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Two-Dimensional Magnetotelluric Model Calculations for Overhanging, High-Resistivity Structures*

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Abstract. Apparent resistivitiy and phase curves across the profiles of highly resistive overhanging and non-overhanging theoretical two-dimensional models as they may be realized by salt domes, mushroom-shaped intrusions etc. are compared with each other. The finite difference approach with a grid of about 8000 points allowed a very fine contouring of the structures' boundaries. The influence of rough and fine contouring is investigated. For the presented models the surface values of the overhanging structure are very different from those of the non-overhanging one if the resistivity of the structure is not of the same order of magnitude as the surrounding layers or if the basement is not too thick. In such cases fine contouring should be applied.

Key words: Finite Difference Method – Grid Spacing – Two-Dimensional Modelling – Salt Domes – Overhanging Structures – Resolving Power of Magnetotellurics.

Introduction

The determination of boundary surfaces of large scale geological structures or bodies is one important aim of applied geophysics. Of special interest are structures of the overhanging type such as mushroom-shaped intrusions, salt domes, overthrusts, overturned folds etc. The more complicate a structure is the more geophysical methods we generally need in order to obtain a good approximation of its shape. Thus, from the point of view of the theoretical geophysicist it is well worth to ask what magnetotellurics could probably contribute to the solution of such problems.

In 1972 magnetotelluric measurements were carried out across a longitudinal salt dome in the North German basin (Losecke, 1972). The apparent resistivities were represented in pseudo cross sections. The shape of the isolines was a clearly recognizable non-linear image of the contours of the salt dome's cross section. This result gave rise to calculations of the magnetotelluric field across certain theoretical two-dimensional geometries which in practice may be realized more or less by geological structures of the types mentioned above.

The governing aim was to get some ideas on the resolving power of magnetotellurics especially if we compare an overhanging structure to a non-overhanging one. It is the question which effects we have to expect if a measurement shall be carried

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out across one of those structures. This includes the problem of how good a geological boundary has to be mathematically approximated in order not to introduce effects due to mathematical errors.

Apart from some modifications the numerical treatment of the present work is applied as proposed by Neves (1957) or Jones and Pascoe (1971). Boundaries between areas of different conductivity follow grid lines; thus, a complicate shape is approximated by a rectangular step curve. The quality of this approximation depends on the number of grid points; the more grid points, the better a boundary may be represented. Moreover, increasing the number of grid points improves accuracy when solving the differential equation. Thus, refining of the grid permits a refined contouring of the two-dimensional structure. When keeping the number of grid points constant it is possible to calculate effects on surface field values which are only due to differences between rough and fine contouring. In other words, we obtain statements on the resolving power of magnetotellurics in the two-dimensional case which allow a decision whether at all or to what degree refining is necessary.

Model Results

For all models the number of grid points was kept constant to 7200 for H-polarization and 8600 for E-polarization. Grids of such a size need a lot of computer time and their field values tend to instability. Therefore, three special acceleration techniques had to be applied. First the fine contoured model was roughly approximated by a pre-model with larger grid spacings and the well iterated field matrix of this pre-model was then spread out over the fine grid. So the iterations of the fine model started with good initial field values. Secondly successive over-relaxation as described by Smith (1965) was used with overrelaxation factors up to 1.9. Thirdly the field values obtained for one period in a special manner were used for initializing the next case with a new period not too different from the previous one. Calculations were carried out on a CDC-CYBER 76—14.

The main model for which computation was done is a fine-contoured, overhanging, 1000 Ohm · m perturbation contained in "sedimentary" rock of 10 Ohm · m resistivity (model A, Fig. 1). Its cross section has an extent of about 2.6 km in the vertical and 2 km in the horizontal direction. It is underlain by a 37 km thick layer of high resistivity basement. This model only is a mathematical one to study its magnetotelluric effects but not a representation of a really existing geological structure. On the other hand, the model parameters are chosen as for models which really could exist. The grid spacing increases with increasing depth and towards the external boundaries. The smallest grid spacing is 50 m and it is kept constant within and near the perturbation (between 12.9 km and 16.5 km on the horizontal scale and up to a depth of 3.4 km).

In order to analyse effects caused by contour differences only, we have to avoid effects which could be introduced by a grid spacing which is too large. Neves (1957) derived from calculations over an uniform earth an actual error of 0.6% when comparing differential with finite difference solution obtained by a grid spacing of $^1/_4$ of the skin depth. In order not to exceed this error the grid spacing must fall below this limit. Our calculations were carried out in a period range of 1 to 1000 sec. For the most disadvantageous conditions $\varrho = 10$ Ohm · m and $T = 1$ sec, the skin

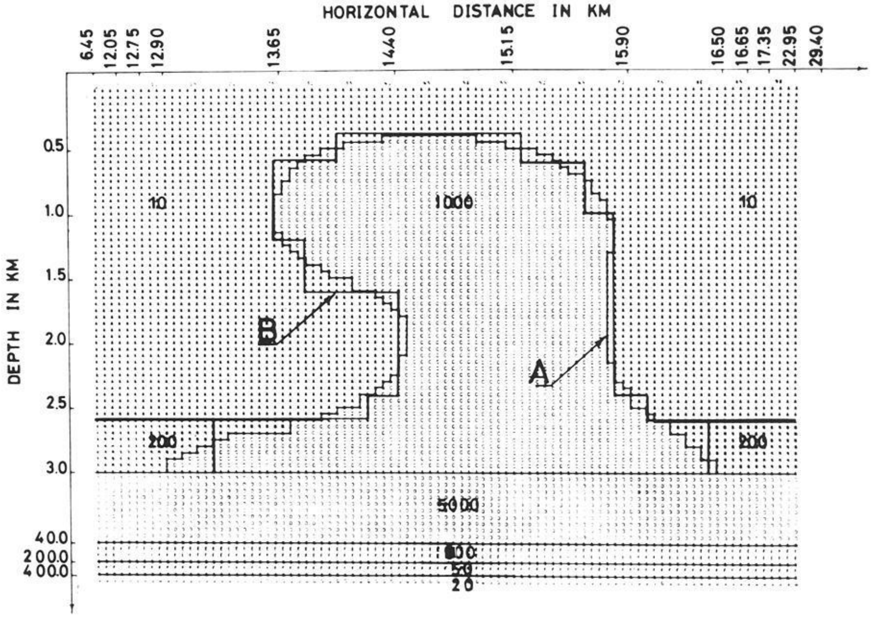

Fig. 1. Vertical cross section of two-dimensional models A and B (resistivity in Ohm · m)

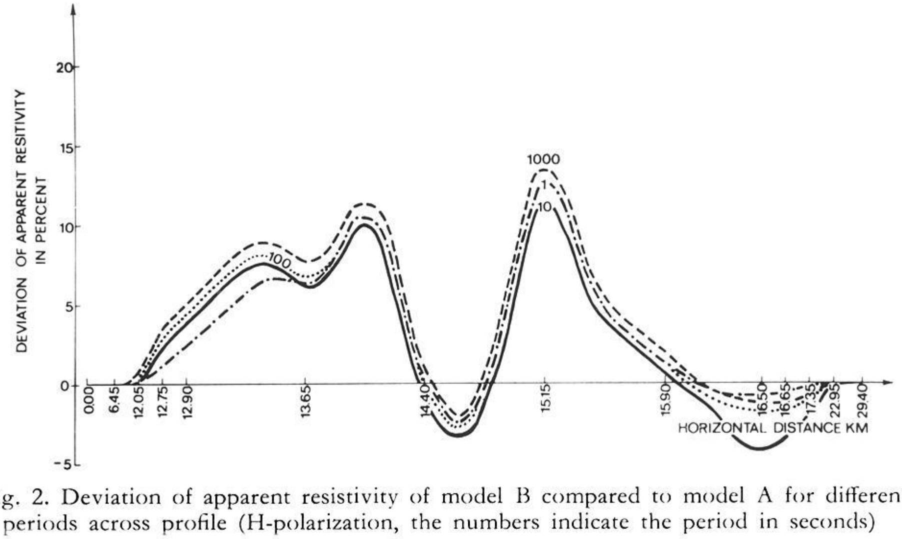

Fig. 2. Deviation of apparent resistivity of model B compared to model A for different periods across profile (H-polarization, the numbers indicate the period in seconds)

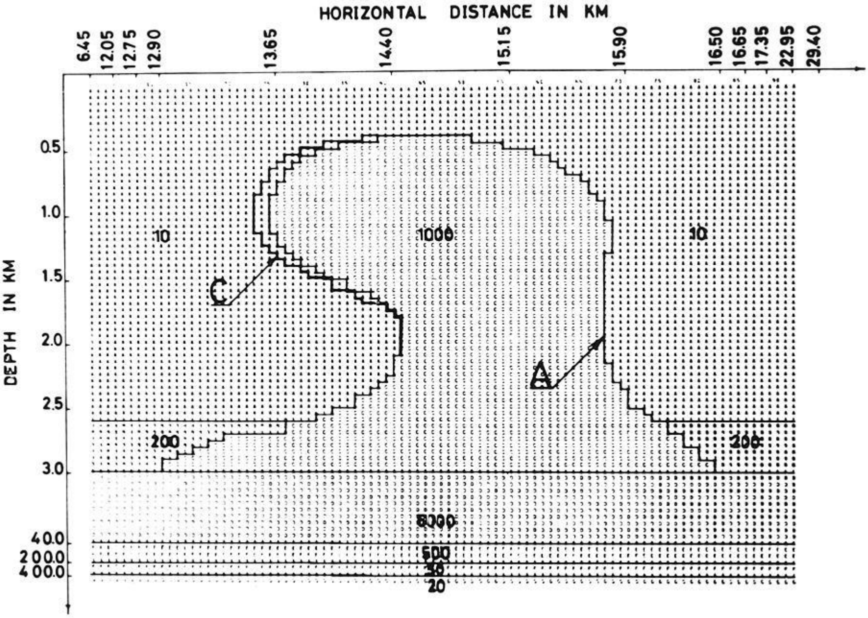

Fig. 3. Vertical cross section of two-dimensional models A and C (resistivity in Ohm · m)

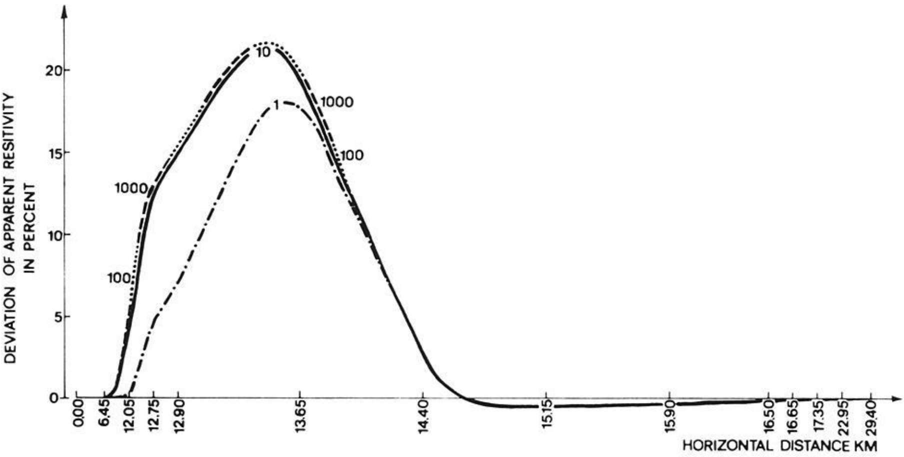

Fig. 4. Deviation of apparent resistivity of model C compared to model A for different periods across profile (H-polarization, the numbers indicate the period in seconds)

depth is about 1.6k m and therefore, the maximum grid size as proposed by Neves is 400 m. For two-dimensional structures this limit might not be small enough but the 50 m ($^1/_{32}$ skin depth) grid spacing of the fine-contouring is so far from this limit that it should guarantee a good accuracy.

Model B in Fig. 1 corresponds to model A but it is more roughly contoured though it is based on the same grid. Both the models were iterated for the periods 1, 10, 100 and 1000 sec for H- and E-polarization and the surface values of apparent resistivity and phase were calculated. Moreover, the relative deviation of apparent resistivity between the two models $((\varrho_\alpha(A)-\varrho_\alpha(B))/\varrho_\alpha(A))$ was computed for each surface point. The maximum deviation for H-polarization is about 13.5% (Fig. 2), whereas for E-polarization it is only 2%, too low to warrant a figure. This smaller rate was to be expected because of the continuity of the apparent resistivity when crossing a vertical boundary. If the resistivity of the perturbation is increased from 1000 to 10.000 Ohm · m, the maximum deviation in the case of H-polarization becomes about 17%. Consequently, it is clear that, in the present case, the H-polarization values react noticably to slight modification of the contours.

In order to obtain further information on the resolving power of H-polarization, calculations for the models shown in Fig. 3 were carried out. Model C is the result of a shifting of the overhanging part of model A by 100 m. The relative deviation of surface values for the above mentioned four periods is given in Fig. 4. The maximum deviation reaches 22% and is located almost exactly above the shifted boundaries. If the resistivity of the structure is assumed to be 10.000 Ohm · m the maximum deviation turns out to be nearly the same. We may conclude that rather small translations of vertical boundaries have considerable effect even if they are overlain by a low resistivity layer. Regarding d'Erceville and Kunetz's (1962) calculations on a fault, this effect is not surprising. Since in our case it is due to only 100 m of translation, it would not have been recognized with a grid spacing larger than 100 m.

The sensitivity of surface values to differences in contour was the reason for comparing apparent resistivities of the far overhanging structure E (Fig. 5) with those of the non-overhanging structure D. Calculations were executed for perturbation resistivities of 10.000, 1000 and 100 Ohm · m. For 10.000 Ohm · m the maximum deviation is less than 2% in H-polarization and 14% in E-polarization. For 1000 Ohm · m the results are presented in Fig. 6 and Fig. 7. If the resistivity is decreased to 100 Ohm · m, maximum deviation is about 14% for E-polarization and 60% for H-polarization. Though the perturbation of 100 Ohm · m has the smallest resistivity contrast with the surrounding "sediments", the surface apparent resistivity deviation of 60% shows the greatest effect. This result seems to be explainable when we note that the rather thick 5000 Ohm · m basement and the relatively thin and small 1000 or 10.000 Ohm · m perturbation have resistivities of the same order of magnitude. If we modify the boundaries, the effect on the surface values remains small. However, if we use 100 Ohm · m for the perturbation, this resistivity differs by at least one order of magnitude from the resistivities of both the basement and the surrounding "sediments". Consequently, a modified contour may cause a larger deviation of the surface values.

The deviation of phase differences between surface electric and magnetic fields were calculated for all models but they react only slightly to changes in contour.

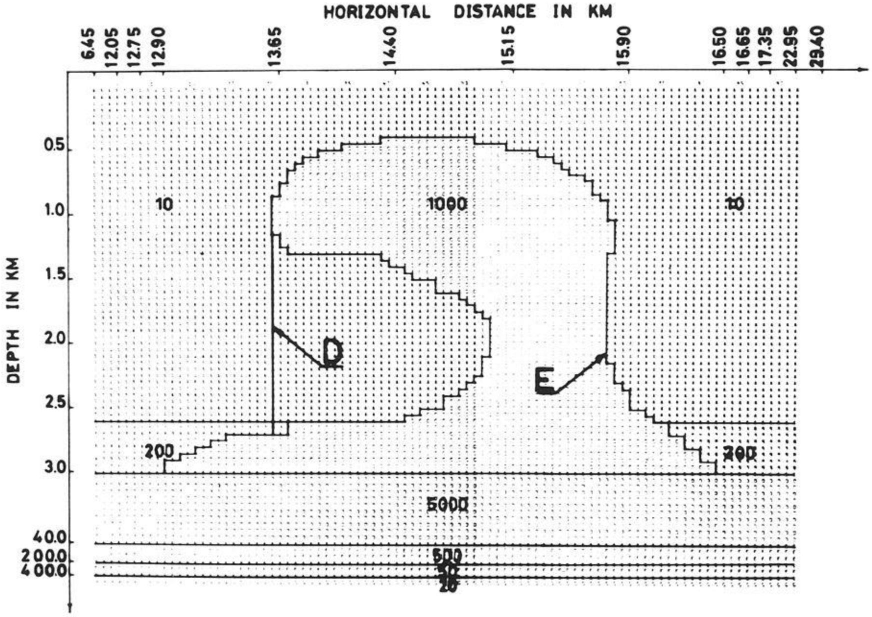

Fig. 5. Vertical cross section of two-dimensional models D and E (resistivity in Ohm · m)

For model A with a perturbation resistivity of 1000 Ohm · m, apparent resistivity and phase curves for 16 periods in the range 1 to 1000 sec in both the modes were calculated at each surface point of the profile. By means of the results the pseudo cross sections of apparent resistivity similar to those from Losecke (1972) were drawn in Fig. 8 and 9. In this case the asymmetric shape of the model is not or only slightly indicated by an asymmetric shape of the isolines for reasons given above, i.e. the dimensions of the basement and the comparatively small difference between the basements and the perturbations resistivities.

Conclusions

The influence of two-dimensional contouring on the surface values of apparent resistivity has been investigated. General statements on the effects of an arbitrary two-dimensional model cannot be given because they depend too much on the shapes and resistivities of the surrounding layers, but from the model results we may conclude:

1. Fine contouring, i.e. using a grid spacing much smaller than $^1/_4$ of a skin depth should be applied in cases where the "basement" layer either is not too thick compared to the height of the perturbation or the perturbation's resistivity is not of the same order of magnitude as the surrounding layers. Apart from that, fine contouring in every case improves the accuracy.

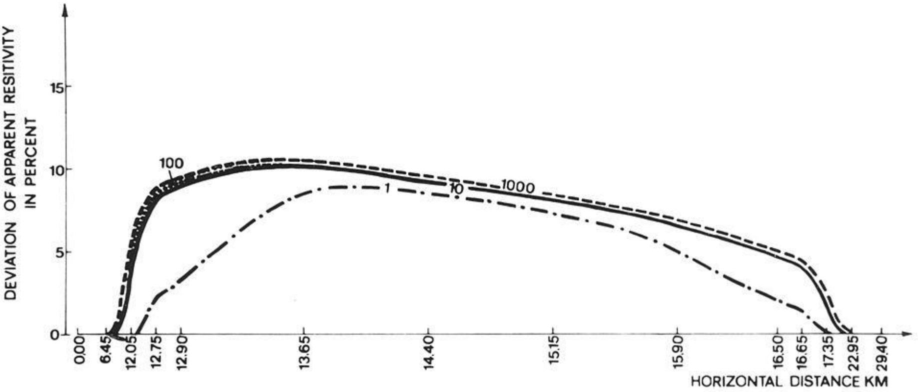

Fig. 6. Deviation of apparent resistivity of model E compared to model D for different periods across profile (H-polarization, the numbers indicate the period in seconds)

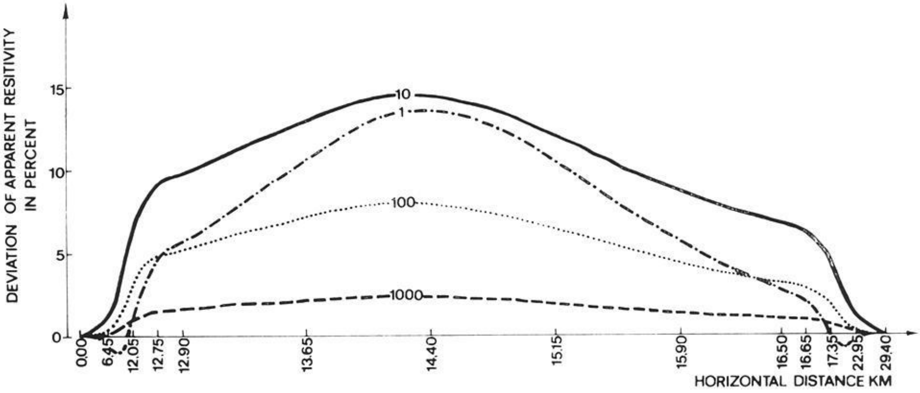

Fig. 7. Deviation of apparent resistivity of model E compared to model D for different periods across profile (E-polarization, the numbers indicate the period in seconds)

2. For cases given under 1. the calculated surface values of an overhanging structure of the modelled type are clearly distinguishable from a non-overhanging one (60% deviation). The question whether or not quite another configuration could produce the same surface values is not subject of the present papre.

3. From the figures we see that the surface effects caused by contour differences are not sharply localized to the area of the modified contour but spread out more or less along the profile. The best localized effects can be expected if a vertical part of a boundary is shifted (Fig. 3).

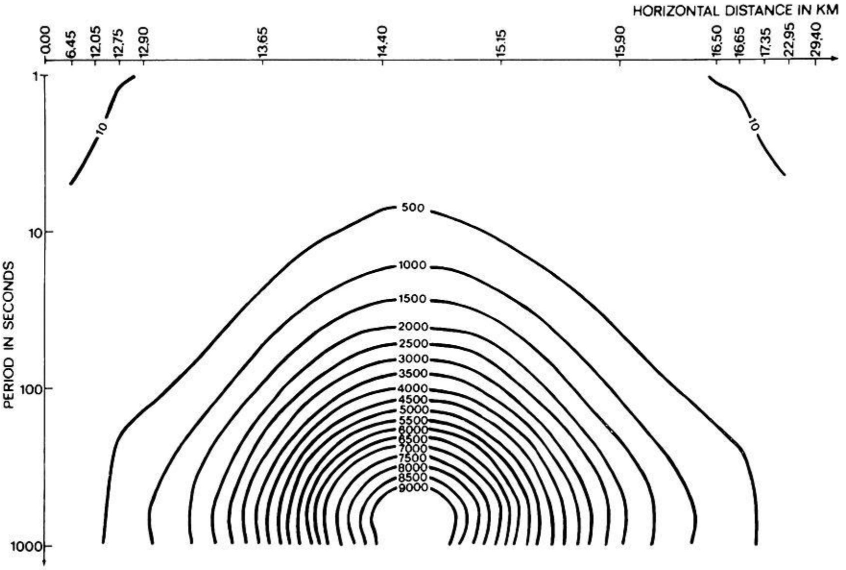

Fig. 8. Magnetotelluric pseudo cross section of model A (H-polarization), isolines of apparent resistivity (numbers in Ohm · m)

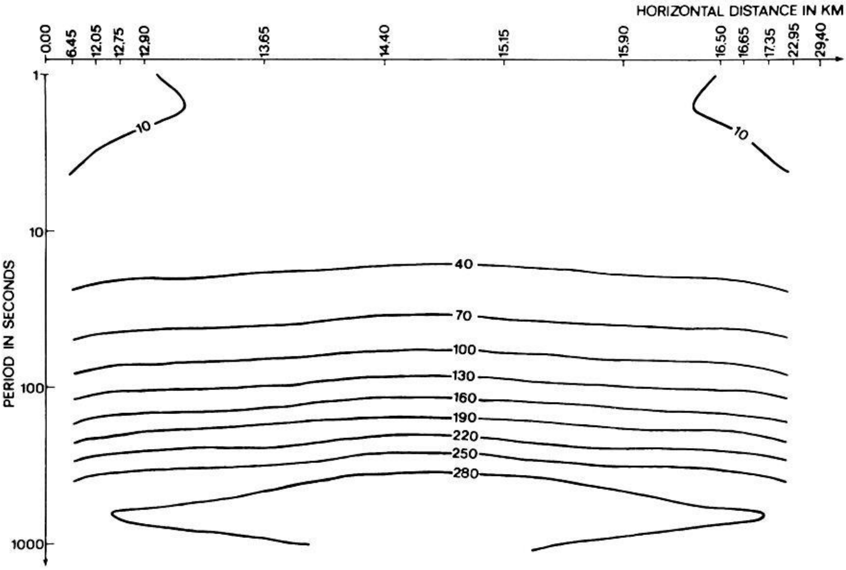

Fig. 9. Magnetotelluric pseudo cross section of model A (E-polarization), isolines of apparent resistivity (numbers in Ohm · m)

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