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A Comparison of Results of Geothermal and Magnetotelluric Investigations in Northwestern Germany

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Abstract. The results of a regional magnetotelluric survey carried out during exploration for new energy resources in the northwestern part of the Federal Republic of Germany were used to make maps of the average electric resistivity of the sediments between the earth's surface and the Zechstein base as well as of the sediments between the Zechstein base and the top of the basement. Structures striking E-W were dominant in these maps.

Furthermore, anomalies occur with a strike of NE-SW to NNE-SSW. A region of very low resistivities of pre-Zechstein layers striking E-W at the southern margin of the North German Basin is of special interest. Maps of the average resistivity are compared with temperature maps of subsurface levels at 2000 m and 3000 m depths in Northwestern Germany. There is a remarkable correspondence between zones of low resistivity and regions of significantly elevated temperatures. The possible origins of both anomalies are discussed.

Key words: Geothermics – Magnetotellurics – North German Basin – Temperature distribution – Conductivity distribution – Prepermian.

Introduction

Geothermal and magnetotelluric studies have been carried out during exploration for new energy resources in North-western Germany since 1975. Investigations to establish a temperature atlas for the Federal Republic of Germany were sponsored by the Federal Ministry of Research and Technology (BMFT) (Wohlenberg, 1978). This project was executed by the Niedersächsisches Landesamt für Bodenforschung (NLfB). Object of the investigations was the mapping of potential geothermal resources in the subsurface of the Federal Republic. Temperature data were taken from
(1) drilling reports from the oil industry, (2) temperature logs recorded in

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boreholes and mines, and (3) calculated temperature-depth functions based on heatflow and thermal conductivity data.

Temperature maps based on these data were plotted for the subsurface of the Federal Republic of Germany.

At the same time, the BMFT and the LEP (Landes-Entwicklungs-Plan) funded large-scale magnetotelluric experiments to investigate the size and structure of the sedimentary basin of NW Germany with special interest in more detailed information on the pre-Zechstein strata. This work was carried out by the BGR (Federal Institute for Geosciences and Natural Resources). The magnetotelluric investigation can be divided into three parts: (1) computer controlled digital recording of the electric and magnetic field components (time series); (2) analysis of the time series by extensive data processing (sounding graphs); (3) construction of a model of the subsurface structure from the sounding graphs combining model computation and geological information.

This paper presents the results of both investigations and discusses the possible common origin of the temperature and electric resistivity anomalies.

Geothermal Investigations

Temperature data for the construction of the temperature maps were collected from more than 4,800 drill holes out of a total of 16,000 bore holes. The geographical distribution of these data is not uniform throughout the area of the Federal Republic of Germany. Only the oil-bearing sedimentary basins have a high density of boreholes, i.e., a high information density. For the region under consideration, namely the sedimentary basin of northwestern Germany, temperature data was obtained from more than 3,770 drill holes. In addition, the NLfB took high quality temperature logs in 26 deep drill holes. Temperature-depth curves could be calculated from 8 heat-flow measurements. The quality of the data taken from the drilling reports is uncertain. Therefore, a statistical treatment was applied to all of the data. Temperature-depth curves were calculated on the basis of all the available temperature data from within areal elements of 12 × 12 km, taken from the 1:25,000 topographical map grid. The so produced temperature maps for several depth levels were smoothed applying a two dimensional moving average over nine elements. On the basis of these refined charts, isothermal maps were constructed for depths of 100 m, 250 m, 500 m, 1,000 m, 1,500 m, 2,000 m, and 3,000 m (Wohlenberg, 1978).

A map of temperatures at a depth of 2,000 m is shown in Fig. 1. Differences of more than 20° C occur at this level. A region of remarkably elevated temperatures stretches from the Netherlands through the area of Hannover to the Flechtinger Hills. Temperatures are significantly lower to the north and south of this region. Less pronounced anomalies striking NE-SW and NNE-SSW appear in the northern and southern part of the region shown in Fig. 1.

A similar pattern of anomalies is shown in Fig. 2 for the 3,000 m level. Temperature differences of more than 30° C are observed at this level. The higher temperatures appear along the southern margin of the North German

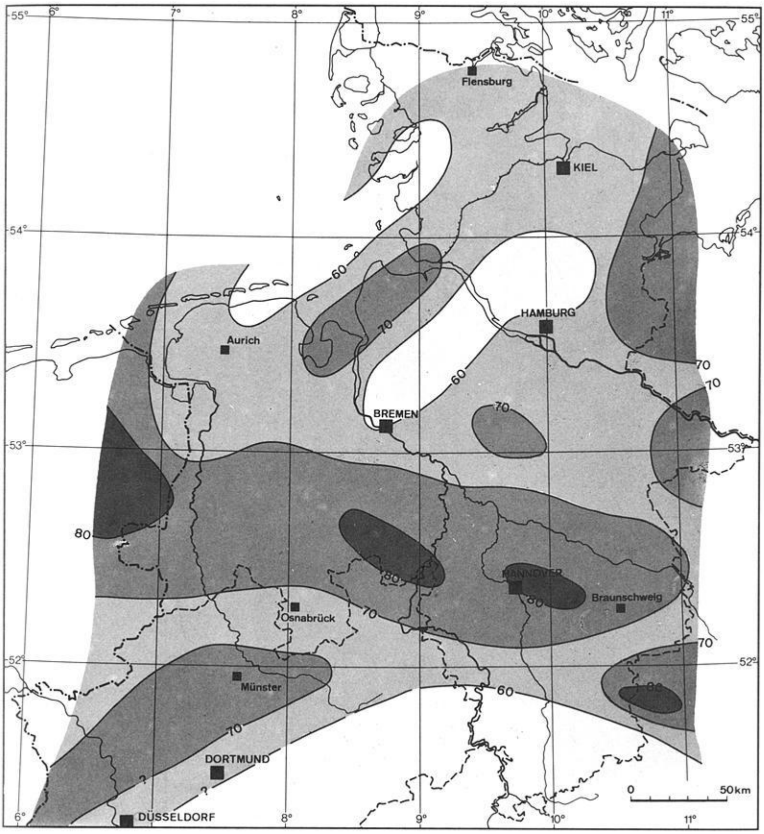

Fig. 1. Isoline map of temperatures at a depth of 2,000 m in the northern part of the Federal Republic of Germany (Wohlenberg, 1978); in °C

Basin, similar to what was observed in Fig. 1 for the 2,000 m level. The E-W striking anomaly obviously becomes more significants with increasing depth.

Magnetotelluric Investigations

The interpretation of the magnetotelluric observations is based on tensor rotated curves of apparent resistivity (ρ_{12}, ρ_{21}) and phase (φ_{12}, φ_{21}), rotation angle of the principal axes and skewness in the period range 0.2 to 2,048 s. For cases in which both the curves of apparent resistivity and both the phase curves did not deviate too much from each other a single new curve of apparent resistivity $\bar{\rho}$ and also a single curve of phase $\bar{\varphi}$ was calculated as follows:

$$\bar{\rho}_\kappa=\sqrt{\rho_{12}(T_\kappa)\cdot\rho_{21}(T_\kappa)},\qquad \bar{\varphi}_\kappa=\tfrac{1}{2}[\varphi_{12}(T_\kappa)+\varphi_{21}(T_\kappa)]$$

$$T_\kappa=\text{period}\qquad \kappa=1,2,3\ldots$$

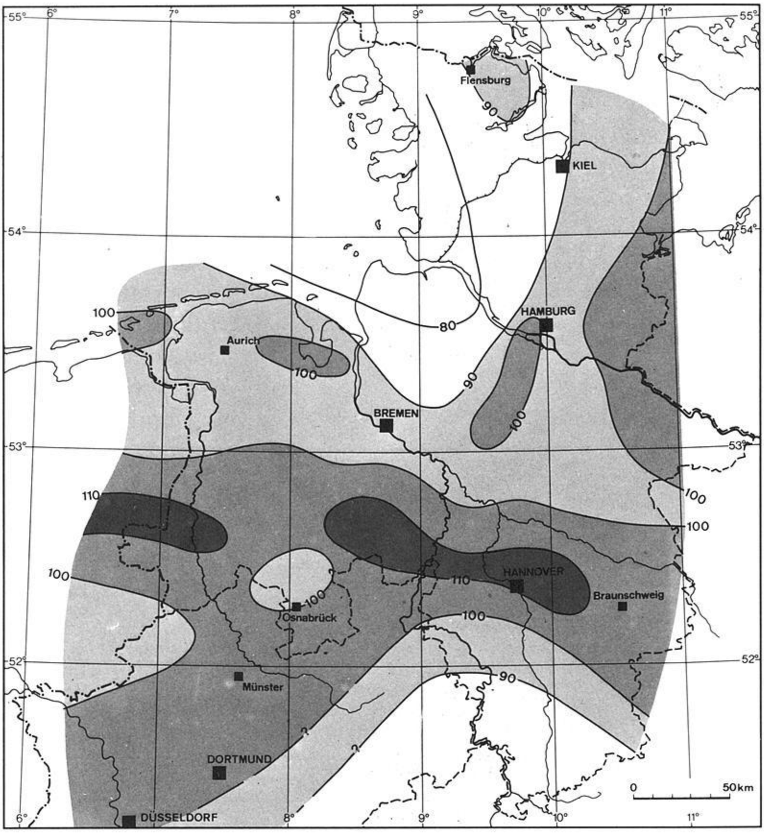

Fig. 2. Isoline map of temperatures at a depth of 3,000 m in the northern part of the Federal Republic of Germany (Wohlenberg, 1978); in °C

For interpretation in a first step, a horizontal layer inversion according to Bostick (1976) resulted in an approximative resistivity-depth curve for each observation point. In a second step, a correlation of maxima and minima of these resistivity-depth functions between the neighbouring points was successful, and first horizontal layer models were constructed. From these models it was possible to derive number, thickness, and approximate resistivity values of the layers down to the high resistivity magnetotelluric basement. An improved second model was constructed using the horizontal layer inversion according to Marquardt-Müller (Müller, 1977).

As a characterizing parameter for the subsurface below each observation point, the integrated conductivity S is of special interest. S is not very sensitive to changes in the model. It is defined for a series of highly conductive layers above a high resistivity basement:

$$S = \sum_{i=1}^{n-1} \frac{h_i}{\rho_i} \tag{1}$$

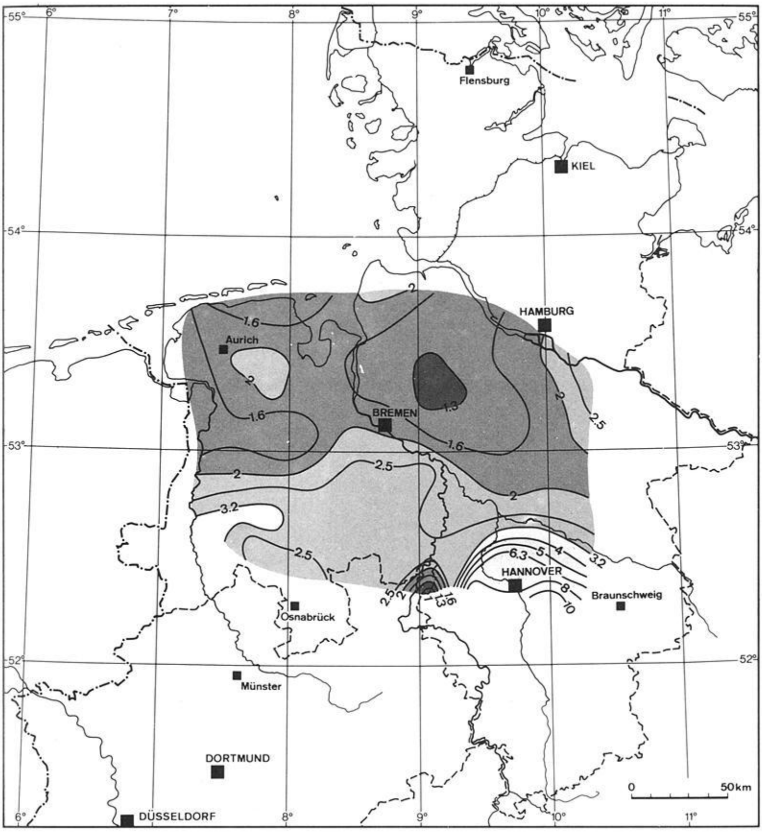

Fig. 3. Isoline map of electric resistivity ρ_m (ohm · m) in the post-Zechstein formations in the northwestern Germany constructed from magnetotelluric data (Knödel et al., 1978)

where h_i = thickness of the layers,
ρ_i = resistivity,
$n-1$ = number of layers above the basement,
n_m = number of layers above the Zechstein base,
n_p = number of layers between the Zechstein base and, the basement, i.e., $n_m + n_p = n-1$.

In addition, the following relationships are valid:

$$h = \sum_{i=1}^{n-1} h_i = \bar{\rho} \cdot S \tag{2}$$

where $\bar{\rho}$ = average resistivity.

Since S behaves additive, the integrated conductivities can be defined for parts of the series as well:

$$S_g = S_m + S_p = \sum_{i=1}^{nm} \frac{h_i}{\rho_i} + \sum_{i=nm+1}^{n-1} \frac{h_i}{\rho_i}. \tag{3}$$

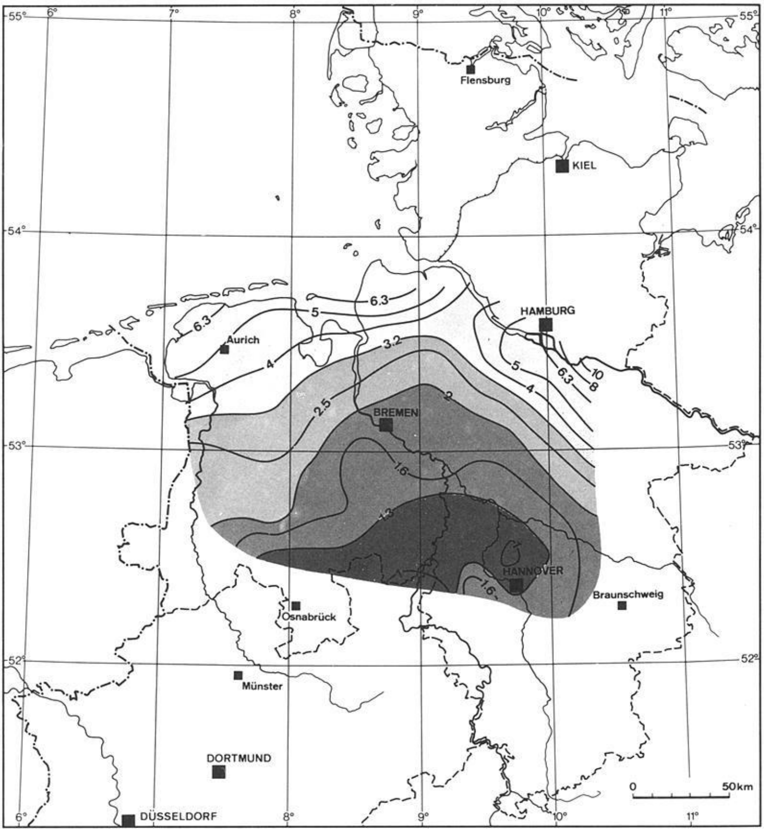

Fig. 4. Isoline map of electric resistivity ρ_p (ohm · m) in the pre-Zechstein formations in northwestern Germany constructed from magnetotelluric data (Knödel et al., 1978)

The S-values can be calculated from results of the horizontal layer inversion at any observation point. The average resistivities ρ_m and ρ_p for the layers above and below the Zechstein base can be determined from S_m, S_p, and the corresponding thicknesses (for the distribution of the depth of the Zechstein base see International Map of Natural Gas Fields in Europe, Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover 1972). The thickness of the layers from the Zechstein base down to the basement is changing from 7 km in the southern part to 11 km in the northern part of the region under consideration (for further information see Losecke et al., in press).

Figure 3 shows an isoline map of the average resistivities ρ_m above the Zechstein base. The isolines were derived from observations at approximately 50 stations arranged on a rectangular grid of about 40 km between points.

Figure 4 shows an isoline map of the average resistivities ρ_p for the layers between the Zechstein base and the basement. The ρ values vary in both maps from 1 to 10 Ωm.

The great difference in the pattern of isolines for ρ_m and ρ_p (Figs. 3 and 4, respectively) is remarkable. While for the post-Zechstein layers the lower resistivities appear in the more northern parts of the region under discussion, the pre-Zechstein pattern is just the reverse, the low resistivity values appear in the southern parts. The very low resistivity values ρ_m near the Weser west of Hannover are an exception. Structures with an E-W strike are prominent in Figs. 3 and 4. Besides these, there are structures with a NE-SW to NNE-SSW strike. Of special interest is a region of very low resistivities on the southern margin of the North German Basin (pre-Zechstein).

Discussion of Results

1. Extrapolating the temperature field presented in Figs. 1 and 2 for pre-Zechstein layers and assuming only electrolytic conduction, temperature controlled differences of not more than 20% of the mean value can be expected for the average resistivity ρ_p. Under these conditions the observed pattern of the resistivity ρ_p (Fig. 4) can be explained by variations of the temperature field to only a small amount (<20%).

2. The attempt to explain the pattern of resistivity ρ_p by variations in the facies is not satisfactory. There is at present no indication of such an extensive facies difference. Moreover, the attempt to correlate the temperature pattern with facies changes leads to a contradiction of the results of the magnetotelluric investigations, because a simultaneous increase in electric and thermal conductivity would be required, which is very unlikely.

3. The assumption of several thin layers of highly concentrated semiconductive or metallic minerals (e.g., pyrite or graphite) could explain the resistivity (ρ_p) pattern. Such high concentrations of conductive minerals over large areas are unknown.

4. Another explanation for the observed anomalies in the parameters ρ_p and T is possible: the regions with the lowest resistivities and elevated temperatures coincide with a region of tectonic activity, namely the basin of Lower Saxony (see Fig. 5) (Boigk, 1968; Stadler and Teichmüller, 1971). The boundaries of the basin to the north and the east are formed by the Pompeckj swell, to the south by the Rhenish Massif along old fault zones. The E-W striking basin crosses the Mediterranian-Mjösen lineament. Two independent tectonic events determined the present shape of the Saxonian basin. Tectonic shear strains during the Upper Jurassic caused the subsidence of a broad crustal strip and the intrusion of magmatic matter. The thickness of the Upper Jurassic and Lower Cretaceous sediments reached 3,000–4,000 m, depending on the amount of subsidence.

An orogenic phase during the Upper Cretaceous caused an uplift of the basin of approximately 1,000 m. During this phase, the inner part of the Lower Saxonian Basin was subjected to intensive block faulting with thrusting along the northern and southern margins. According to Boigk (1968), the possible origin of these dynamic processes are vertical movements within subsaliniferous and/or still deeper crustal layers. Seismic studies by Polskov et al. (1976) in the North German-Polish basin east of Lower Saxony under discussion have shown that extensive fault zones exist across the entire crust. Phases of repeated tectonic activity occured along these geologically unstable zones during all the

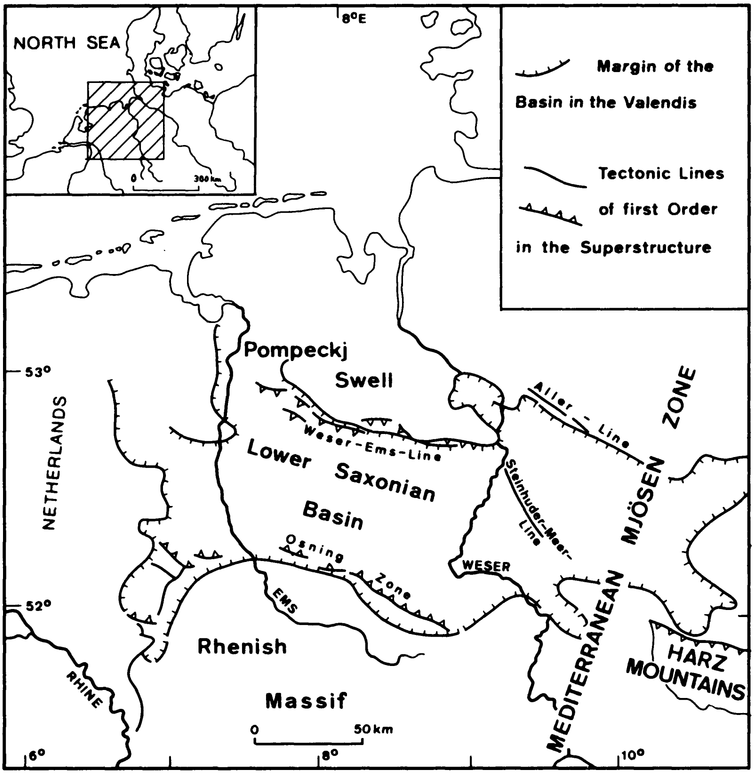

Fig. 5. The geologic and tectonic macro-structure of northern Germany according to Boigk (1968)

times and in Precambrian created E-W striking fault systems were reactivated and extended by different dynamic processes (Lauterbach and Lauterbach, 1973).

These continuous tectonic activities probably not only produced numerous fault systems, but also increased the crack porosity. Particularly the pre-Zechstein sedimentary layers were subjected to phases of uplift and subsidence during the Jurassic and Cretaceous.

The crack porosity still exists even under effective pressures of more than 3 kbars (Hurtig et al., 1972). Since the water filling the pore volume reduces the effective pressure, fracture porosities can be expected for the whole Palaeozoic formation. It may be remarked within this context, that within several deep drillings at depths larger than 5 km porosities of more than 5% have been found for Palaeozoic formations. In many cases the pore space was filled by water.

This model easily explains the pattern of resistivity ρ_p of the pre-Zechstein sedimentary layers by electrolytic conductivity in a medium with regional differences in fracture porosities. The high temperatures at the 2,000 m and 3,000 m levels are then caused by heat convection processes along the unstable zones described above. Hurtig et al. (1975) have discussed connections between geoelectromagnetic and geothermal anomalies on the one hand and fault zones on the other hand.

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