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Magnetotelluric Investigation of a Nearly Circular Saltdome in North Germany

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Abstract. In the years 1973 and 1974 magnetotelluric measurements were carried out over the salt dome of Höfer in North Germany, which has a nearly cylindrical structure. By statistical frequency analysis of the recorded signals a resistivity distribution was obtained, which allowed to localize the boundary of the salt dome. The results were in good agreement with data from seismic and gravimetric investigations. Exact statements about relations between depth and resistivity distribution, however, could not be made.

Key words. Magnetotellurics – Salt domes.

In the years 1973 and 1974 magnetotelluric measurements were carried out over the salt dome of Höfer in North Germany, which has a nearly cylindrical structure. Figure 1 shows the measuring site and the measuring profile lying in N76°E direction. The closed line represents the formerly assumed contour of the salt dome as suggested by Jaritz (1972), which together with the position of Mine Mariaglück (near point 7) was used to fix the profile. The measurements consisted in recording the time-dependent variations of the electromagnetic horizontal components $H_x(t)$, $H_y(t)$, $E_x(t)$, $E_y(t)$ for periods T between 2 s and about 1000 s (H = magnetic, E = electric fields at the surface). The x-axis was right-angled to the y-axis, which lay parallel to the measuring profile.

A complex impedance tensor Z as a function of T was determined from these variations for each of the eleven measuring points. This impedance tensor was used to calculate the apparent resistivities $\rho_{\parallel}$ (T) and the phases $\phi_{\parallel}(T)$ for E parallel to the x-axis ("E-polarization") as well as $\rho_{\perp}(T)$ and $\phi_{\perp}(T)$ for E perpendicular to the x-axis ("H-polarization"), which was about parallel to the rim of the diapir. (The expressions "H-" or "E-polarization" are used by analogy to two-dimensional cases, because there are some similarities, for example the abrupt change in $\rho_{\perp}$ along the profile.)

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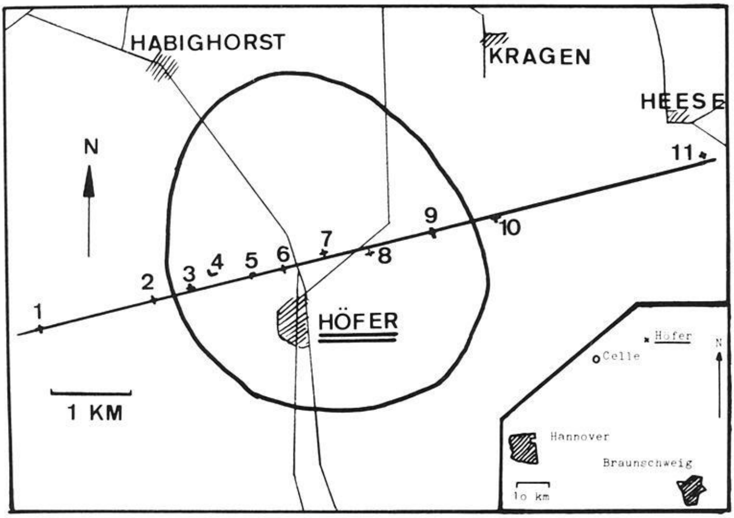

Fig. 1. Measuring sites and measuring profile. The closed line represents the contour of the salt dome after Jaritz (1972)

The impedance tensor Z introduced by Cantwell (1960) is defined by the equations

$$E_x = Z_{11} H_x + Z_{12} H_y$$

and

$$E_y = Z_{21} H_x + Z_{22} H_y.$$

The tensor elements were computed from the power- and cross-spectra of the digitized and fast Fourier transformed time series $H_x(t)$, $H_y(t)$, $E_x(t)$ and $E_y(t)$. An exact representation of this spectral analysis can be found in the works of Scheelke (1972) and Breymann (1975). To minimize $(Z_{11} + Z_{22})$ the tensor Z was rotated by a matrix D,

$$D = \begin{pmatrix} \cos\varphi & \sin\varphi \\ -\sin\varphi & \cos\varphi \end{pmatrix}$$

according to

$$Z' = DZD^{-1}.$$

The rotation angle φ gives the deviation of the main direction of the conductivity change from the measuring profile. The mean of φ for each station amounted to values between $-10°$ and $-20°$. The apparent resistivities and phases were computed as follows:

$$\rho_{\parallel}(T) = 0{,}2\, T\, |Z'_{12}|^2$$

$$\rho_{\perp}(T) = 0{,}2\, T\, |Z'_{21}|^2$$

$$\phi_{\parallel}(T) = \arctan\left(\frac{\mathrm{im}\,(Z'_{12})}{\mathrm{re}\,(Z'_{12})}\right)$$

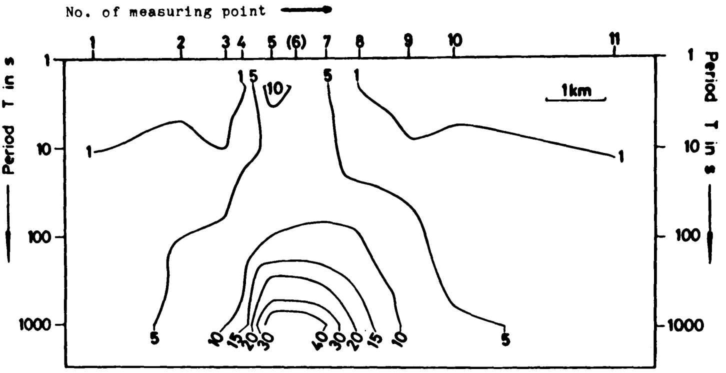

Fig. 2. Magnetotelluric pseudo cross section of the diapir (E-polarization), isolines of $\rho_{\parallel}$ (in ohm · m)

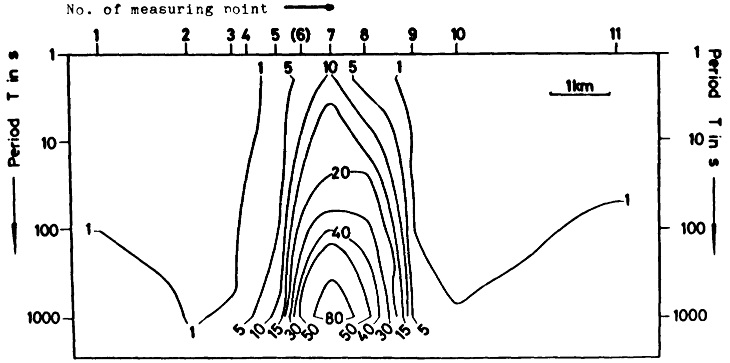

Fig. 3. Magnetotelluric pseudo cross section of the diapir (H-polarization), isolines of $\rho_{\perp}$ (in ohm · m)

$$\phi_{\perp}(T) = \arctan\left(\frac{\mathrm{im}\,(Z'_{21})}{\mathrm{re}\,(Z'_{21})}\right)$$

with

$$\mathrm{im}\,(Z'_{ij}) = \text{imaginary part of } Z'_{ij}$$
$$\mathrm{re}\,(Z'_{ij}) = \text{real part of } Z'_{ij}.$$

These equations are valid for ρ in ohm · m, T in s, E in mV/km and H in γ.

All calculations were carried out with a computer program developed by Scheelke (1972). The values of log $\rho_{\parallel}$ and log $_{\perp}$ were plotted vs. log T. The strong fluctuations in the phases did not allow a reasonable interpretation, and so they are not regarded in this paper. For a graphic display pseudosections showing lines of same apparent resistivity were constructed for $\rho_{\parallel}$ and $\rho_{\perp}$ (Figs. 2 and 3). This method as applied to salt domes has been described by Losecke (1972). The values of measuring point 6, however, had to be omitted because of bad quality of data.

Figures 2 and 3 give an idea of the resistivity distribution. The numbers at the lines indicate the apparent resistivities. They should not be confused with the real specific resistivities, which only approximate the apparent resistivities if the extensions of the structure are large compared with the skindepths of the observed periods.

In horizontal direction one can well localize the rim of the salt dome, which is between point 4 and 5 and 8 and 9 with the centre being between 6 and 7. As expected, a clear boundary effect is to be seen. $\rho_{\|}$ varies smoothly for currents perpendicular to the profile, but $\rho_{\perp}$ varies discontinously (with an overshoot) for currents along the profile because the abrupt resistivity change causes an abrupt change in $E_{\perp}$, and hence in $\rho_{\perp}$ (Breymann, 1975). Corresponding to this the conductivity contrast between sediment and salt becomes apparent much clearer in Figure 3 than in Figure 2. Looking at Figures 2 and 3 one finds that the lines of constant apparent resistivity are more dense at the west side, leading to the conclusion that the western flank is steeper than the eastern one.

These results were compared to a simple theoretical model, consisting of a vertical cylinder surrounded by a horizontal layer of high conductivity, bounded by an insulating half space above and below. The computer program used was developed by Rodemann (Personal Communication). It is based on an analytical approximation. Part of the calculation has already been described (Rodemann, 1974).

The best fit obtained was a model with a resistivity contrast of 1 ohm · m (layer) to 1000 ohm · m (cylinder). The cylinder's diameter was 2 km and the height of layer and cylinder 3 km.[1] The model differs from that one described earlier (Breymann, 1975), as the computations referring to the cylinder-model had to be carried out again because the approximation method was improved in the meantime. Although this model is very simple compared with the real diapir, the agreement between measured and calculated apparent resistivities was quite good (Figs. 4 and 5)[2] with the exception of measuring point 5, whose ρ-values were too low for H-polarization. A possible explanation, but not confirmed by model calculations, is the existence of a step or an overhang at the western rim. This asymmetry is also to be seen in Figures 2 and 3. In the case of E-polarization discontinuities appear strongly smoothed, and the resistivity distributions of point 5 *and* 7 look rather similar, in contrast to Figure 3 (H-polarization). In this case $\rho_{\perp}$ responds to lateral changes in conductivity very sensitively. However, this is only a hint at a step or an overhang, for it is not automatically clear that a structure in the isolines represents a similar structure in reality, as Losecke and Müller (1975) have shown.

With regard to this circumstances the cross section shown in Figure 6 approaches the reality in a satisfactory way. The plotted depth of the Zechstein salt base (more than 3 km) and the thickness of the uppermost layer covering the salt (about 120 m) are based on Schachl (1968), just as the salt dome boundaries from seismic and gravimetric measurements. The bounds of the calculated cylinder-

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[1] One can obtain fairly good models, too, by varying the diameter from 1.8 to 2.2 km, or by decreasing simultaneously the resistivity of the layer and the height of layer and cylinder. As resistivities less than 1 ohm · m in sediments are not realistic and the depth of the salt should be more than 3 km (after Schachl (1968)) the model used seems to be justifiable

[2] The values in Figures 2 and 4 and Figures 3 and 5 may differ slightly, as Figures 2 and 3 were derived from curves drawn by hand to smooth the course of ρ vs. the period T (Breymann, 1975)

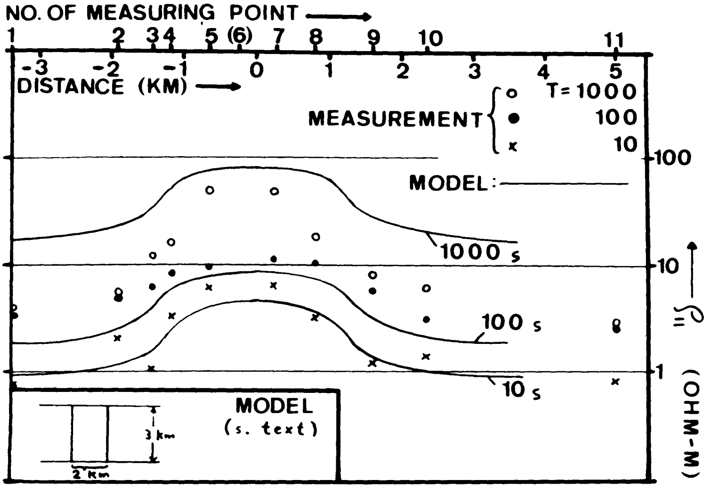

Fig. 4. $\rho_\parallel$-values along the measuring profile for different periods T (in s), compared with the apparent resistivities derived from the cyclinder model (E-polarization)

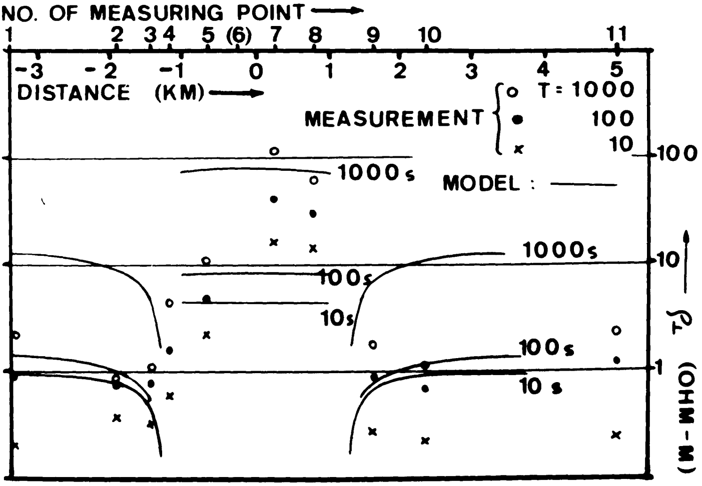

Fig. 5. $\rho_\perp$-values along the measuring profile for different periods T (in s), compared with the apparent resistivities derived from the cyclinder model (H-polarization)

model coincide nearly with the flanks of the diapir derived from seismic investigation, and hence they are not drawn.

For the region undisturbed by the salt (point 11) a horizontally layered model of the sediment's resistivity distribution was developed. The best fit was a three-layer model with a 1 km thick first layer of 1 ohm · m resistivity, a 7 km thick intermediate layer of 4 ohm · m, and an underlying substratum of 37 ohm · m (Breymann, 1975). The method used was a least squares estimation of nonlinear parameters (= depths and resistivities), described by Müller (1974).

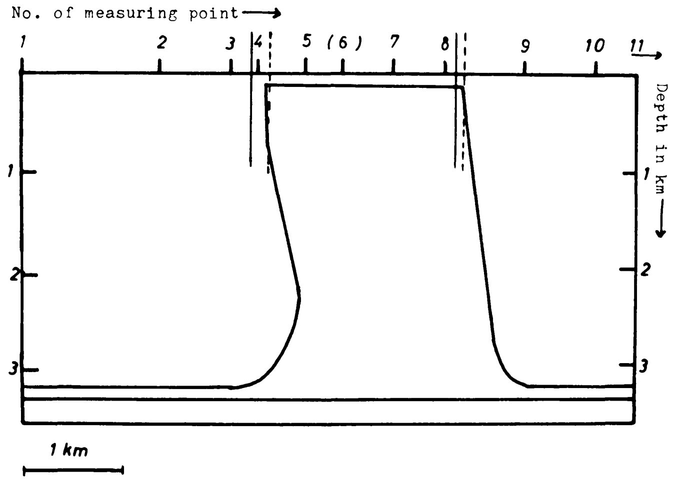

Fig. 6. Cross section of the diapir with boundaries derived from seismic (------) and gravimetric (———) investigations

Summarizing the following can be stated: The magnetotelluric method allows to localize quite well the rim of salt domes, even if (like in this case) the dimensions of the salt dome are smaller than the skin depths of the considered periods (except for the "high" frequency domain with periods less than 10 s), and even if it is not possible to apply a two-dimensional model. Exact statements about the relation between resistivity and depth, however, cannot be made until detailed three-dimensional model calculations are made.

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