ELECTRICAL CONDUCTIVITY OF THE EARTH'S CRUST AND UPPER MANTLE

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Abstract. This review summarizes recent results of electrical resistivity studies of the earth's crust and upper mantle. Where available, the data are discussed in the context of further regional geophysical information. Electrical resistivity is very sensitive to a wide range of petrological and physical parameters, e.g., to carbon, fluids, volatiles and enhanced temperatures, making electrical resistivity methods a powerful tool in crust and upper mantle investigations. Yet, the general increase in resistivity data of the crust and mantle has not ended the battle of explanations for 'anomalous' crustal conductivities.

Introduction

Electrical resistivity of crustal rocks may vary over several orders of magnitude (0.1–100 000 Ω m), depending on a wide range of petrological and physical parameters (e.g., bound *vs* free water, volatiles, enhanced temperatures). Because of its sensitivity e.g., to fluid content, electrical resistivity provides independent information on the physical state of the crust almost inaccessible by more traditional methods like seismics. A little confusing 'electromagnetic (EM) people' speak of electrical resistivity as well as of electrical conductivity, both representing the same physical property, but one as the reciprocal of the other.

Until recently, geoscientists thought of high electrical resistivity in the crust as normal. The resistivity depth function which was under discussion in the 1960s is shown in Figure 1 (Angenheister, 1962). Low resistive zones in the lower crust, e.g., of less than 100 Ω m have been reported to be anomalous, and the term 'conductivity anomaly' (CA) was born. Knowledge of the physical structure of the lithosphere has increased considerably in the last few years, due to the increased number of studies in various geological settings as well as in the laboratory. These observations now support the tendency to classify high resistive zones in the lower crust as the exception. As long as the question on the 'normal' physical state of the crust is open one should avoid the term CA, and instead use 'high conductivity layers' (HCL).

Electromagnetic (EM) methods respond to an integration of the electrical conductivity structure from the surface down to the depth of maximum induced current. This results in non-unique models with limited depth resolution to conductive structures. Magnetotelluric (MT) and geomagnetic deep soundings (GDS) are the techniques most common for probing electrical conductivity of the deep crust and upper mantle. Models calculated from magnetotelluric measurements may be distorted due to a 'static shift' of electrical fields caused by local inhomogeneities,

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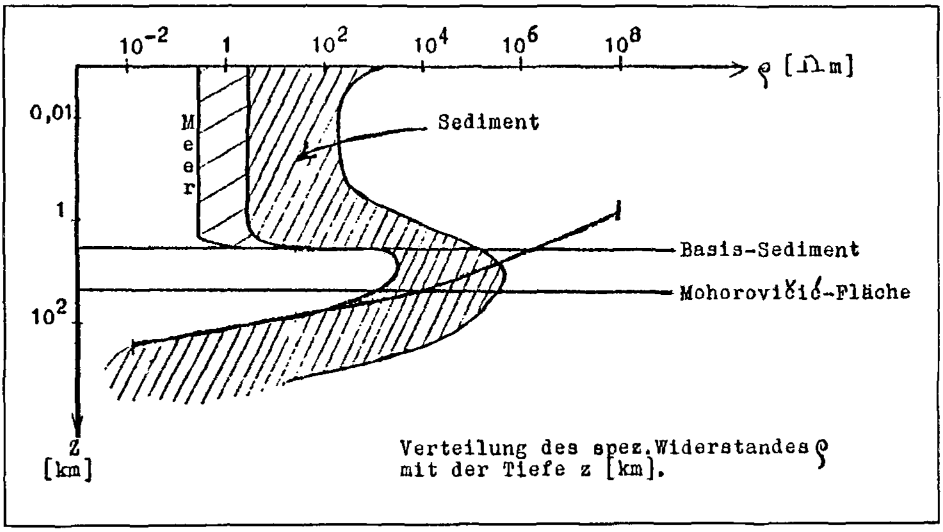

Fig. 1. Ancient view on electrical resistivity versus depth (Angenheister, 1962): Due to the decreasing fluid-filled pore volume with depth in the sedimentary cover, electrical resistivity increases. In the crystalline basement solid state resistivity should be controlled by the non-electrolytic temperature dependent conductance (thick line). Resistivity of ocean water (Meer) is given for comparison.

affecting the ability to resolve the vertical and lateral extent of conductive zones. Superposed conductive structures at depth are hard to resolve by magnetotellurics, e.g., a conducting layer beneath another conducting layer is difficult to detect. Interpretation of coherent noisy data is also problematic (e.g., Fontes *et al.*, 1988). Geomagnetic deep soundings as well as other geophysical methods suffer from lack of resolution if the station spacing versus depth of the investigated structure is too large, and in fact calculated models are not unique (Figure 2). On the other hand geomagnetic deep soundings may detect the center of an induction anomaly in the lateral direction better than any other EM-method, due to the vanishing vertical component of the induced magnetic field.

Recent discussions on electrical conductivity studies include Hjelt (1988), Chave and Booker (1987), Roberts (1986a), Haak and Hutton (1986), Schmucker (1985b), Haak (1985). In this discussion, I focus on reported electrical structures in continental regions that have further geophysical or geological information available, excluding shallow low conductive structures, e.g., in geothermal areas. I also discuss the efforts to interpret low electrical resistivities, e.g., the role of fluids, volatiles and graphite in the crust and upper mantle.

Conductive Structures of Regional Extent

Regional studies can be divided into two generic classes: those carried out in tectonically active areas, e.g., subduction or rifting zones, and those concerning stable, passive regions, e.g., cratons. In reviewing electrical conductivity of the

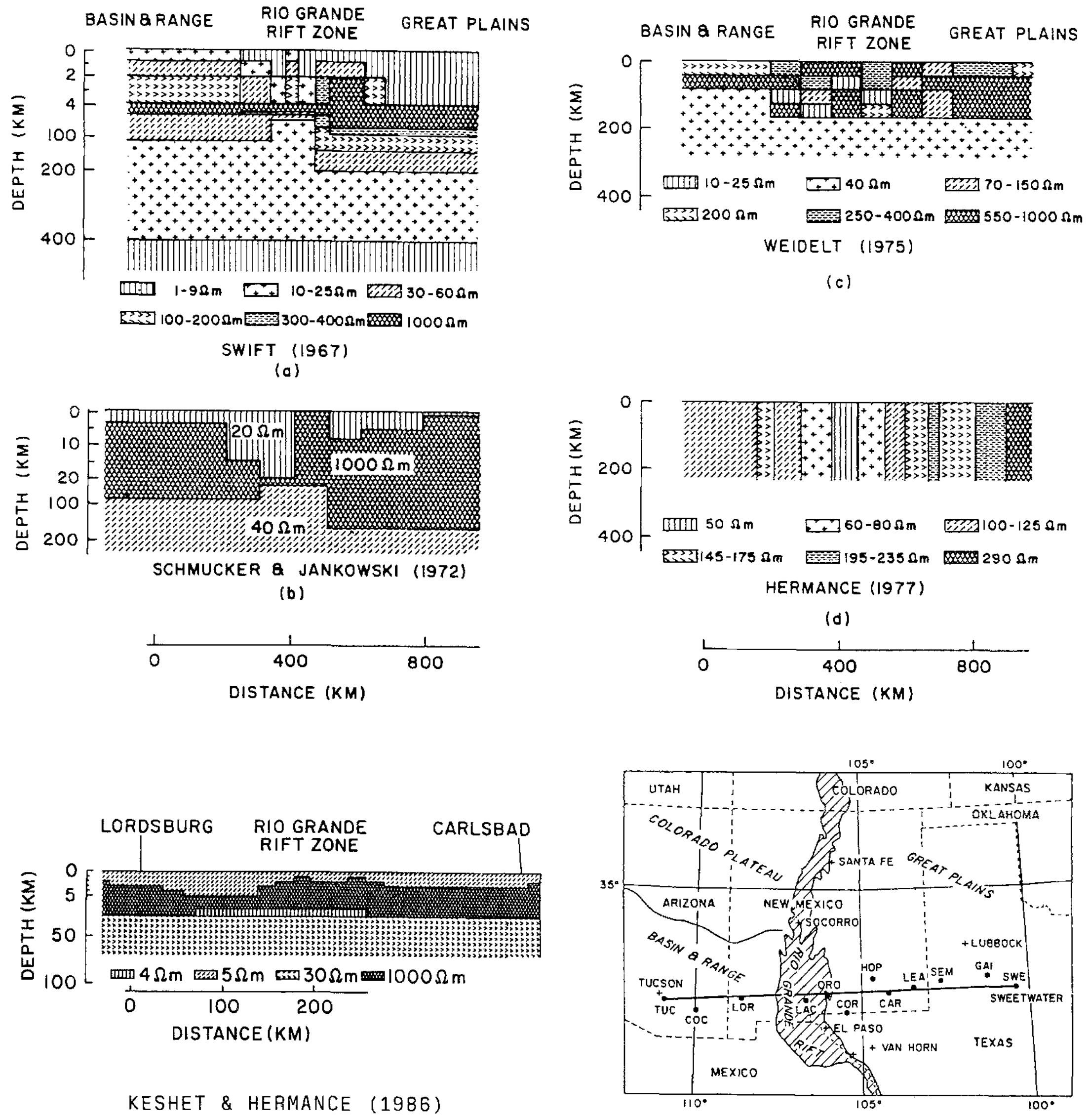

Fig. 2. Magnetovariational methods and their limited resolution of resistivity structures: Five different models (a–e) for the Rio Grande rift zone and adjacent areas (f) along latitude 32° N equally explaining the data (after Keshet and Hermance, 1986). Note that the scale used in Figure 2e is different from the scale in Figure 2a–d, and vertical scale is partly exaggerated

earth, there is no way to give adequate coverage to all papers published in the last few years. Only some of the studies described are discussed, concentrating on common geophysical features or causes. However, the reader will find an extended list of references at the end. If some papers have escaped my attention I apologize and assure the authors that the omissions are inadvertent. Electrical conductivity studies carried out in the early 1980s have been briefly reviewed by Hjelt (1988). In this review the conductivity studies are grouped by continents, which will be treated in alphabetical order.

AFRICA

The Atlas system of Morocco (NW-Africa) is still a puzzle as far as its origin is considered. An upwelling upper mantle, a low velocity zone (LVZ) and partially correlated low-resistivity layers both at crustal depths indicate a rift zone with mantle diapirism (Schwarz and Wigger, 1988), although other investigations suggest wide-spanned zones of overthrusting. Clearly more elaborate models are necessary to reveal the contradicting evidence.

The Senegal basin of West Africa has been studied by dense EM profiles. Sediments about 4000 m thick have very low resistivities of 0.7–2 Ω m (Ritz and Vassal, 1986, 1987). Most of the resistivity structures found seem to be 3-D, making interpretation difficult.

ASIA

The subduction of the Indian plate under the Tibetan plateau has for some time attracted the attention of geoscientists. Srivastava and Prasad (1982) compiled observed induction anomalies in India and demonstrated their connection to geology. The MT-soundings of Pham *et al.* (1986) in southern Tibet indicate low resistivities of a few Ω m in the upper crust, interpreted as partial melts at a depth of between 3 and 33 km with average vertical extent of 10–20 km. Strong anisotropies on their southern profile segment may be accounted for by melts intruding into fracture zones following the direction of regional tectonic strike. High heat flow values seem to support the presence of a melt fraction, though low frequency seismic wave studies suggest a zone of at least partial melting in the lowermost part of the crust (40–50 km), which here is thickened to about 70 km.

Arora (1987), Arora and Mahashabde (1987) and Chamalaun *et al.* (1987) report geomagnetic induction studies in the northwestern Himalayas. Anomalous vertical to horizontal (Z/H) ratios of the geomagnetic field reveal a SSW-NNE striking significant conductor underneath the Ganges basin at a depth of 32 km, extending up to 110 km laterally with a conductivity contrast of 1000. The authors suggest the anomaly may be caused by partial melting due to the fracturing of the lithosphere in connection with the continent/continent collision event. The anomaly in the northern part of the profile of A and M may originate from a 2-D conductive structure stretching 60° E, about 45 km wide, with its top at a depth of 15 km. This model was criticised by Singh and Pedersen (1988), who claim it to be not compatible with measured data.

Further Indian studies were concerned with anomalous induction in the surrounding ocean, including current channelling in the Palk strait (e.g., Kunaratnam, 1987). Mareschal *et al.* (1987) and Agarwal and Weaver (1989) modelled induction in Southern India and Palk strait. Their results suggest thick sedimentary layers and a rift system below the strait, which is deeply fractured and probably mineralized.

In Sri Lanka and Southern India many deposits of graphite exist, among them the largest economic ones in the world (e.g., Katz, 1987). They owe their existence mainly to redistribution of carbon of carbonate rock or sedimentary origin. Although carbon is common in most of the metamorphic rocks, it is questionable whether it is electrically connected on a regional scale as well as microscopically. Laboratory and field studies concerning this problem are still missing and should be encouraged.

Further north in Asia a shallow anomaly of electrical conductivity was investigated by Babadzhanov *et al.* (1986): the Tien-Shan CA, Western Uzbekistan. They claim formations containing conductive carbon and/or sulphide – which are located in the metamorphic complex of the fold system – to be responsible for their observations. Okulesskii *et al.* (1985) carried out magnetovariational soundings in the Baikal rift zone. As in other active rift zones, the upper mantle and lower crust show anomalous conductive structures as well as a seismic low velocity zone (LVZ), explained by partial melting at this depth.

AUSTRALIA

Conductivity studies in Australia detected a zone of high electrical conductivity in the Flinders (ref. to Constable, 1985, 1988), which seems to continue into the Adelaide geosyncline (White and Polatayko, 1985). It correlates with the arcuate fold pattern and with the local occurrence of seismicity. The enhanced conductivity in the elongated structure is probably caused by saline waters within fractured crustal rocks.

In the North of New Zealand, Ingham (1987, 1988) undertook several EM soundings across the subduction zone in an attempt to map the subducted plate itself. Unfortunately, highly conductive surface layers shield the deeper structures in this case.

EUROPE

On the Baltic shield, Rasmussen *et al.* (1987) carried out MT-measurements along the seismic refraction line FENNOLORA. The resistivity data indicate the existence of strong anisotropy but are inconsistent from site to site. A low resistive structure (about 4 Ω m) was found in the Skellefte ore district of Northern Sweden stretching over 150 km in SW-NE direction, with a minimum thickness of 15 km, and appears to correlate with isolated ore bodies. The presence of a free fluid phase in the upper crust can explain the measured low resistivities, but structures enriched in graphite or sulphite cannot be excluded. The lithosphere-asthenosphere boundary is now very well resolved. Rasmussen (1988) modelled a strongly anisotropic lower crust to explain his resistivity data from NW-Sweden (at about 60° N). The uppermost conductive layer is found at a depth of more than 200 km. Pedersen *et al.* (1988) and Zhang *et al.* (1988) investigated the Siljan meteoritic impact structure in middle Sweden with magnetotellurics. An impact generated anomaly can be detected to

15–20 km depth. A strong anisotropy of apparent resistivities is explained by deep-reaching, fluid-filled fracture systems. The lower crust and upper mantle seem to be laterally homogeneous.

The detection of a conductivity anomaly in northern Germany (Meyer, 1951; Wiese, 1955) is one of the first examples of current concentrations found at shallow (i.e., crustal) depths. The maximum depth of a line current was calculated to be about 85 km (Fleischer, 1954). But this interpretation did not use the period dependence of magnetic field variations. With the present knowledge, a sheet current flowing at 6–10 km depth is the only interpretation: Recent magnetotelluric measurements have confirmed the presence of a good conductor in the uppermost roughly 10 km of the crust (Jödicke and Volbers, 1987 *et al.*). The authors assume that the high conductance (thickness-resistivity ratio) of about 5000 S (Siemens) is related to electronic conduction within highly coalified organic material of black shale comparable rocks (c.f., Figure 3). Electrolytic conduction cannot be the dominant conduction mechanism, because porosities higher than 10% are necessary to explain the high conductance, even when thick layers of some kilometres extent are assumed. The good conductor under northern Germany might be connected with good conductors found beneath the Münsterland and Rhenish Massif (Volbers *et al.*, 1988; Untiedt *et al.*, priv. comm.). Beneath the Rhenish Massif the good conductor is bound to a seismically transparent zone above a layer with enhanced reflectivity. The total conductance beneath the Münsterland is about 1000 S, decreasing under the Rhenish Massif to about 100–300 S. Duba *et al.* (1988) measured extremely low resistivities of about 0.1 Ω m in samples of black shale from the Münsterland borehole (Figure 4). This black shale contains about 5% organic matter. The sequence outcrops about 80 km SE of Münster and can be detected in this region by selfpotential measurements as well as by other EM methods (Jödicke, 1985; Jödicke and Grinat, 1985).

The search for the continental deep drilling (KTB) site in West Germany motivated extended investigations of the electrical resistivity structure of the crust as well as 3D-seismic reflection and refraction experiments. Main target areas were the crystalline areas of the Schwarzwald and the Oberpfalz (Untiedt, 1986; Teufel *et al.*, 1986; Tezkan, 1988; Strack *et al.*, 1988b). The upper crystalline crust in both areas have typical resistivities of more than 1000 Ω m. In the Oberpfalz a good conductor (conductance of at least 1000 S) was found at a depth of approximately 10 km or less, with a shallow one at about 1 km depth. Beneath the crust in the Schwarzwald exists a good conductor at about 6–8 km depth (with about 50 S). A mid crustal conductor was detected by MT and GDS under the Schwarzwald gneiss massif at a depth of 12 km – with a conductance of 650 S. The deep conductor beneath the Oberpfalz corresponds to a high velocity layer (HVL), whereas the upper crustal conductor beneath the Schwarzwald correlates with a zone of low velocity (LVZ). Data from the KTB borehole site in the Oberpfalz turned out to be of high significance for the discovery of low resistivities in the crust (for detailed information see the many KTB reports). A sub-vertical low resistivity structure

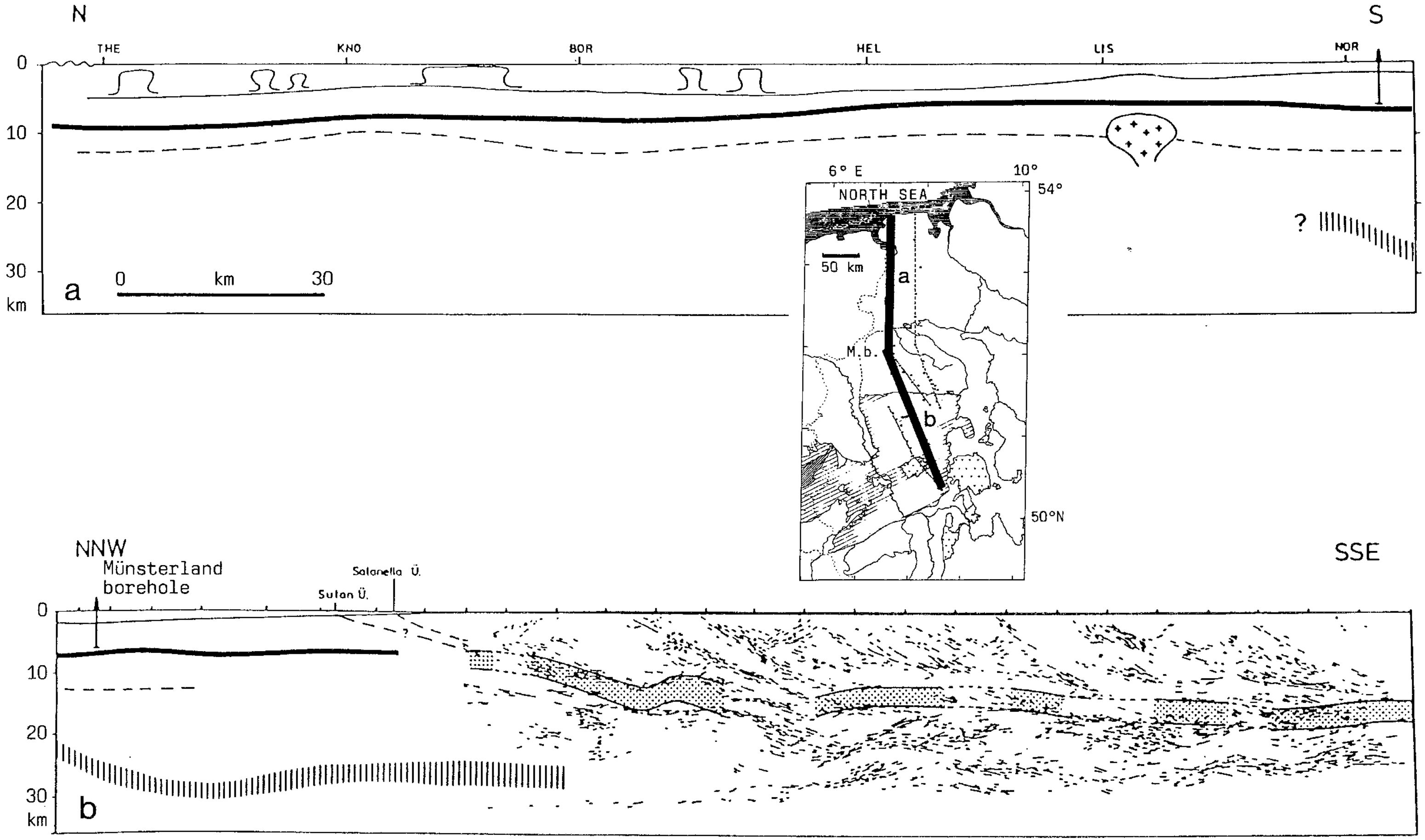

Fig. 3. Magnetotelluric measurements in northern Germany (after Jödicke and Volbers, 1987; Untiedt *et al.*, priv. comm). The insert shows the position of profiles. (a) Electrical cross-section from the North Sea to the Münsterland basin. The heavy black line represents a total conductance of 5000 S. (b) Profile along one of the German reflection seismic lines (DEKORP 2-N). – Shaded areas represent zones of high conductivity. Most of them correlate with transparent crustal zones, above a reflective lower crust.

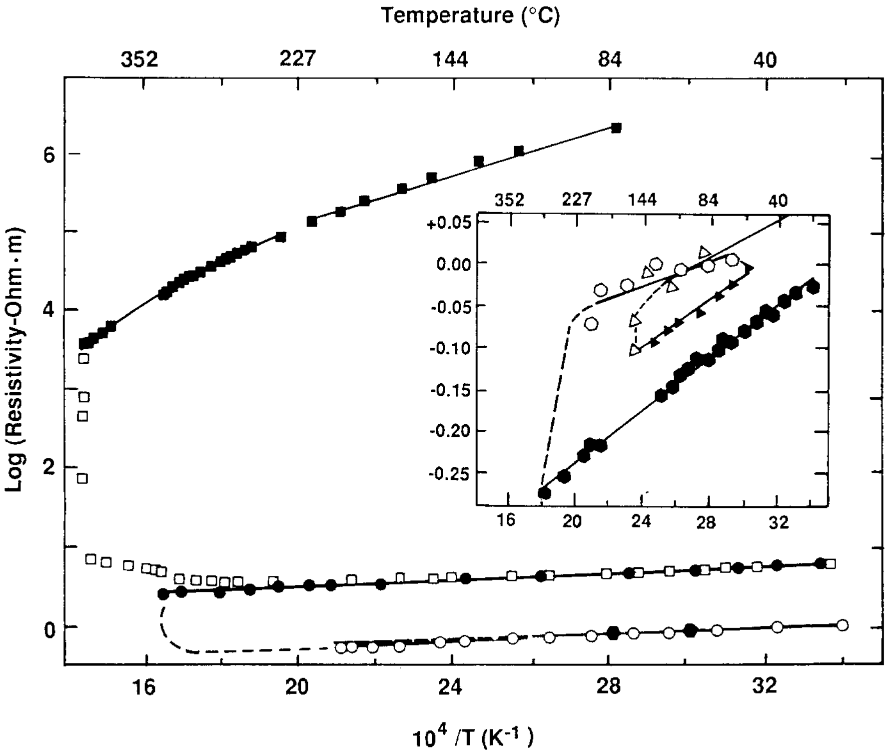

Fig. 4. Temperature dependence of resistivity of black shale from the Münsterland I borehole at 1.6 kHz (Duba *et al.*, 1988). For position of the borehole, see Figure 3b – NNW-border. The very low resistivity of the black shale probe should be attributed to a thin film of interconnected carbon at grain boundaries, though not visible even by electron microscopy. The low resistive sample when heated up in air up to 320 °C – outside the stability field of graphite –, lost the low resistive film and became very resistive. Open symbols are data from heating cycles, closed symbols refer to cooling cycles.

close to the first KTB hole coincides with a graphite deposit outcropping at the surface and in all depths down to the bottom hole at 4000 m, as well as with a large electrical self-potential anomaly, and a static magnetic field anomaly (Haak *et al.*, 1989; Leonhardt, 1987). Finally, fluids with twice the salinity of sea-water invaded the very last meters of the borehole, obviously another source for the observed high electrical conductivity in the crust.

NORTH AMERICA

The west coast of both Americas experiences very intense activities of geoscientists from various disciplines. One of the most ambitious investigations of electromagnetic soundings is the EMSLAB project onshore and offshore the Juan de Fuca plate (e.g.: EMSLAB, 1988; McKirdy *et al.*, 1988; Green *et al.*, 1987; Gough, 1986b; Dosso and Nienaber, 1986). Further details of these investigations and their results will be reported elsewhere. At the northernmost extent of the EMSLAB area, on Vancouver Island, the upper boundary of an electrically conductive zone correlates remarkably well with a seismic reflector, believed to be near the top of the subducting plate itself (Kurtz *et al.*, 1986a). The measured electrical conductivity may be explained by trapped saline fluids in a rock matrix with a porosity of a few percent. Subduction induced dehydration reactions may both enhance porosity and provide the source of the fluid (Hyndman, 1988). Stanley *et al.* (1987) report a broad upper crustal zone of high conductivity in the southern Washington Cascade ranges, within a triangle formed by three volcanoes. The conductive rocks are about 15 km thick and have resistivities of 1–4 Ω m. Magnetic lows follow the trend of the conducting structure. It may be noteworthy that, although in a volcano-tectonic active region, the conductive structure seems to coincide with a suture zone, and anomalous resistivities correspond to a compressed forearc basin and accreted sedimentary rocks.

In the last few years, magnetovariational array studies have been performed to detect and characterize conductive structures related to the tectonics of the Rocky Mountains (Ingham *et al.*, 1987; Gough, 1986a; Bingham *et al.*, 1985). A very conductive ridge is situated beneath the main range of the Rockies with its top 5 km below the surface. Recently these studies were complemented by magnetotelluric measurements (Hutton *et al.*, 1987) close to the center of the major anomaly. They show very low resistivities in the range between 1–10 Ω m in the upper crust under the Rocky Mountain trench and even lower values under the main ranges. The high conductivities may be due to partial melts in the upper mantle and saline hot waters filling interconnected pores in the crust.

Jiracek *et al.* (1987) present a model for the central Rio Grande rift based on magnetotellurics. A conductive layer of at least 1500 S has been identified at a depth of about 10 km along a profile at about 34.5° northern latitude. However, no conductive zone is found 40 km to the south where magmatic activity and microseismicity is highest. The conductive zone in the north should be attributed to trapped water beneath an undisturbed ductile cap. For the more resistive crust in the south, it is hypothesized that magma injection through the cap may have released the water. But to my understanding the models presented are not strictly argued for. Keshet and Hermance (1986) calculated induction models for the Rio Grande rift (at 32° N) and suggest that the major anomaly lies at a depth of approximately 20 km with a conductance of 2000 S (Figure 2). Their model does not need an anomalous mantle to explain measured data, but its lateral boundaries are not very well resolved.

One of the most striking EM-features in North America is the Central Plains (NACP) high conductivity zone discovered by Reitzel *et al.* (1970) using magnetovariational methods. New MT measurements at 51° northern latitude (Jones and Savage, 1986, 1988) help resolve the location of the conductive body at a depth of approx. 10 km. It may be related to a NW-SE striking sinistral fault in the deep crust. The anomaly is located 75 km further to the east than inferred from earlier large scale GDS surveys.

SOUTH AMERICA

The first EM investigations date back to the 60s, when Schmucker *et al.* (1964) reported the discovery of the later famous Andean CA in southern Peru and Bolivia. Being situated 20 km beneath the Cordillera and extending laterally about 400 km it was impressive indeed. The picture of the classical subduction zone was nearly perfect: magma rising from the Benioff plane to the surface, where it is stored in vast magma chambers detectable by their high electrical conductivity. The published data have been subject to several reinterpretations (among them Osella, priv. comm., and Tarits and Menvielle, 1986), though the resulting models did not change the picture seriously.

When the Carnegie Institution – which had initiated Schmuckers project – finished its Andean research programme, it left behind a zone of inductive tranquillity.

It took 20 yr until an Argentinian induction group started measurements in the NW of Argentina (Baldis *et al.*, 1985). The possible extension of Schmucker's anomaly into Bolivia and later to northern Argentina was investigated by Schwarz *et al.* (1986, 1989). Anomalous conductivity structures were found in the upper crust, related to relatively thick sediments and processes (plutonism and subsequent hydrothermal circulation) which had led to the formation of the so-called tin belt in southern Peru, Bolivia and northern Argentina. A relationship between high conductivity structures and large overthrusting events may be suspected, too (Reutter *et al.*, 1988). The Western Cordillera in northern Chile coincides with the strike of another high conductivity zone, even more highly conductive than that mentioned above (Schwarz *et al.*, 1984), although the connection between the two anomalies is far from clear (Figure 5). MT results suggest the presence of very conductive material in the upper crust of the Western Cordillera where the gravity has local minima, seismic waves have probably reduced velocities and are strongly attenuated and/or scattered (Götze *et al.*, 1988; Wigger, 1988). These observations may be unified by the hypothesis of partially molten acidic intrusions emplaced in the crust. The Altiplano of Bolivia is underlain by material of very low resistivity at a depth of 40–50 km, while total crustal thickness in this area is calculated from gravity to be about 60 km. Geophysical investigations in the Andes are still going on.

Conductivity Studies in the Laboratory

The interpretation of electrical conductivity data measured *in situ* in terms of geological formations, physical structures and processes in the earth needs the laboratory: Electrical properties of representative materials must be studied under those thermodynamic and environmental conditions which exist in the geological system of interest. But this demand sounds easier than it is: Even if one gets rock samples under realistic conditions into the laboratory, investigating techniques have

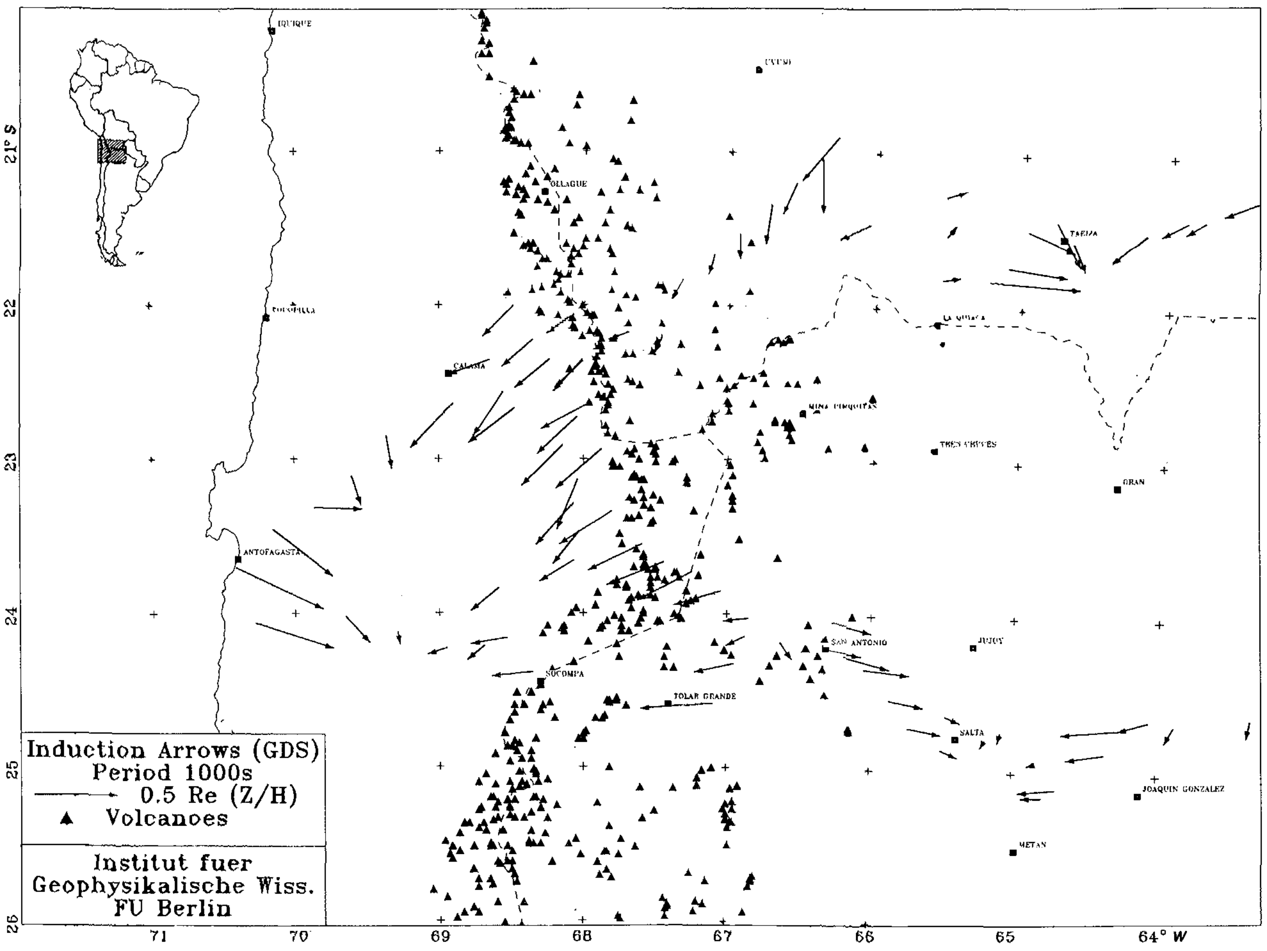

Fig. 5. Geomagnetic induction arrows (period T: 1000 S) and distribution of volcanoes in the southern Central Andes (Schwarz *et al.*, 1986, 1989). Arrows point away from the induction anomaly. A zone of high electrical conductivity (conductance of 20 000–30 000 S) beneath the Western Cordillera (the volcanic belt) of northern Chile and southwestern Bolivia – most likely attributed to partially molten acidic intrusions – is striking under NNW-SSE, running into northwestern Argentina. The eastern border of this large scale anomaly is found in the Eastern Cordillera of southern Bolivia and northwestern Argentina. High electrical conductivity should be related here to thick sedimantary layers and hydrothermal circulation in the upper crust.

to be adequate (e.g., Duba, 1982; Hinze, 1982; Laštovičková, 1983). Thermodynamic variables, e.g., pressure, temperature and oxygen fugacity as well as time to equilibriate the sample may significantly influence electrical conductivity and have to be kept under control. And in fact there exists a discrepancy between data from the laboratory and those from the field. Kariya and Shankland (1983) list several reasons for being skeptical of laboratory conductivities, but these reasons could not account at all for such large differences. I will refer to this matter again later.

Due to the problems of handling rock samples in the laboratory, it seems to be easier to investigate electrical resistivity of single phases, e.g., minerals. These data can then be used to calculate electrical bulk resistivity from the individual phase resistivities using assumptions from theoretical models. These models include various geometrical parameter of rocks which strongly affect bulk resistivity. Imagining the great variability in grain geometries, the dilemma with resistivity data from the laboratory representative for the crust turns out again.

Electrical conductivity of olivines and pyroxenes, the most prominent and abundant upper mantle minerals, has attracted the interest of laboratory workers since long (e.g., Sato, 1986). As the stability field of olivine is very narrow, care must be taken to control thermodynamic conditions during laboratory experiments. Shankland and Duba (1988) measured the olivine conductivity tensor under controlled oxygen fugacity, giving upper and lower bounds for conductivity *vs* temperature under the conditions of the upper mantle. Point defects as carriers of electrical charge play an important role in the electrical conduction and creep behaviour of olivine. For iron-bearing olivine, the conduction mechanism is by iron holes localized on iron ions (Schock *et al.*, 1984), and iron can act as an electron donor (Schock and Duba, 1985). Hirsch and Wang (1986) investigated the pressure- and temperature dependance of electrical conductivity of olivine and resume that conductivity of the upper mantle is not affected by lateral variations of tectonic stress.

Electrical conductivity of rock melts was investigated in various laboratories. Haak (1982) reviews the results of basaltic and upper mantle probes. The electrical resistivity of all types of melt is very low and depends among other parameters on temperature, e.g., basaltic melts at about 1200 °C have specific resistivities of 0.5 Ω m.

Olhoeft (1986) claims that electrical conductivity of silicate rock is dominantly controlled by the content of free water and temperature, whereas the state of stress, oxygen fugacity and structurally bound water provide minor contributions. Sulphur, carbon and metallic minerals should provide local effects on electrical conductivity. Hydrothermal alternation and the lining of silicate pores with highly surface-reactive materials, such as zeolite, may control electrical properties through the dominance of surface over volume conductance. Highly conductive zones of at least some tens of kilometers extent may be produced by a thin film of zeolite coating on silicate grains with low concentration of water and temperatures of less than 200 °C. The advantage of surface over volume conduction as a mechanism for high electrical conductivity is the minimal porosity required (e.g., Schopper, 1982). At high salinities and temperatures of up to 400 °C volume conduction will dominate (Olhoeft, 1986).

On the Nature of Lower Crustal Conductors

Electrical conductivity in the earth depends on the amount of free particle charges and their mobility. As porosity is decreasing with increasing depth the hydrostatic pore volume should be reduced exponentially, leaving a residual isolated pore volume of highly saline fluids. One should expect continuously increasing electrical resistivity with depth with a change from electrolytic conduction in pore space to finally solid state electrical conduction in minerals. Magnetotelluric investigations of the continental lower crust revealed a different picture (e.g., Shankland and Ander, 1983; Haak and Hutton, 1986), showing lower electrical resistivities than one would expect under these conditions. Physical and chemical mechanisms leading to this phenomenon are still a matter of discussion. Candidates for lowering electrical resistivity of the continental crust are: (a) free water with a high ionic content (*fluids*), (b) free carbon (*graphite*) and (c) other *conducting minerals*, such as magnetic oxides or sulphur, or (d) *rock-melts.*

FLUIDS IN THE DEEP CRUST?

When a certain correlation of zones of high electrical conductivity and high seismic reflectivity in the lower crust was observed (e.g., Gough, 1986c; Jones, 1987a; Hyndman and Shearer, 1989), the matter seemed to be clear: the existence of fluids, especially in the deep, ductile crust. This assumption on the state of the crust opposed the more traditional ideas of petrologists. Dry rocks, when measured in the laboratory have electrical resistivities of 10 000 Ω m or even more, whereas *in situ* resistivities in the field are much lower and seldom exceed 10 000 Ω m. Kariya and Shankland (1983) searched for systematic differences of electrical resistivities in published laboratory data for dry mafic and silicic rocks in the temperature range of 500 to 1000 °C. Mafic rocks seem to be statistically better conductors than granitic material. Comparing these data with measured field data and temperature, Shankland and Ander (1983) tried to show that in tectonically active as well as in stable zones the mechanism of conductance is the same (Figure 6). In the Arrhenius-diagram of temperature dependant conductivity, data sets of both zones may be linearly fitted, giving the same slope. S and A postulate a fluid phase, e.g., free saline water to serve as the common electrical charge mechanism and to be responsible for the decreased resistivity. Free water of about 0.01–0.1 vol% kept in fracture porosity will be sufficient to justify the observations. If one assumes graphite as the resistivity decreasing interstitial material an even smaller amount would be sufficient. But as tectonically active regions show systematically higher conductivities than do shield areas, it would be necessary to argue that there is more graphite in the crust in tectonic than in shield areas. The problem with both

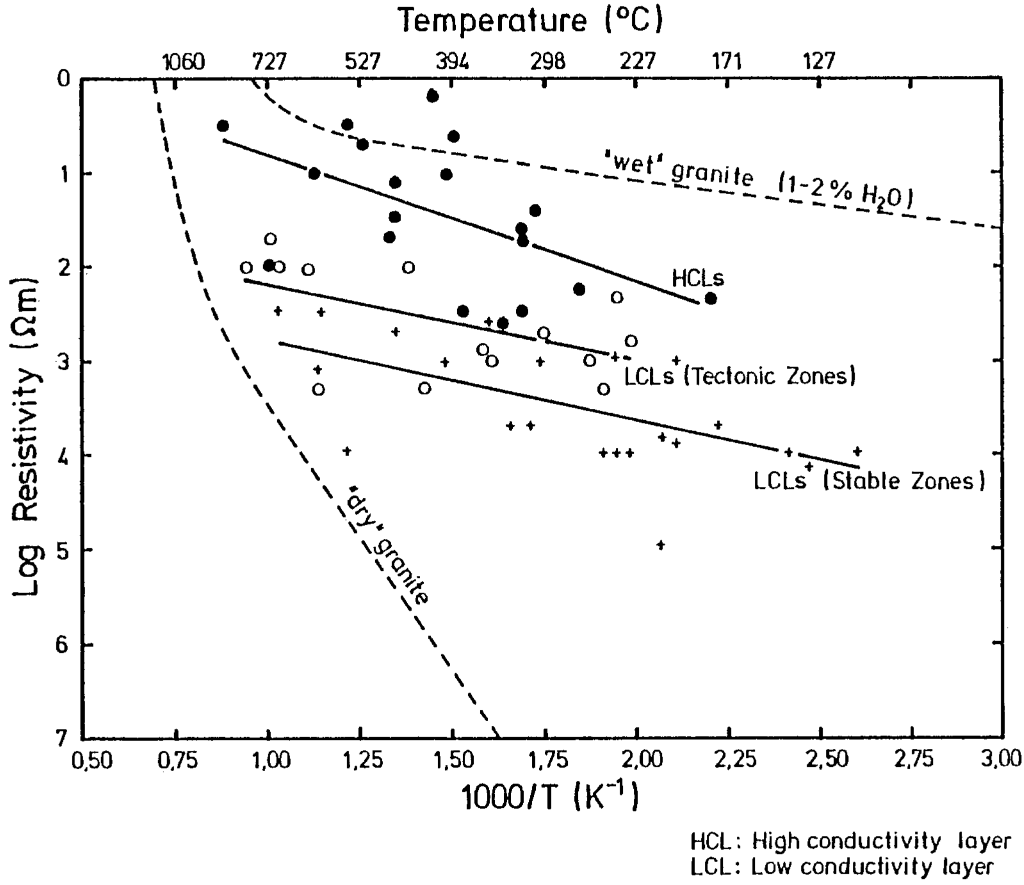

Fig. 6. Arrheniusplot of electrical resistivity from MT measurements versus estimated temperature (according to Shankland and Ander, 1983). Tectonically active as well as stable zones show the same electrical characteristics: a thermally activated electrical conductance in the crust. Increased fluid concentration seems to be a probable cause for enhanced conductivities.

materials – the most important question – is that of how to establish physically an interconnection over a distance of some tens or even hundreds of kilometres.

It is widely accepted that water may be present in the lower crust (e.g., Fyfe, 1985; Liu, 1986; 1987; Kay and Mahlburg Kay, 1986), e.g., originating from dehydration processes. On the contrary, granulite facies have a very low water content in fluid phases. To reduce electrical resistivity requires large interconnected fluid systems and demands an effective pore pressure near to zero. This has to be kept for geological times (at least for some millions of years). Mase and Smith (1987) review the role of pore pressure, stating it to be the fundamental problem in tectonics. High pore pressures can reduce effective normal stress to near zero values, causing solid grains to lose frictional cohesion and the rock matrix to deform as a viscous solid over geological times. To keep pressure, fluid transport to the surface must also be inhibited. Walder and Nur (1984) showed that for a static conversation of such a lithostatic fluid system unrealistically small permeabilities are necessary (less than 10^{-21} m^2). Though there are enough plausible reasons to accept fluids as the source of lower crustal conductors, the latter arguments make it hard to favor them.

GRAPHITE ....?

Nearly all crustal rocks contain carbon as anthracitic or graphitic material in small quantities. Carbon at crustal depth may originate from redistribution of carbonate rocks or sedimentary rocks with organic compounds included, as well as from carbon being emitted from the mantle (e.g., Des Marais, 1985). Carbon recycling by subduction is still controversially discussed (e.g., Marty, 1989; Des Marais, 1989). Relevant studies of the high-pressure (> 10 kbar) stability of organic substances are missing (Tingle, 1989), but it is widely accepted that most organic compounds are graphitized or combusted at high temperatures (> 1000 °C). Graphite decreases electrical resistivity by several orders of magnitude and accounts for large-scale resistivity anomalies in the continental crust (Duba and Shankland, 1982). However, there exist metamorphic rocks at the earth's surface containing graphite which do not show large-scale low resistivities. Graphite in connected form, e.g., veins, are rare compared to other minerals (Rath, 1988). The fundamental question is, therefore, whether graphite could form grain boundary films over large distances which remain thermodynamically stable over geological times. Duba and Shankland (1982) found grain boundary carbon produced during pyrolysis in oil shales. Duba *et al.* (1988) conclude that such carbon films though not visible even by electron microscopy, decrease the bulk resistivity effectively (Figure 4). Such connected carbon films may be hard to generate and should not exist over large distances (Tsong *et al.*, 1985; Watson, 1986). Transport and generating mechanisms of graphite were investigated in the mentioned KTB hole (Stroh *et al.*, 1988), where graphite is assumed to have been transported in the gaseous form – within the carbon-oxygen-hydrogen-sulphur (C-O-H-S) volatile system. Mobilisation of carbon from preexisting sources strongly depends on oxygen fugacity, and generating graphite from methane needs oxydizing conditions or changes in pressure and temperature. Graphite will be kept stable under reducing conditions. Rath (1988) concludes that it seems difficult to exclude graphite as the source for lower crustal conductors on purely theoretical reasons, though the relative rareness of graphite veins found at the surface does not speak in favor of its importance. But the carbon film coating grain boundaries proposed by Duba *et al.* (1988) could offer an exit from this dilemma.

... AND OTHER CONDUCTING MINERALS?

Solubility of most ore minerals depends very weakly on pressure, whereas temperature plays a major role. Hydrothermal ore deposits can be expected to have originated mainly by cooling reactions with wall rocks or mixing with other fluids.

Deposition by chemical reactions at lower crustal depth seems rarely to be the case. Most of the known hydrothermal deposits have originated in the uppermost crust at temperatures below 400 °C and pressures of less than 2 kbar (Naumov, 1984). This points towards the existence of metal mainly as part of the fluid phase at greater depth (Rath, 1988). The occurrence of magnetic anomalies together with high conductivity zones was observed but up to now not paid very much attention on (Stanley, 1989; Haak *et al.*, 1989). Reducing conditions may generate a stable phase of magnetite as well as of graphite (Frost *et al.*, 1989).

. . . AND MELTS AS THE EXCEPTION!

The occurrence of rock-melts in the crust is connected with extreme temperatures (above 700 °C), which may only be found in tectonically active zones at crustal depth. Connected melt along grain boundaries applies for lowering resistivities (Sato and Ida, 1984). To serve as an explanation for decreased resistivity zones in the large scale, melts must be connected over large distances as well as having to form a lamellae structure of some centimetres height to remain stable (Shankland and Waff, 1977; Waff and Bulau, 1979). The dynamic behaviour of melts is controlled too by their volume and density (e.g., Stolper *et al.*, 1981), but many aspects of magma migration are poorly understood (Turcotte, 1982).

Electrical resistivity of water-undersaturated melting was investigated by Wannamaker (1986). Water-undersaturated melts in equilibrium with their source appear in the deep crust of lower conductivity than corresponding water-saturated melts, even though the latter occur at much reduced temperatures. For the deep crust melt fractions, from 10–50 vol% may be needed for bulk resistivity to fall below 10 Ω m (Wannamaker, 1986). In summary I conclude that the occurrence of melts is probably limited to a few cases.

Concluding Remarks

This short review has been unable to cover all interesting topics on electrical structures in the crust and upper mantle. For instance, theoretical aspects of data improvement (especially the methods of removing the distortion of the impedance tensor, e.g., Bahr, 1988; Groom and Bailey, 1989) as well as improved modelling techniques (e.g., Wannamaker, 1986) have not been included, although they are of crucial importance for any physical/petrological interpretation of results. It should be noticed that larger projects have stimulated considerable progress in this field. Considering the problems mentioned in lateral as well as vertical resolution of resistivity structures, there is a need of denser mapping, of more precise data, e.g., phase errors of response functions of less than 1% (Cavaliere and Jones, 1984), and of using the whole magnetotelluric impedance tensor information. Horizontal anisotropies should be considered much more in the future. Vertical, stretched 'lamellae'-structures may serve for modelling (e.g., Tezkan, 1988) as well as to explain apparent inconsistency between MT and GDS data. This leads to the

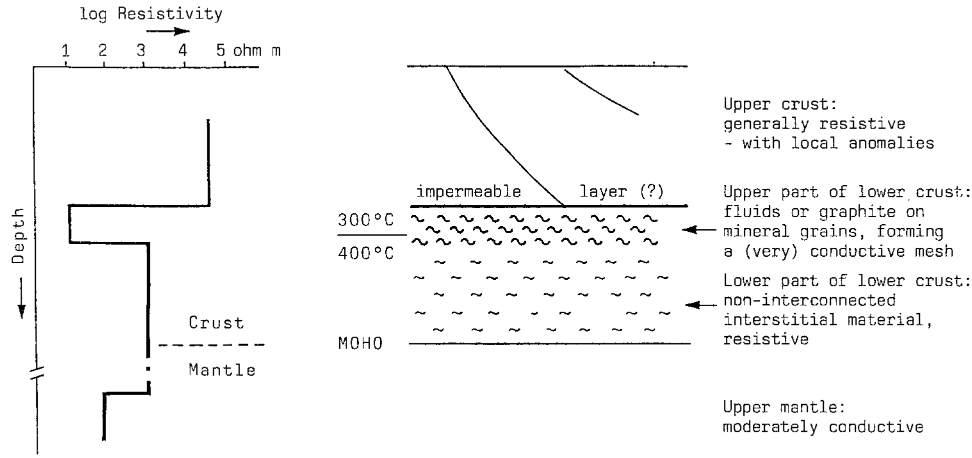

Fig. 7. A model for the continental crust – though competing explanations for crustal low resistivities? (modified from Gough, 1986c; Rath and Haak, 1986; Jones, 1987a). A resistive upper crust is underlain by a two-layer crust. The top part of the (reflective?) lower crust contains interconnected free water and thus is a well-conducting zone. It is divided from the upper crust by an impermeable zone, necessary to trap fluids. Temperature is between 300 and 400 °C. This impermeable layer was introduced by Etheridge *et al.* (1984) but its general existence seems questionable (Rath, 1988). A graphite film coating grain boundaries will effectively lower resistivity as well, and not require this impermeable zone. Graphite as the conductive interstitial material is not limited to this depth range, but will be kept stable only under reducing conditions. The crust/mantle boundary (Moho) is seldom exposed in field data by changing electrical resistivity.

assumption that well-conducting structures need not be layers but could be of vertical extent: The earlier mentioned KTB studies give a good example with observed strong horizontal anisotropy which can be explained by zones of cataclastic deformation enriched in graphite (Haak *et al.*, 1989).

The battle between the competing explanations – fluids, carbon or other conducting minerals (e.g., sulphides) – for 'anomalous' crustal conductivities is far from reaching an end (Figure 7). As shown in this review, there are plausible arguments for each of these in a given area. The continental crust contains conductive structures of different lateral and vertical extent, some of them are strongly anisotropic. These anisotropies may point towards stress and strain features existing in the crust. The main question, with our present knowledge concerning these conducting zones, seems that of generating large interconnected structures or interstitial material within a host matrix in the deep crust, whatever the source material might be. The concept of intergranular coated films seems to be promising.

Since the studies of Adam (1978) and Shankland and Ander (1983) there have only been a few attempts to reach conclusions of a more general kind. Some of these (Adam, 1987; Hyndman, 1988; Hyndman and Shearer, 1989) try to correlate the usually well determined upper boundaries of the conductors with the ones of the reflective zones found by seismic techniques, or with geodynamic characteristics like heat flow. It seems that both boundaries depend on actual crustal temperature, requiring values of 300–400 °C. From this it follows that these zones may have a more or less transient character. This kind of statistical research has already produced some interesting results and – fortunately – also new questions. I feel that more coincident measurements with seismic reflection investigations or other geophysical methods and a better contact between earth scientists are necessesary to improve our knowledge.

There seem to be no limitations for EM people in finding new areas of interest for field investigations, especially when going to remote areas (e.g., Niblett *et al.*, 1987; Beblo and Liebig, 1988). This enthusiasm feeds the hope of a much better insight into structures, physical properties and of a better understanding of processes in the Earth.

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