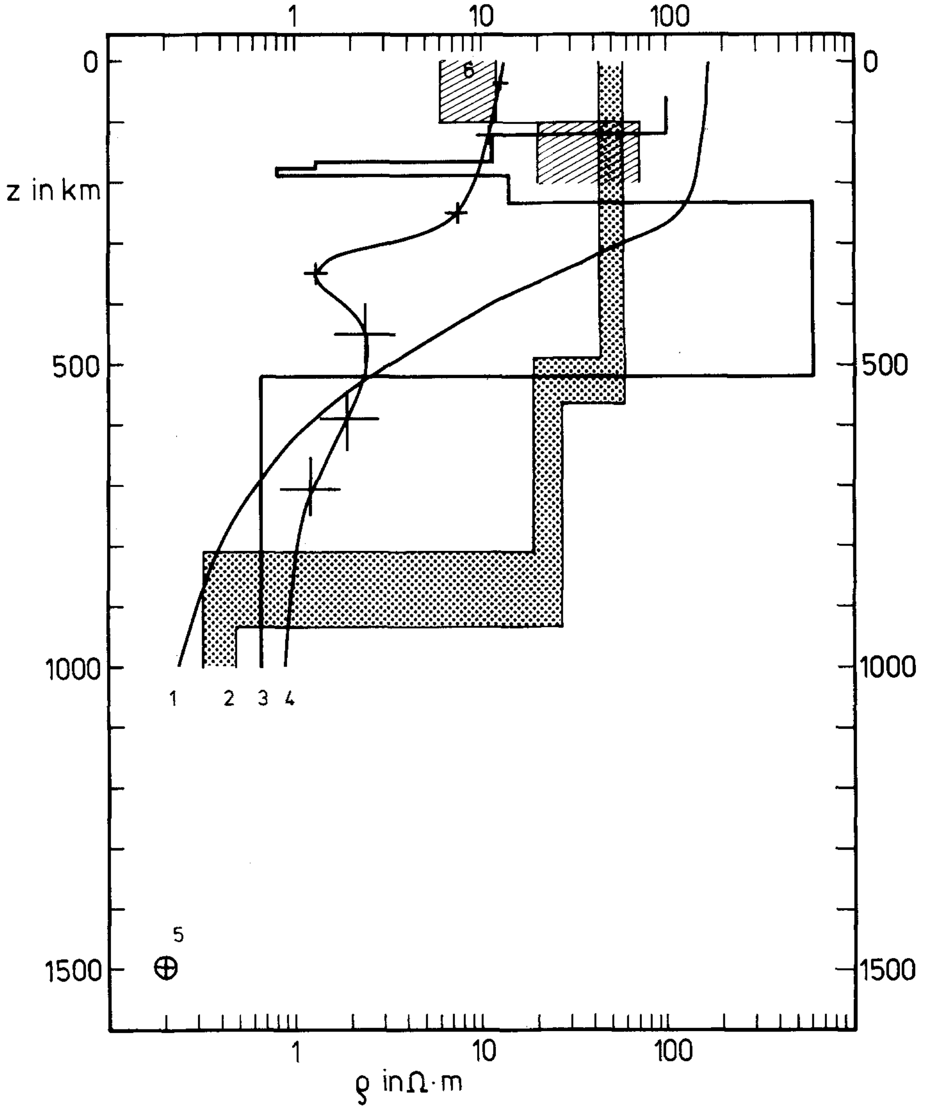

Fig. 4. Electrical resistivity of crust and upper mantle as determined by electromagnetic induction studies. (1) Banks (from Rikitake 1974); (2) Schmucker, 1974; (3) Tucson model (Larsen, 1977); (4) Hawaii model (Larsen, 1977); (5) Isikara, 1977; (6) Poehls and Von Herzen, 1976.

possibility refers to the poor resolution of conductivity-depth structures of the electromagnetic induction method with its averaged conductivity values which are without direct physical significance. Both methods appear of equivalent significance and could both be used to deduce any wanted temperature distribution in the upper mantle.

Figure 4 does not display the suggested low resistivity layer between 100 and 300 km except for the resistivity profile for Tucson (Larsen, 1977). Larsen comments that his model is preliminary. Poehls and Von Herzen (1976) construct a 'geological' model with a low resistive layer at 100 km depth which is still compatible with their data (not presented in Figure 4). But as their measurements are carried out on the ocean floor it must be taken into account that the highly conducting seawater further decreases the conductivity-depth resolution. It seems to me that the geological model of Poehls and Von Herzen should not hold for the existence of a low resistive layer. If the asthenosphere is defined as a seismic low velocity zone, and if the low velocity is explained by partial melt as low as 1% or less (Green and Liebermann, 1976) containing 0.1% water at 1100°C, then a measurable decrease of the resistivity appears unlikely. Indeed, there must be a transition zone of the high resistivity of the crustal rocks to the low resistivity of the mantle. But it is questionable whether this transition zone can be located at the top of the asthenosphere.

The role of high pressure on conductivity cannot be summarized adequately within the limited space of this review. Quite generally there exists only a slight dependence of the conductivity on pressure, at least at high temperatures as can be expected at corresponding depths. The spectacular increase of conductivity in shock pressure experiments (Schulien *et al.* 1978) possibly only exists at low (room-) temperatures. Duba (1976) doubted the conductivity jump at the transition from the olivine- to the spinel-structure as far as laboratory data are concerned. This result may also be inferred from the global induction studies presented in Figure 4. However, the strong decrease of the resistivity at still greater depths (800 km in Schmucker's curve, no. 2 in Figure 4) could probably be an effect of pressure and phase transition. Quite obviously all conductivity curves converge at a depth of about 1000 km and at a resistivity of 0.2–0.5 Ωm, pointing to the lowermost conductivity value ever calculated from external inducing magnetic fields (Isikara, 1977).

4. Regional Field Studies

Correlations between conductivity, temperature and composition can possibly be given on the smaller scale of local anomalies, which will be discussed in the following two examples in the context of the Shankland-Waff and the pyrolite model. For the Afro-Arabian dome Gass (1975) proposed a petrological model (see Figure 5) which can be transformed into a resistivity model. The anomalous mantle – defined as a material of low seismic velocity – is correlated with partial melt. The melt fraction must be of the order of 20% to be able to produce the rising melt batches shown. Applying Maxwell's Model 2 the anomalous mantle should have resistivities around 1 Ωm and less. The lithosphere is defined by normal seismic velocities. Since the melt batches apparently succeed in penetrating the lithosphere, the material is heated up and depleted from all low melting minerals as e.g. clinopyroxene and garnet. Thus a mineral composition close to harzburgite is attained. Its conductivity at a given temperature should be close to the conductivity of the olivine crystals given in Figure 1. The melt batches are well conducting, but they are not interconnected. Then Maxwell's Model 1 yields a resistivity of about 1000 Ωm at

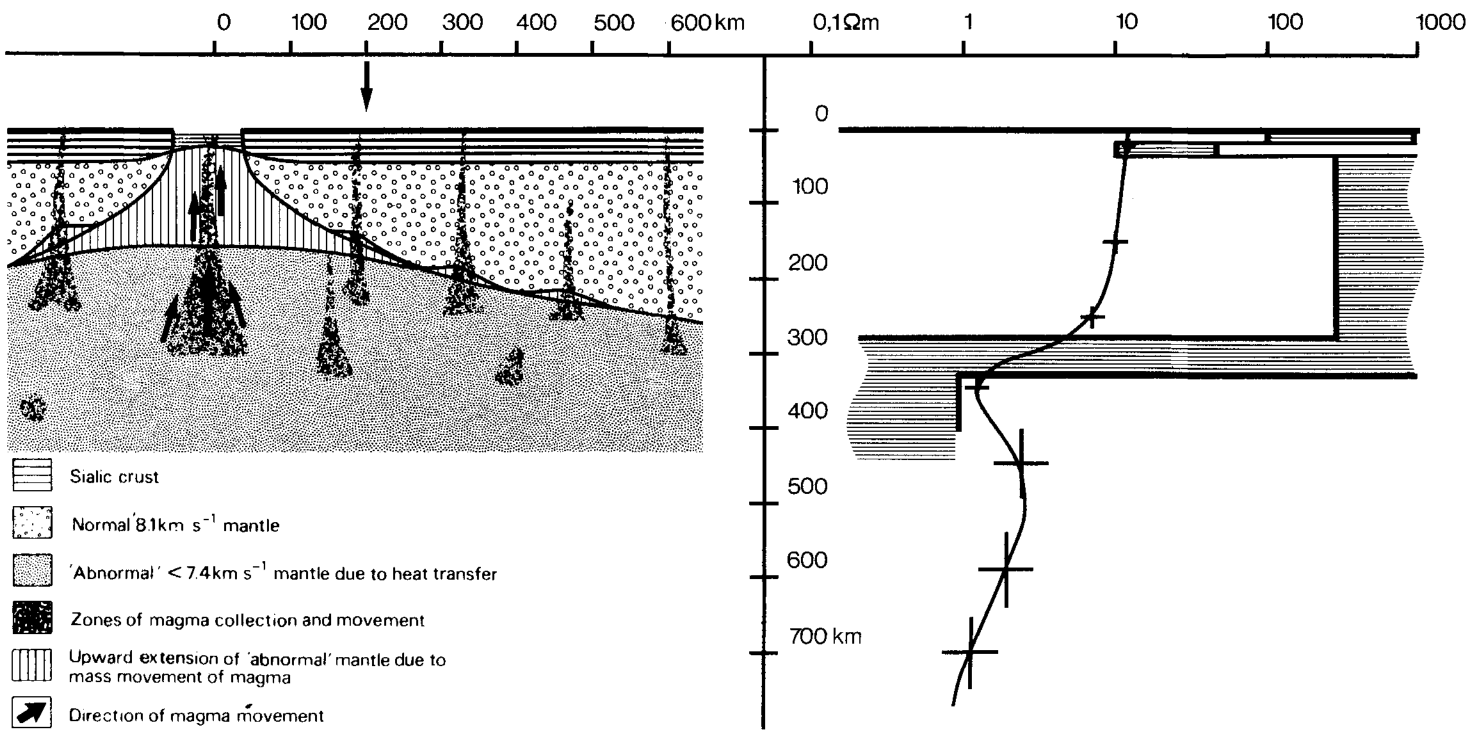

Fig. 5. The Afar 'hot spot' in Ethiopia. Left a petrological model proposed by Gass (1975) for the Afro-Arabian dome, to the right the resistivity-depth distribution derived by long period magnetotelluric measurements (Haak, 1977) represented by the shaded area within the bounds of minimum and maximum resistivities. For comparison the resistivity-depth profile for the hot spot Hawaii (Larsen, 1975) is included as a smooth curve. The arrow indicates the approximate position of the measuring site (SE-Escarpment) in relation to the central rift. The given petrological model can be transformed into a conductivity depth distribution which agrees with the magnetotelluric result.

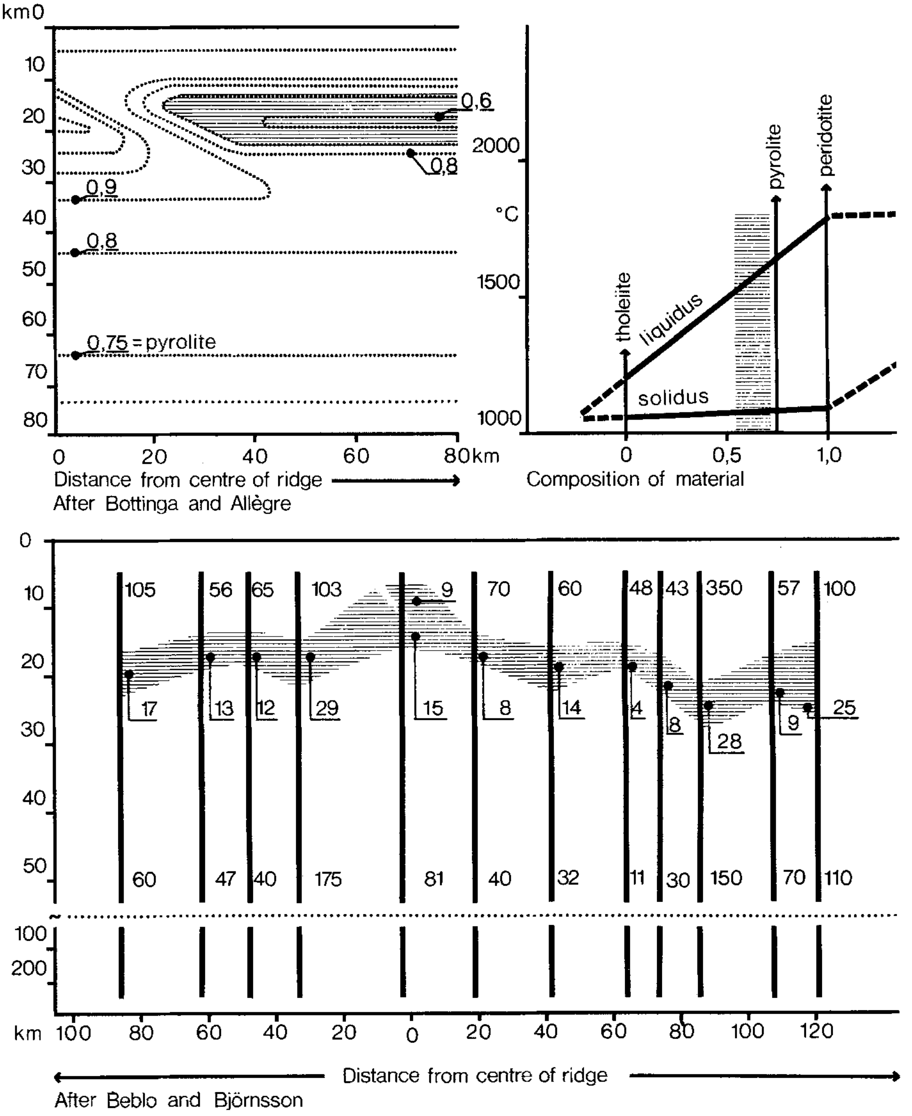

Fig. 6. Comparison of a petrological model for an oceanic rift (Bottinga and Allegre, 1976) and a resistivity distribution obtained by magnetotelluric measurements on a profile across the neovulcanic zone in Iceland (Beblo and Björnsson, 1978). The upper two panels display the final distribution of the composition of the original pyrolite. The composition is described by a fractional number between 0 and 1, e.g. pyrolite consisting of 25% basalt and 75% peridotite by the number 0.75. The shaded layer at 20 km depth consists of a material more basaltic than pyrolite resting on a material less basaltic than pyrolite. If incorporating the experimental results from Fig. 1 and 2 as to the theory of the effective conductivity, a low resistive layer at about 20 km resting on a higher resistive halfspace is obtained. In the lower panel such a low resistive layer (the numbers represent the resistivity in units of 1 Ωm) at a depth of about 20 km has actually been derived from manetotelluric measurements in an active rifting zone. The long extension of the low resistive material at least up to 120 km from the central neovulcanic zone cannot be explained by temperature alone, but must be attributed additionally to mineral composition. This essential feature agrees with the results from the above model calculation.

a temperature between 1150 and 1300°C of the upper 300 km. This 'petrological' conductivity profile agrees with the results of the magnetotelluric method in the Afar 'hot spot' in Ethiopia (Haak, 1977). In the uppermost 50 km basaltic material with temperatures close to the melting point yields low resistive layers (Berktold *et al.*, 1975). DC-resistivity measurements with extreme long electrode spacings have been performed on the African shield (Worzyk, 1978; Blohm *et al.*, 1977; Van Zijl and Joubert, 1975) yielding nearly the same resistivity profile as in the Afar Region-unfortunately. Petrick *et al.* (1977) deduced from the results of these d.c-measurements a geothermal gradient of about 20°C/km, whereas Berktold *et al.* (1975) inferred about 60°C/km in the Afar region.

The last example is a mid oceanic rift model as proposed by Bottinga and Allegre (1976). A few models exist for rifting with each model capable of explaining a limited number of observations, e.g. the magnetic pattern and the heat flow. The present model, called the asthenospheric upwelling model, tries to explain also high seismic velocities beneath the central rift. The convecting material consists of two components, olivine crystals and basaltic material, both moving with different velocities and thus yielding a differentiation of the original pyrolitic composition. The solutions of this rift model therefore seem suitable for calculating the distribution of the effective resistivity. It is impossible even to summarize here the most important steps, petrological contraints, etc. The relation between solidus, liquidus and their composition is presented in Figure 6. The resulting distribution of the composition shows a layer of low melting material around 20 km depth. It should be observable as a low resistive layer. The distribution of the resistivity obtained by magnetotelluric measurements (Beblo and Björnsson, 1978) clearly displays a low resistive layer at about 20 km depth and thus seems to confirm the asthenospheric upwelling model as proposed by Bottinga and Allégre.

Acknowledgement

Thanks are due to Dr. M. Beblo, München, for many helpful discussions about the interpretation of the magnetotelluric results in Iceland.

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