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An Anomaly of the Upper Mantle below the Rhine Graben, Studied by the Inductive Response of Natural Electromagnetic Fields *

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Abstract. The methods of Magnetotellurics (MT) and Geomagnetic Deep Sounding (GDS) have been applied to study the electromagnetic response of the rift structure of the Rhine Graben. The measurements at 17 MT and 7 GDS stations were carried out along a profile running perpendicular across the Graben. Fourier analysis and numerical filters were tried for separation of the frequencies and a least squares technique was applied for data reduction. The thus gained transfer functions can be explained well by two-dimensional models under the following assumption: a well conducting layer at the depth between about 80 and 100 km exists at distances 50 km West and 100 km East of the Rhine Graben. Immediately below the Graben, however, a zone of similar good conductivity lies between about 25 and 45 km depth. The lateral extension of this zone is only some tens of km from the Graben's edges.

Key words: Electromagnetic induction – Magnetotellurics – Geomagnetic deep sounding – Electrical conductivity – Upper mantle – Rift structure – Rhine graben.

Introduction

The aim of geophysical studies of electromagnetic (em) induction is to gain information about the electrical resistivity and its distribution within the earth's interior. Artificial em fields are usually excited in the frequency range of much more than 1 Hz and one gets—because of the skin effect—therefore only insight into the first hundreds of metres of the subsurface. By using slowly, temporally varying natural fields, under favourable circumstances it is possible to extend the estimates down to some hundred kilometres. Not only the physical quantity of the electrical resistivity of the lower crust and the upper mantle itself, however, is of great interest, but of equal importance is its correlation with temperature (an effect of semiconductivity). Further, temperatures within the earth's interior

* This publication is a summary of results of the author's thesis. Details about data analysis and model calculation can be found therein.

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and the associated anomalies connected with tectonically active zones such as faults and rifts are an important aid to understand the origin and development of our earth.

The Scope of Studies

The object of our investigations is the Rhine Graben, the central part of the rifting structure traversing Western Europe in SSW–NNE direction: the Mediterranian–Møsjen Zone. Numerous geophysical and other geoscientific activities in this area have been reported. Among them are the methods of tellurics (Haak *et al.*, 1970), magnetotellurics (Losecke, 1970; Scheelke, 1972) and geomagnetic deep sounding (Winter, 1973), all of which make use of the response of natural em induction. The most complex models applied for interpretation were two-dimensional: a thin sedimentary overburden with a laterally (in one direction) varying resistivity lying over a stratified substratum built up of homogeneous layers, infinite in horizontal directions. The most important finding of the previous investigations was the deduction of a low resistivity layer (resistivity $\varrho \approx 30\ \Omega\mathrm{m}$) within the basement ($\varrho \approx 10^3\ \Omega\mathrm{m}$) at a relatively shallow depth of 20 or 30 km. The thickness of this layer was found to be 20 to 30 km by Scheelke (1972) and 50 to 90 km by Winter (1973). The extension of it from the Graben's edges could thereby not be determined since those measurements were mainly conducted over the Graben zone itself and in the immediately adjacent areas and, of course, because of the model typ used, which does not admit lateral changes in the deeper structures.

The Measurements and the Applied Interpretation Technique

The locations where we performed our measurements lie on the southern line in Fig. 1, labeled "R II". The time variations of the horizontal components of the electrical field **E** were recorded at 17 stations distributed over a length of approximately 240 km. At two stations the time variations of the horizontal components of the magnetic field **F**, were measured in order to be able to apply the magnetotelluric method (MT). At seven stations of the Eastern part of the profile geomagnetic deep soundings (GDS) were carried out in registering simultaneously the variations of the three components of the magnetic field **F**.

The quantities one usually intends to derive from the recorded time variations in order to compare them with those obtained by model calculations are the so-called transfer functions as a function of period T. In MT they are the apparent resistivity

$$\varrho_a = 2 \cdot T \cdot (E/F)^2$$

(in e.m.u., E and F are horizontal components (orthogonal to each other) of the fields **E** and **F**) and the phase φ. Together they describe the dependence

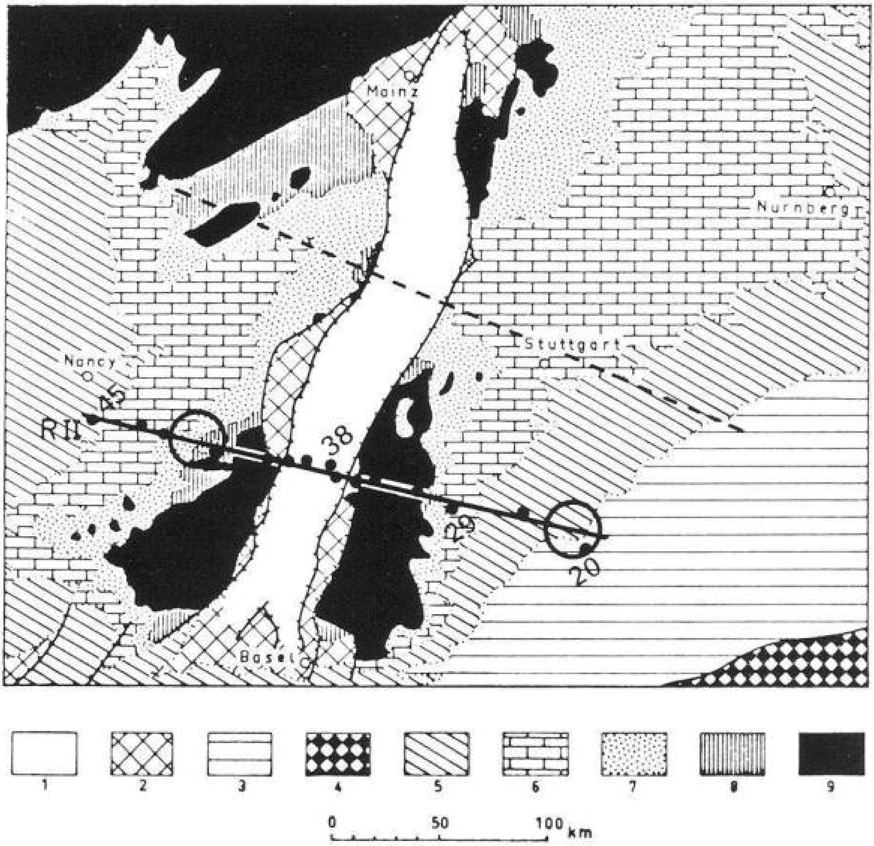


Fig. 1. Generalized geological map of the Rhine Graben area (after Illies, 1967). The lines are profiles on which induction studies have been carried out. On the southern line, labeled "R II", the stations are situated as described in the text. Most of the stations are indicated by dots, a few by numbers. Areas marked with circles represent the zones, where the measurements could be explained with one-dimensional models. *1* Graben trough, *2* Marginal blocks and basins, *3* Molasse trough, *4* Alps, *5* Jurassic, *6* Middle and upper Triassic, *7* Lower triassic, *8* Permian, *9* Prepermian basement

of the horizontal **E**-field components on those of the **F**-field. In GDS they are the geomagnetic induction arrows

$$\mathbf{c} = a \cdot \mathbf{N} + b\mathbf{M}$$

(where **N** and **M** are the vectors of unit length in the northern and eastern direction, respectively), as complex quantities, appropriate to express the linear relations between the vertical component Z of the variations of the magnetic field and the horizontal components:

$$Z = a \cdot H + b \cdot D$$

(H is the north component of **F**, D the east component) (Parkinson, 1959; Schmucker, 1970). Model calculations are commonly computed under the

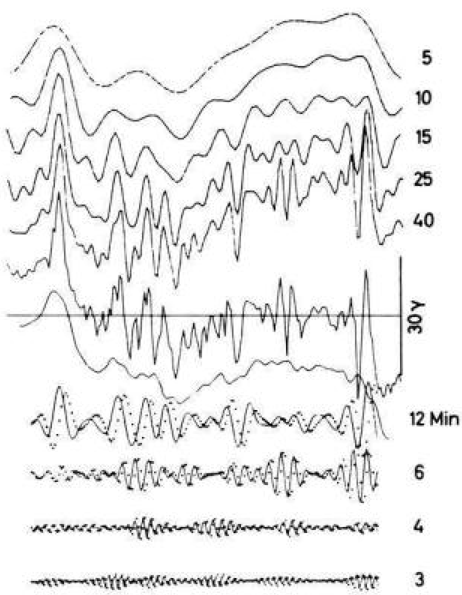


Fig. 2. Around the central line: recorded time variations of the East (D) component of the magnetic field **F** from 7^{20} UT until 10^{30} UT, Dec. 25, 1968 (interval length 190 min), measured at a site near the Eastern border of the Rhine Graben. At the top: after Fourier analysis re-synthetisized variations with different numbers k_{max} of harmonics included (written at the right hand side). Below: results of numerical filtering: continous lines in-phase filter, small crosses out-of-phase filter. The periods of the maximum of the frequency response function in minutes are indicated at the right

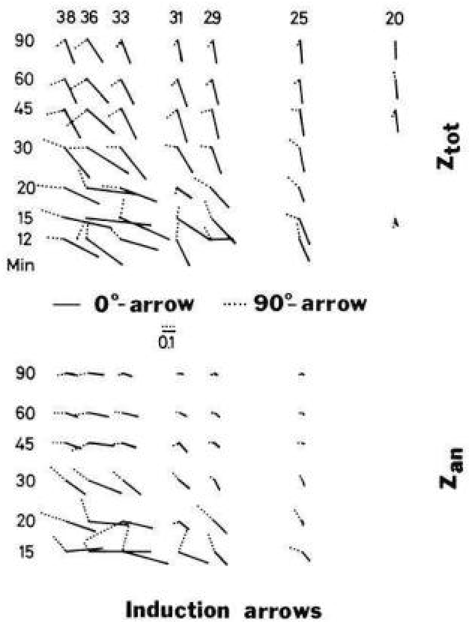


Fig. 3. Induction arrows **c** (after Schmucker, 1970) at measuring sites at the Eastern half of our profile R II across the Rhine Graben (Fig. 1): station 38 is in the middle of the Graben, station 20 at the extreme East is approximately 130 km from it. On the two halves of the figure from top to bottom the results for different periods, written in minutes at the left side, are shown. Upper half: Arrows that have been derived from the variations of the measured total field (Z_{tot}). Lower half: An attempt to use only the part of the vertical component Z (Z_{an}) caused by the anomaly of the Graben itself (*i.e.* the regional Z-variations noticed everywhere in Southern Germany outside the Rhine Graben anomaly have been subtracted). Heavy lines: Real parts of **c**—in-phase or 0°-arrows. Dotted lines: Imaginary parts—out-of-phase or 90°-arrows

assumption that the fields are harmonically oscillating. Therefore, one has to apply a frequency analysis onto the recorded variations. The periodes T we used were about 10 to $2 \cdot 10^4$ s in the case of MT and $2 \cdot 10^2$ to 10^4 s in the case of GDS. Two different methods for the frequency separations were tried:

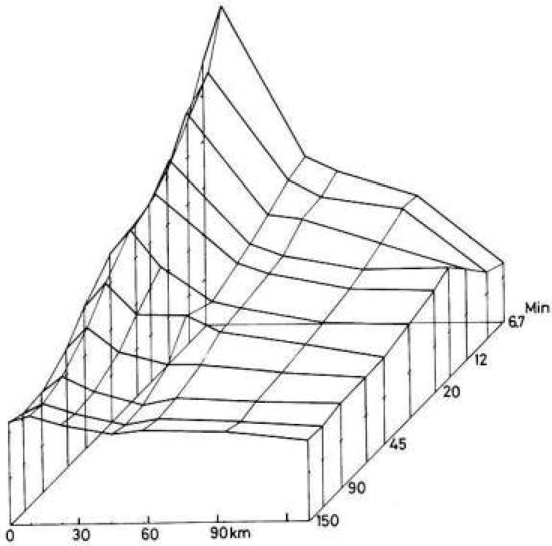


Fig. 4. Length of the empirical induction arrows |**c**| versus location and period for the Eastern half of the profile R II: at the left side lies the middle of the Graben and at right is the Eastern end of it at a distance of about 130 km: from front to back the periods from 150 to 6.7 min are drawn. At the ordinates the values are marked in a distance of 0.1

the Fourier analysis and application of numerical filters. In Fig. 2 examples are shown. For deduction of the transfer functions the concept of least squares was used. An example of some results thus gained is being shown in Figs. 3 and 4 for the induction arrows.

Another problem in interpreting the field measurements is to compute the transfer functions of model structures in order to be able to compare them with those derived from the measurements: the best fitting model represents the structure existing in nature with highest probability. A two-dimensional model for the Graben structure should represent the real situation quite well. We used two techniques for the model computations:

a method making use of the concept of a thin inhomogeneous layer over an one-dimensional substratum after Schmucker (1971) (who developed some ideas of Price);

the method of finite differences after Jones and Pascoe (1971), improved and programmed by Haak (1974).

Results are shown in Figs. 5 and 6.

Results

In the case of two-dimensional configurations one can choose from a great variety of parameters to find the best fitting model. However, fortunately, one can reduce the troublesome task to define the best model by incorporating knowledge gained from other geoscientific studies and, above all, by trying first simpler models, *i.e.* one-dimensional ones, if such models seem to be appropriate. On our profile we found areas at some distance of the Rhine Graben, about 50 km West and 100 km East (marked by circles in Fig. 1), below which the resistivity

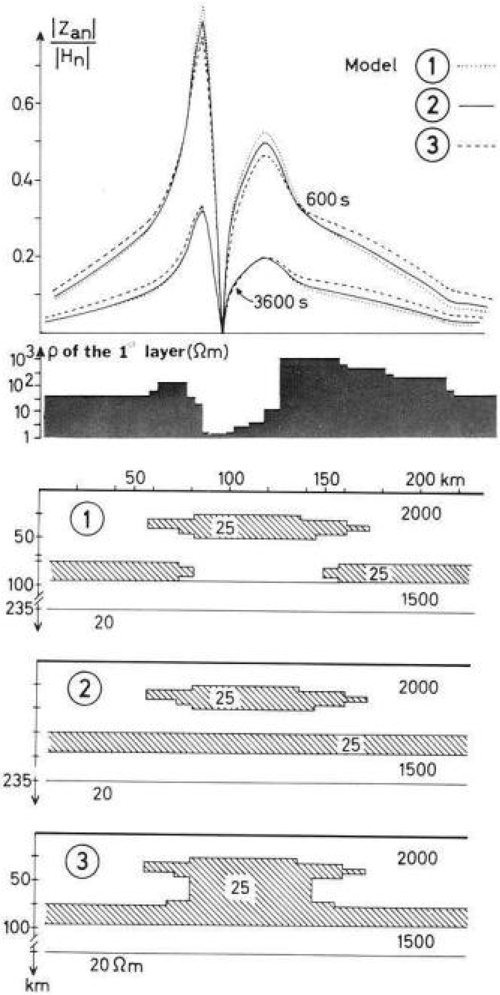
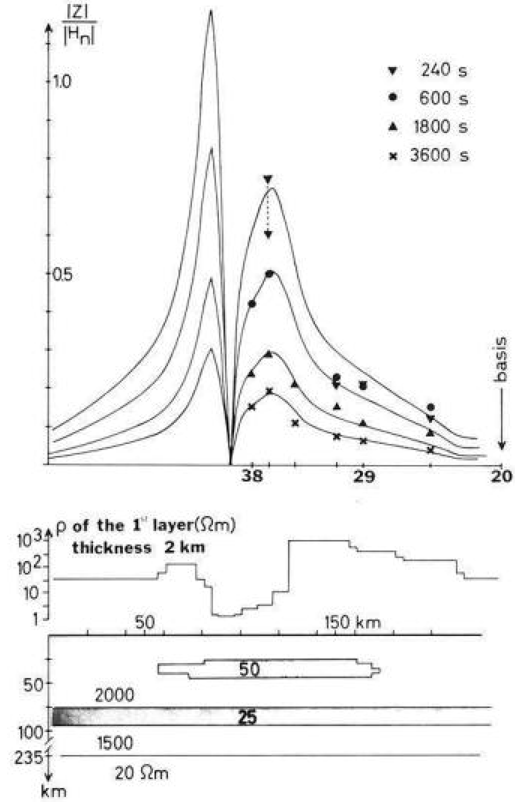


Fig. 5. Above: Length of the induction arrows |**c**| along profiles for three models, in which only the deeper structures are altered, as results of two-dimensional model calculations. Second diagram from above: Resistivities ϱ in Ωm of the first layer with a thickness of 2 km. Below: The three models of the deeper substratum. The results of calculation are shown for two periods, 10 min and 1 h

distribution can be assumed to be a function of depth only, approximately. In this case the technique of interpretation of the MT data is much less complicate. One can use for example Cagniard's method or the $\varrho^*(z^*)$-inversion-technique of Schmucker (1970). We are confident that the situation in nature at the areas mentioned is not very different from the following model (Haak and Reitmayr, 1974): below the locally varying sedimentary cover the basement has high resistivities $\varrho > 1{,}000$ Ωm. At a depth of approximately 80 km (74–95 km) a low resistivity layer ($\varrho = 10-100$ Ωm) with a thickness of about 20 km (14–25 km) exists. The high resistivities below this conductor do not decrease for several hundred km. A similar distribution has been found in other parts of Southern Germany and around the surrounding areas (Beblo, 1974; Berktold, 1974). Many authors regard this case as a normal continental situation (Fournier *et al.*, 1971).

Fig. 6. Length of the induction arrows as derived from our measurements and their explanation by a two-dimensional model. Best fitting with the model shown in which there are two low resistivity zones in the deeper structure: One laterally limited between 25 and 45 km depth below the Rhine Graben (resistivity 50 Ωm) and one running through between 75 and 95 km depth (25 Ωm)



Starting with this knowledge we tried to interpret the local variations of our derived transfer functions by local variations in the sedimentary cover alone; soon, however, there arose difficulties. We noted for instance, that the lengths of the calculated induction arrows do not decrease as slowly as they do in nature when the recording stations are remote from the Graben. This and other results can only be explained by the assumption of deeper situated lateral inhomogenities. Finally we obtained best agreement by introducing in our models a poorly resistant ($\approx 50\ \Omega$m) zone, laterally limited to a few tens of km below the Graben, between the depths of 25 to 45 km. The model as well as one of its transfer functions (here the length of the induction arrow) and the corresponding function derived from the measurements can be seen in Fig. 6. An uncertainty, however, remains about the exact geometry (and the resistivities), as demonstrated in Fig. 5.

Above we mentioned our intention to get also information about the distribution of temperature with knowledge of the resistivity within the earth's interior. If one assumes a predominant olivine composition of the upper mantle with approximatley 10% fayalite and a high content of ferric iron (perhaps 0.5% Fe_2O_3)—a composition which is rather probable—a resistivity in the order of 30 Ωm, as found below the Rhine Graben at about 25 km depth and in some distance of it at 80 km, seems to indicate temperatures of roughly 800° C (after

Schult, 1974). Recent investigations, however, suggest that resistivity may be strongly influenced by the content of Fe^{3+}, and so the increase in resistivity below the well conducting layers might be caused by a change in the petrological composition, in the sense that the ferric iron diminishes nearly or totally.

Other authors have tried to interpret those low resistivity layers within the upper mantle by zones of partially melted material (*e.g.* Berdichevsky *et al.*, 1972). Statements concerning the temperatures are then much more uncertain.

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