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"Magnetotelluric Studies in the Geothermal Area of Travale"

Vorbemerkung: Der folgende Bericht wurde für ein Treffen verschiedener Magnetotellurik-Gruppen in Brüssel im Juli 1982 geschrieben. Die Kommission der Europäischen Gemeinschaften finanziert dieses Projekt, mit dem untersucht werden soll, ob die Magnetotellurik tatsächlich eine Methode ist, mit der geothermische Energie gefunden werden kann. An dem Projekt beteiligen sich die Universitäten von Edinburgh, Padua, Braunschweig und München, sowie einige Gesellschaften wie die CGG in Paris.Wir haben diesen in englisch verfaßten Bericht nicht übersetzt, haben ihn aber mit einigen kleinen Änderungen gegenüber dem Originalbericht versehen.

Summary: Magnetotelluric measurements have been continued in the geothermal area of Travale in autumn 1981. Strong lateral variations of the apparent resistivities have been observed which possibly correlate with the known geothermal areas.

1. Introduction

In continuation of our first field campaign in the "Travale Geophysical Test Site" in 1980 magnetotelluric measurements have been carried out in the Travale area at additional 12 sites in autumn 1981. Most of the stations are to be found on a profile, running out of the centre of the known geothermal anomaly towards NW, parallel to the strike of the Travale Graben (Fig. 1). The instrumentation included 3-component fluxgate magnetometers, induction coil magnetometers and telluric devices.
The time-varying electric and magnetic fields have been recorded on digital magnetic cassettes in the period range of 8-2500 s. The sampling rate for the data was 2 or 4 s, resp. The recording time at one station was from one to three weeks.
Additional measurements have been made with a VLF-R instrument to investigate the shallowest structure beneath the stations.

2. Data processing

All field data (electric and magnetic field) which have been recorded digitally at the different field sites had to be transferred to tapes which are computer-compatible. It turned out that all the digital cassetta-tapes contained considerable amount of technical noise. The cause of this partially tremendous noise seems to be of "cultural nature". Finally, essential magnetically active time-intervals could be selected, which contained no visible technical disturbances for further analysis. One of these selected perfect time-intervals is presented in fig. 2 . Nevertheless, the following stages of data-processing never yielded results without problems. The course of data processing was the frequency-analysis, calculation of transfer functions and apparent resistivities. Since the amount of scatter of the apparent resistivities was too large, several methods to "improve" the original data sets were tried. One of these methods*) sieves out all data of a given data set which destroys a high coherency (V. Rath, in preparation). This method uses the normalized, multiple coherency as indicator of the quality of the data. The puzzling result of this method was, that the coherencies between electric and magnetic field data could be increased most considerably while the scatter of single apparent resistivity could scarcely be diminished, sometimes even increased. Our conclusion of this "experiment" is, that there exists highly coherent, cultural noise in the Travale Area, undistinguishable from the natural signal to the human eye. Possibly, the only method to improve the results is the application of the remote references method. All the results presented here are "stable" curves calculated from all available and reliable field data.

3. Rotation of coordinate systems

Only in the case of a resistivity function which depends on depth only (1D-case) the transformation of the measured apparent re-

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*) (e.g. Jödicke 1978)

sistivity into the true resistivity is possible in all coordinate systems. In this case the coordinate systems must not be rotated, the interpretation will be correct. However, in the 2D-case (like in a two-dimensional graben), the coordinate systems (mostly EW/NS) must be rotated in order to separate to the E- and B-mode. The corresponding ρa-curve for the E-mode can in many cases be interpreted by 1D-inversion algorithms. The actual measurements in Travale yielded three cases. For short periods (<1 s) the data behave 1D, for periods up to 50 s the data behave 2D (the Travale Graben as the dominant 2D-structure), for periods > 50 s the data behave 3D. In this case the inductive effective structure turns out to be a more or less EW-striking structure, probably the northern boundary of the Tuscan microplate (see Haak & Schwarz, 1981). Thus in the longer period range the Travalé Graben is not anymore a 2D-inductive structure, but a local d.c.-distortion anomaly (Haak, 1978). In this case the maximum-minimum coordinate systems suit much better the physical conditions of such complicated structures than non-rotated or only graben-parallel coordinate systems. Since two apparent resistivity curves result at one station, the maximum curve inside the Travale Graben must be taken as the "E-mode" curve. In the following figures the resulting apparent resistivities, phases and 1D-models are presented.

4. Apparent and true resistivity functions

The apparent resistivities which correspond to the E- and B-polarization mode are plotted in fig. 3 (see upper panel). The apparent resistivities have been calculated in the maximum-minimum coordinate system as discussed earlier. The rotation angles of the E- and B-field ($\alpha_{E,B}$) and the phase differences (φ) are represented in the middle panels. The true resistivity-depth-function has been deduced from the E-polarization mode by the PSI-algorithm of Schmucker (1974). The theory clearly indicates the E-polarization as a good approximation of the resistivities in a layered earth (1D-case). As has already been discussed this assumption is only true for the uppermost km in the Travale Graben.

For a better comparison of the apparent resistivities calculated by other groups with different methods in the Travale field, the same set of data has been analysed in a fixed graben-parallel coordinate system (fig. 4). The calculations under a rotation angle of N 40° W are showing, that the shape of the apparent resistivity-curves does not alter very much, whereas the niveau of the curves is more affected.

A general view on all calculated apparent resistivity-curves gives a picture not so clear as would have been expected when considering a 2D-structure. The ρ_a-curve inside the known geothermal field is rather flat, starting at 20 Ωm and rising up to 40 Ωm. Outside the Travale field the ρ_a-curves are of a different type, ascending from about 10 Ωm to about 100 Ωm. These curves are representing a type of resistivity curves measured at other places in Tuscany, too, e.g. MUR (Haak & Schwarz, 1981). Further to the north (stations Mat & GAT) the ρ_a-curves are very similar to those which have been calculated for the stations inside the geothermal field.

The apparent resistivities in the B-polarization mode are by more than an order of magnitude lower than the one of the E-mode. It is impossible to interpret them by any 1D-algorithm. For that reason 2D-models have been calculated which were described below.

The variation of the apparent resistivities for the E-polarization mode on a profile from NW to SE for the periods 100 and 1000 sec has been plotted in fig.5. The resistivity function for the period 100 s shows clearly a low inside the known geothermal field which is seperated by a high in the apparent resistivity from a second low at the northern most stations. The apparent resistivity curve for the period 1000 s shows a remarkable low in the north, rising up to high values in the middle of the profile and is becoming more or less flat inside the geothermal field.

5. 2D-model calculations

5.1 All results clearly point to the at least 2-dimensionality of the true resistivity structure. This means that a perfect, quantitative transformation of the apparent resistivity into the true resistivity is possible if the 2-dimensional structure (the Travale Graben) is covered at least by one perpendicular profile by measuring station from one side to the other. Such measurements have not been allowed in the Travale area, but the measurements had to be confined to the geothermal area proper. Therefore any interpretation of the results will be ambiguous with respect of the lateral effect of the Travale Graben on our apparent resistivities within the graben.

5.2 Nevertheless, it seemed to be very important to estimate the lateral effect of different possible graben configurations. We have assumed two quite different types of grabens, calculated by a 2D-method all the necessary field quantities for a large number of frequencies. From some selected sites of these theoretical, graben-traversing profiles we represented the apparent resistivity curves as function of period. Our ideas and conclusion will be discussed separately for each of both models.

5.3 Shallow graben model

The graben itself is a rather shallow structure, filled with 10 Ωm resistive sediments. It can be shown that such a shallow structure is in clear contrast to all magnetotelluric results. The question was whether a deeply buried, low resistive "geothermal reservoir" could change the apparent resistivities in such a way as have been observed. The result is indicated in fig. 6, the sites are marked by the two arrows. If one compares the resulting ρa-curves with actually observed ρa-curves (e.g. FOR, MAT) one will confirm a striking similarity.

However, at the same time, the high-resistive transition from the graben sediments to the "reservoir" provides a resistive basement as worked out by d.c. methods (dipole-dipole, Schlumberger, (ENEL, 1969; Patella et al., 1981)). The lateral effect of the small "reservoir" is small, but is not confined to the short periods only but also to the long periods up to 1000 s.

The lateral effect is not very clear in the phases. Our conclusion is, that such deeply buried "reservoirs" could be detected if the apparent resistivities could be determined accurately enough. The location of the borders and the resistivities outside of the graben are invented since no measurements have been performed to know these parameters.

5.4 Deep graben structure

Since results as that from MAT and GAT indicated no high resistive basement, and according to geological and geophysical results (Wigger et al., 1981) the Travale Graben constitutes a recent fracture zone of the crust, the deep graben structure was invented (see fig. 7). Again, the apparent resistivities of a whole profile from one side to the other were calculated for a large number of periods. One ϱ_a- and phase curve of a site in the middle of the graben is represented in the fig. 8. The ϱ_a-curve resembles again some of our actual measured curves. In a final stage, this 2D-apparent resistivity curve was interpreted by a 1D-inversion algorithm, to see, which structures correspond to a ϱ-curve which must be affected considerably by lateral effects: Observe that below the indicated "grabenstation" no resistive, crustal basement exists! The resulting 1D-models all contain such a resistive, crustal basement which is clearly a lateral effect.

5.5 Reason to decide between shallow and deep graben model

The strongest reason against a shallow graben in favour of a deep graben seems to be the actually observed huge difference between E- and B-polarization. The apparent resistivity of E- and B-polarization for 3 periods along the whole profile is represented in fig. 7. At present we do not see any other possibility to explain the large differences between E- and B-polarization (e.g. MAT, QUA) than by this deep model. However, this conclusion is inferred only from the sites inside the graben proper, we do not have knowledge about the fields at the transition and outside the graben.

6. The question whether shallow or deep graben structure answers only long distance variations of the apparent resistivities.

   Short distance variations indicate lateral resistivity variations in the graben centre. To see and delineate some low and high resistivity areas all results from the different MT-groups have to be combined. This work is still going on.

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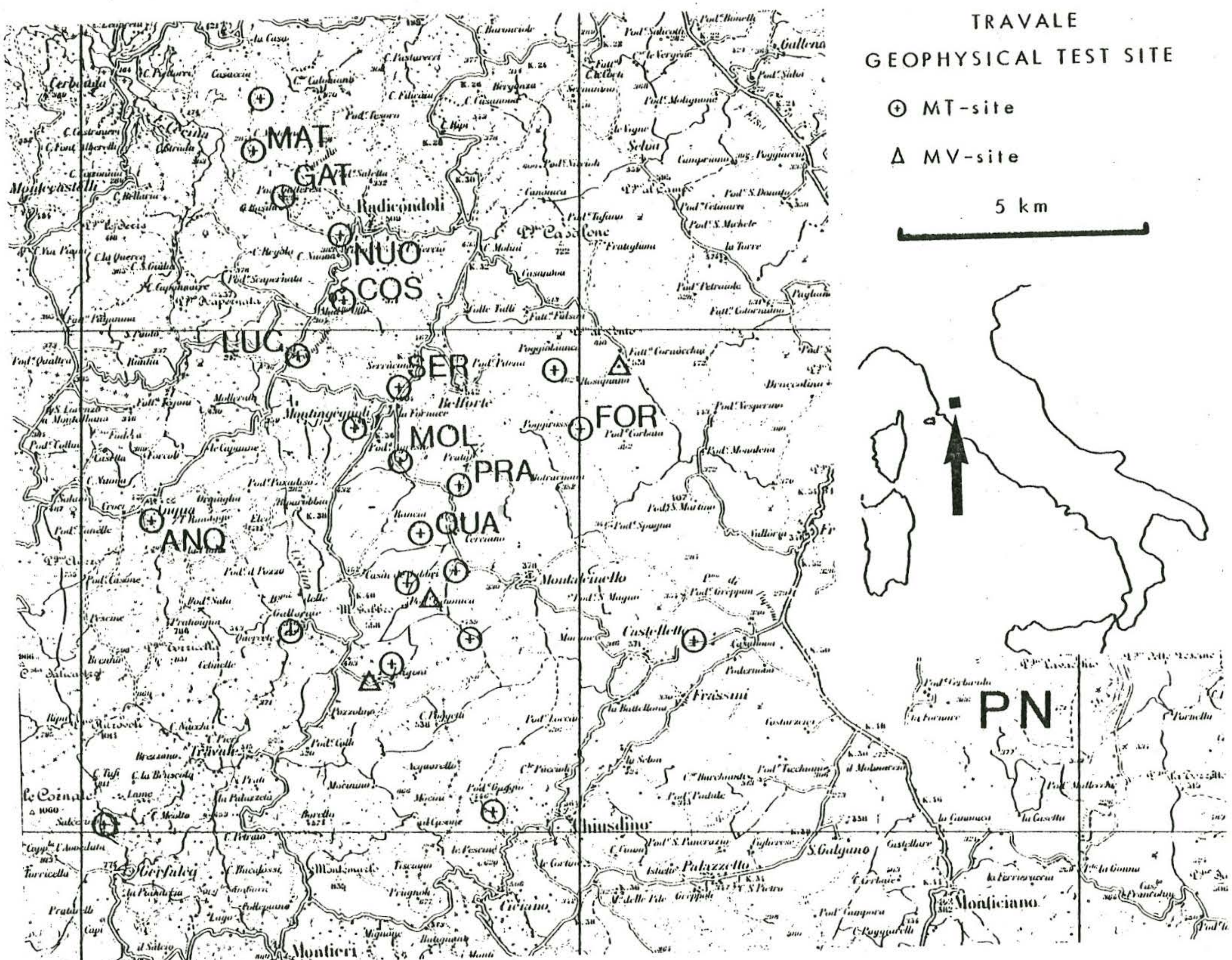

Fig. 1: Position map of measuring sites in the Travale area. The recordings of those sites indicated with a name have been analysed up to now.

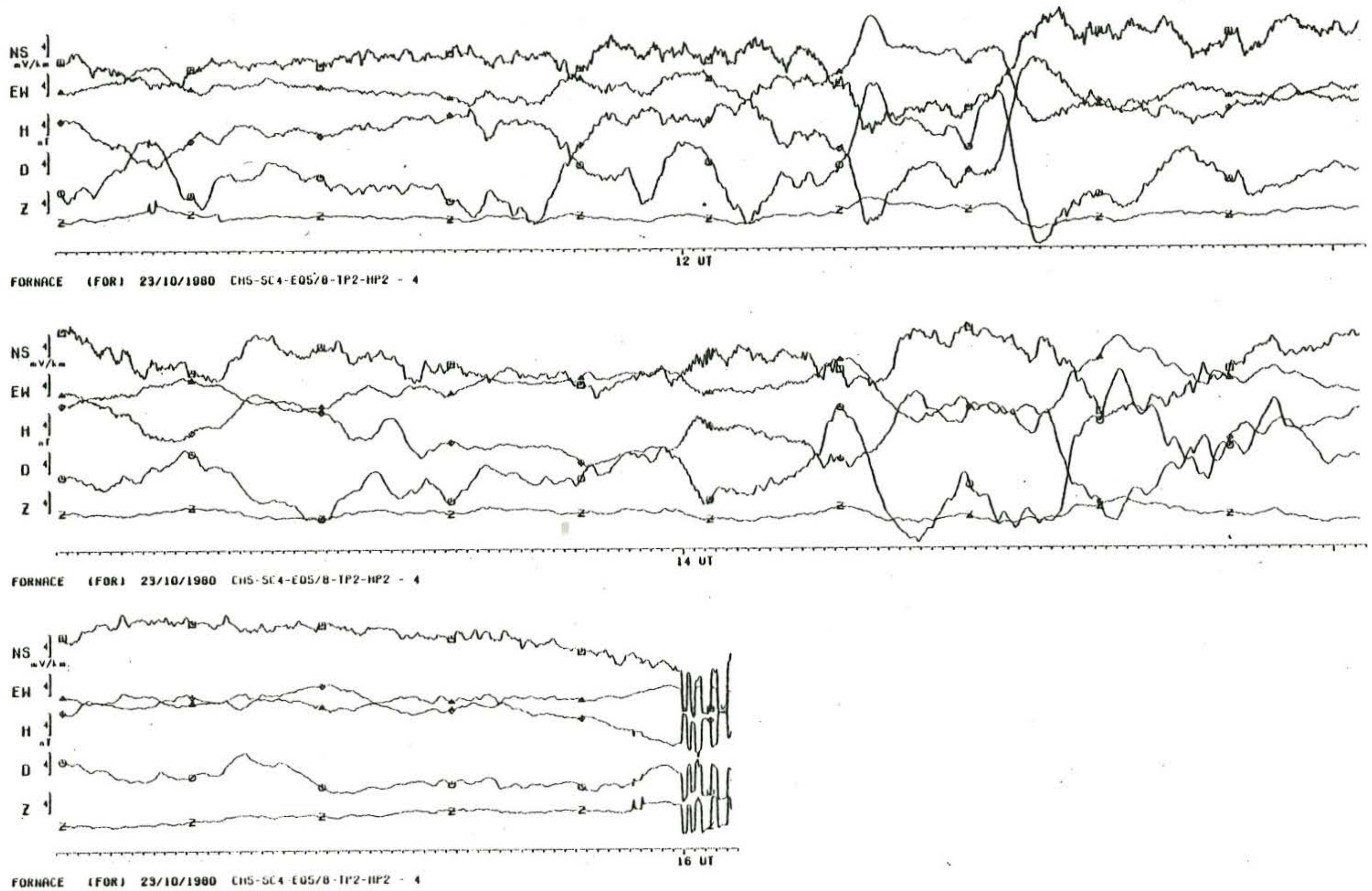

Fig. 2: Recording sample of the time varying electric and magnetic field at the station FOR. The upper two traces represent the two horizontal components of the electric field, the lower three traces the components of the magnetic field.

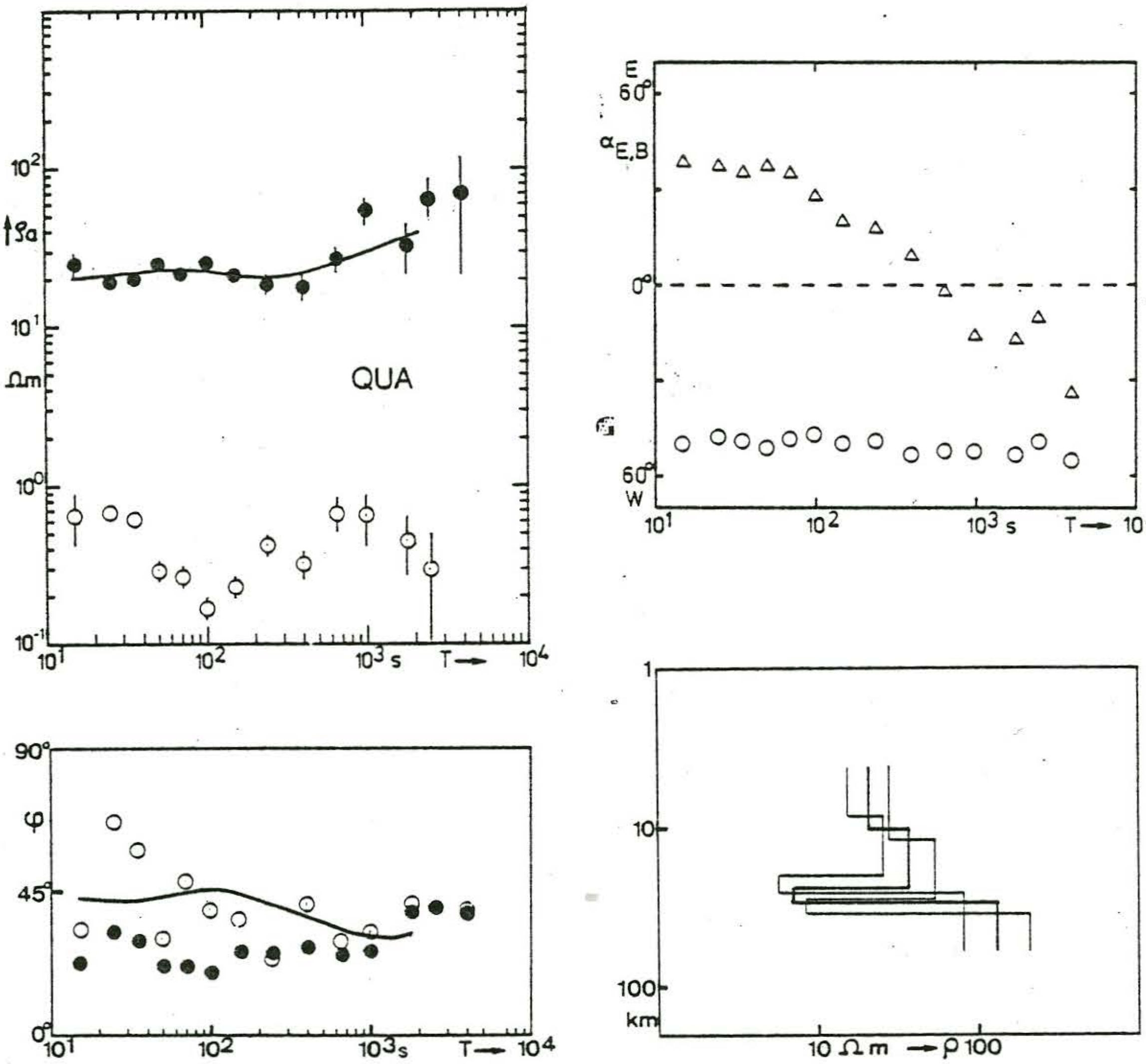

Fig. 3: Uppermost panel on the left the apparent resistivity as function of period, calculated in the maximum-minimum-coordinate system. The black dots represent the E-mode, open circles represent B-mode. Below the phasedifferences between E- and B-field. Uppermost panel on the right the azimuths of both fields (○: rotation angle of E-field, Δ: rotation angle of B-field), below the resistivity-models obtained by an inversion algorithm from the apparent resistivities.

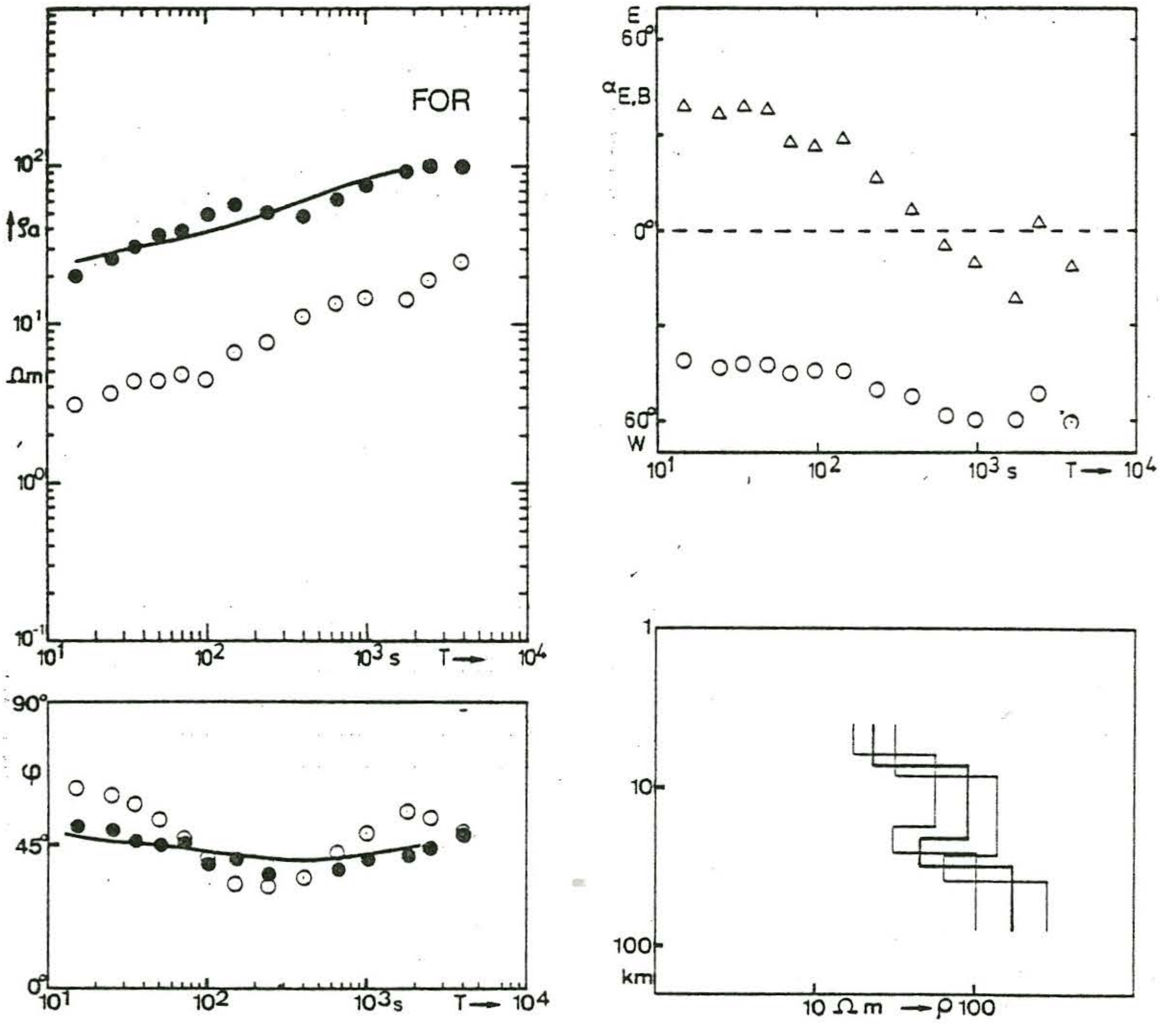

Fig. 3a: Captions see fig. 3.

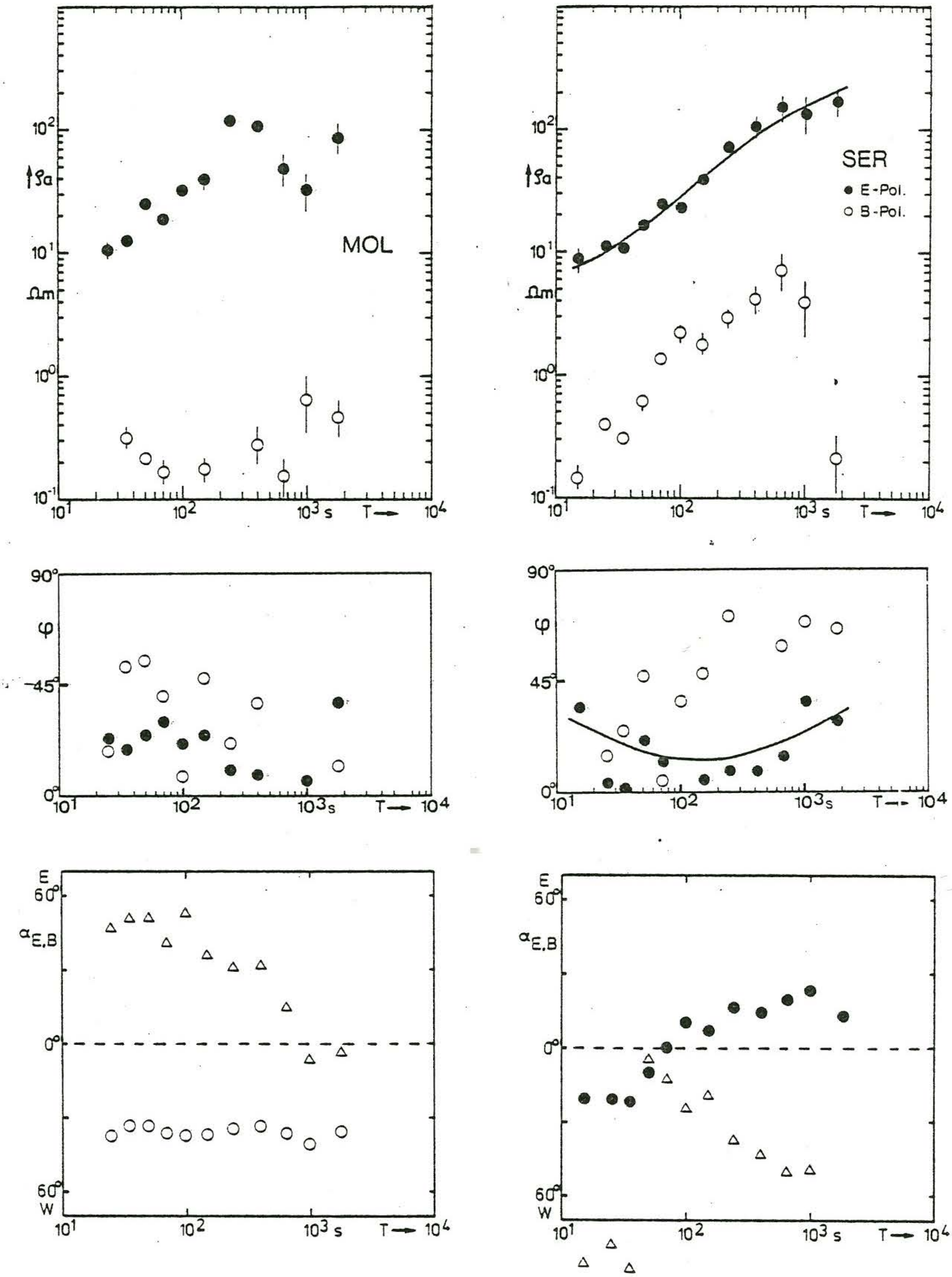

Fig. 3b: Apparent resistivities, phasedifferences and azimuths at the stations MOL and SER. The site MOL has been measured in 1979 (Haak & Schwarz, 1981). The consistency between ϱ_a and phase at the site SER has been prooved by 1D-modelling: the drawn curves result from a two-layered-model (not shown here).

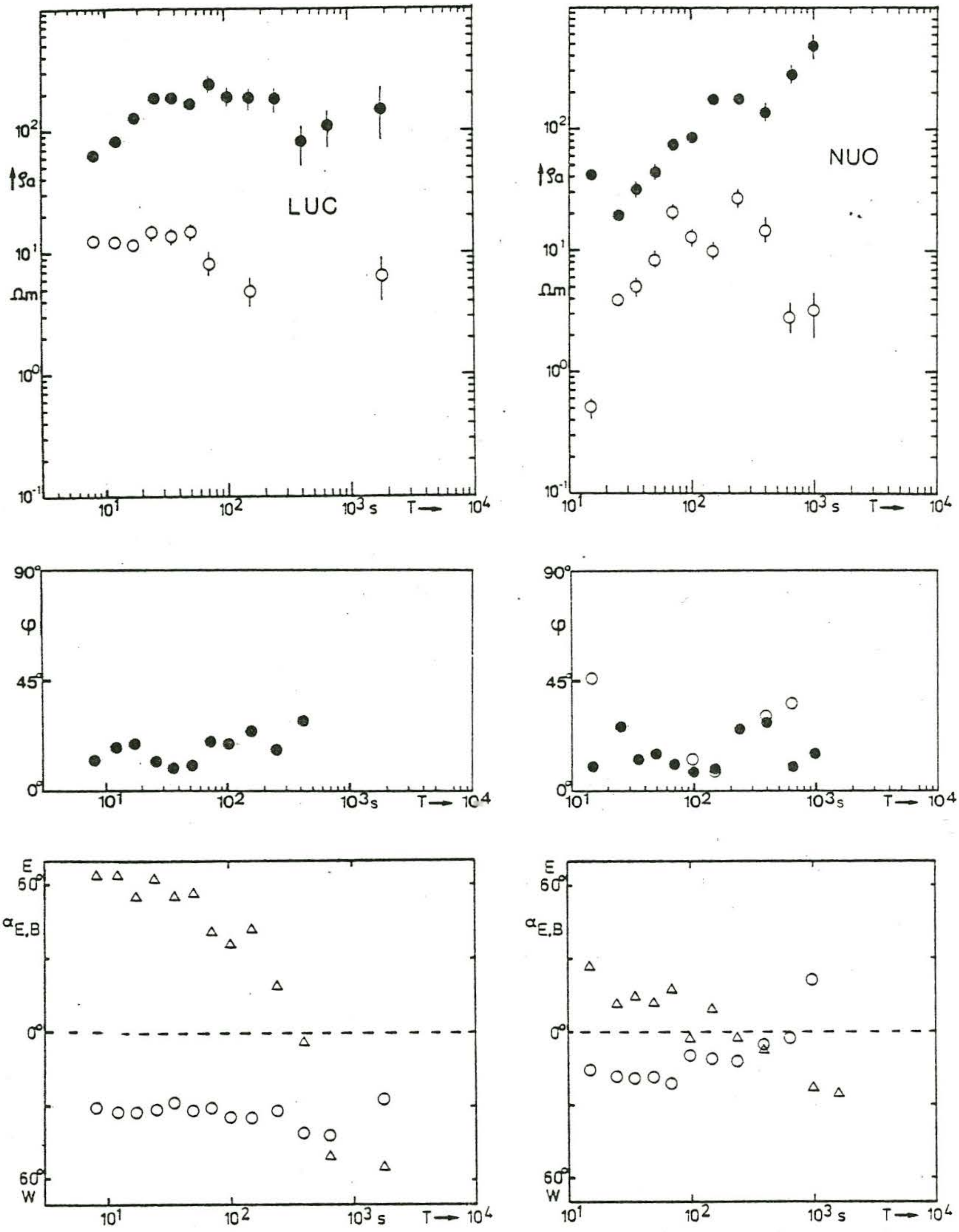

Fig. 3c: Captions see fig 3b.

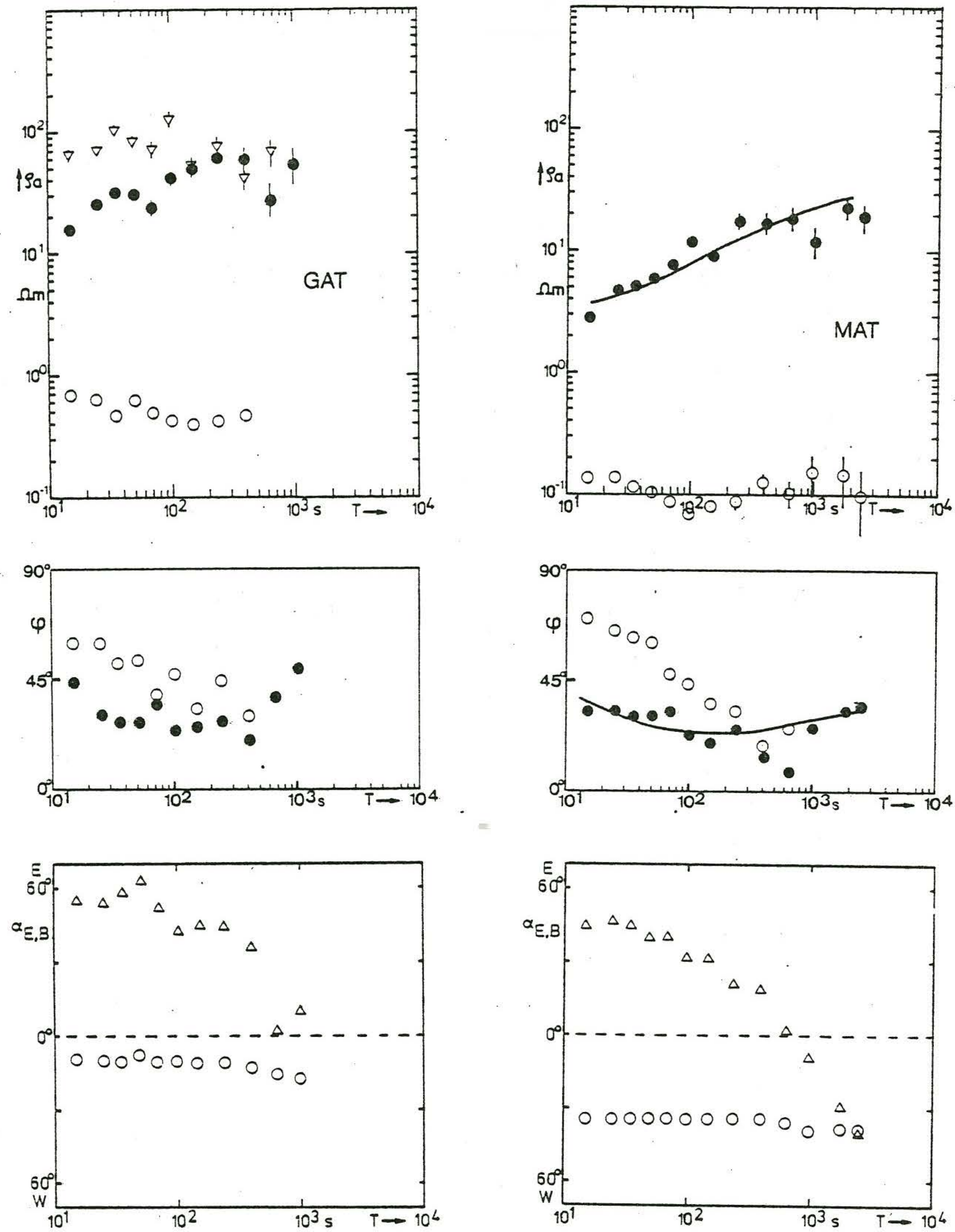

Fig. 3d: Captions see fig. 3b. The open triangles in the ρ_a-curve at the station GAT are the result of adding one time interval to the data set in the analysing procedure.

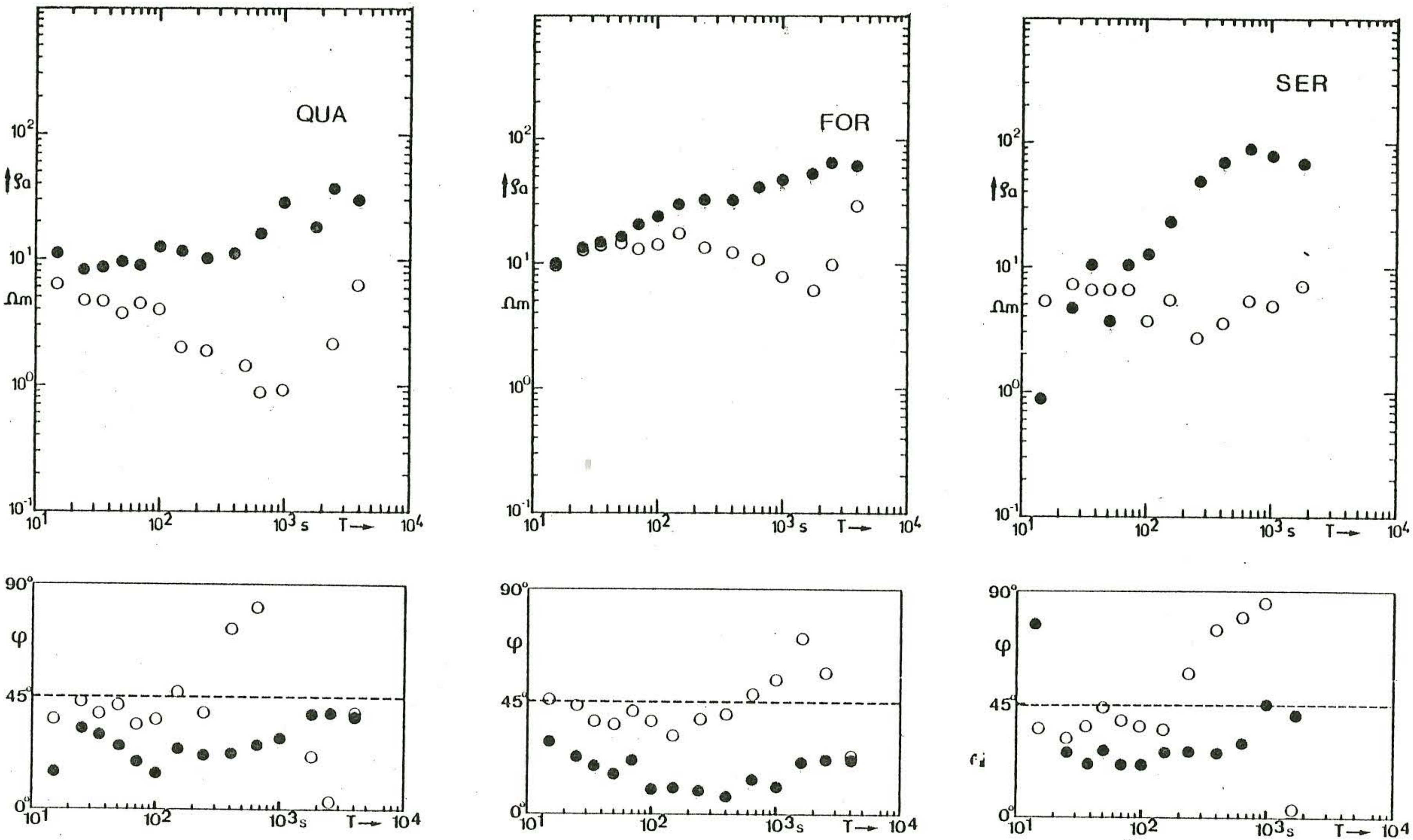

Fig. 4: Apparent resistivities and phasedifferences calculated in a graben-parallel coordinate system.

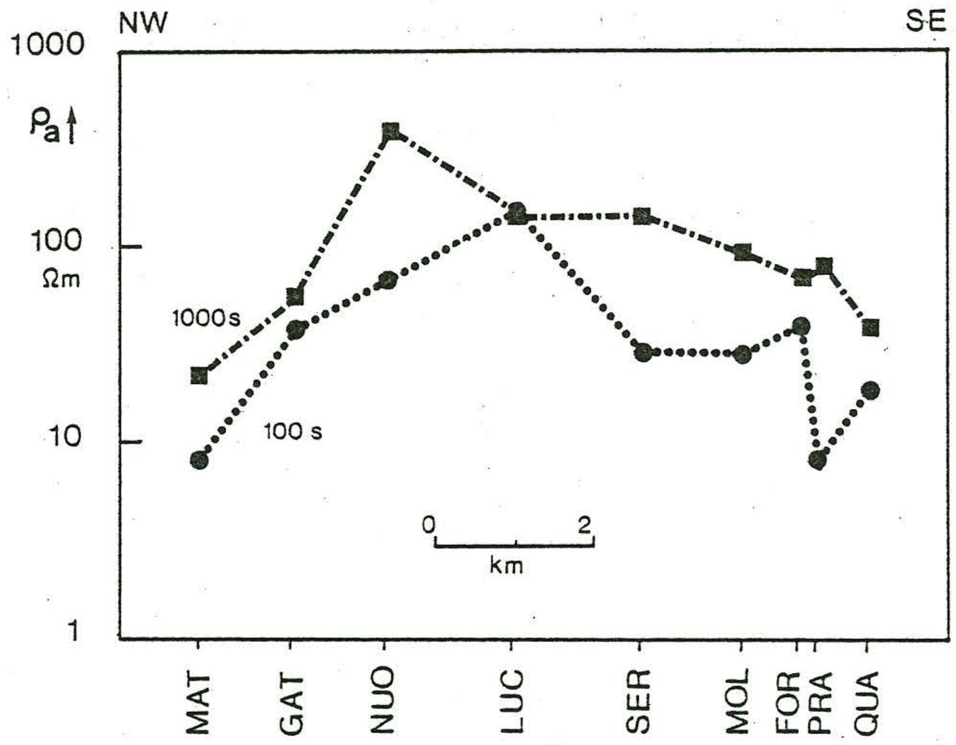

Fig. 5: Variation of the apparent resistivities on a profile parallel to the Travale Graben, running out of the known geothermal field towards NW.

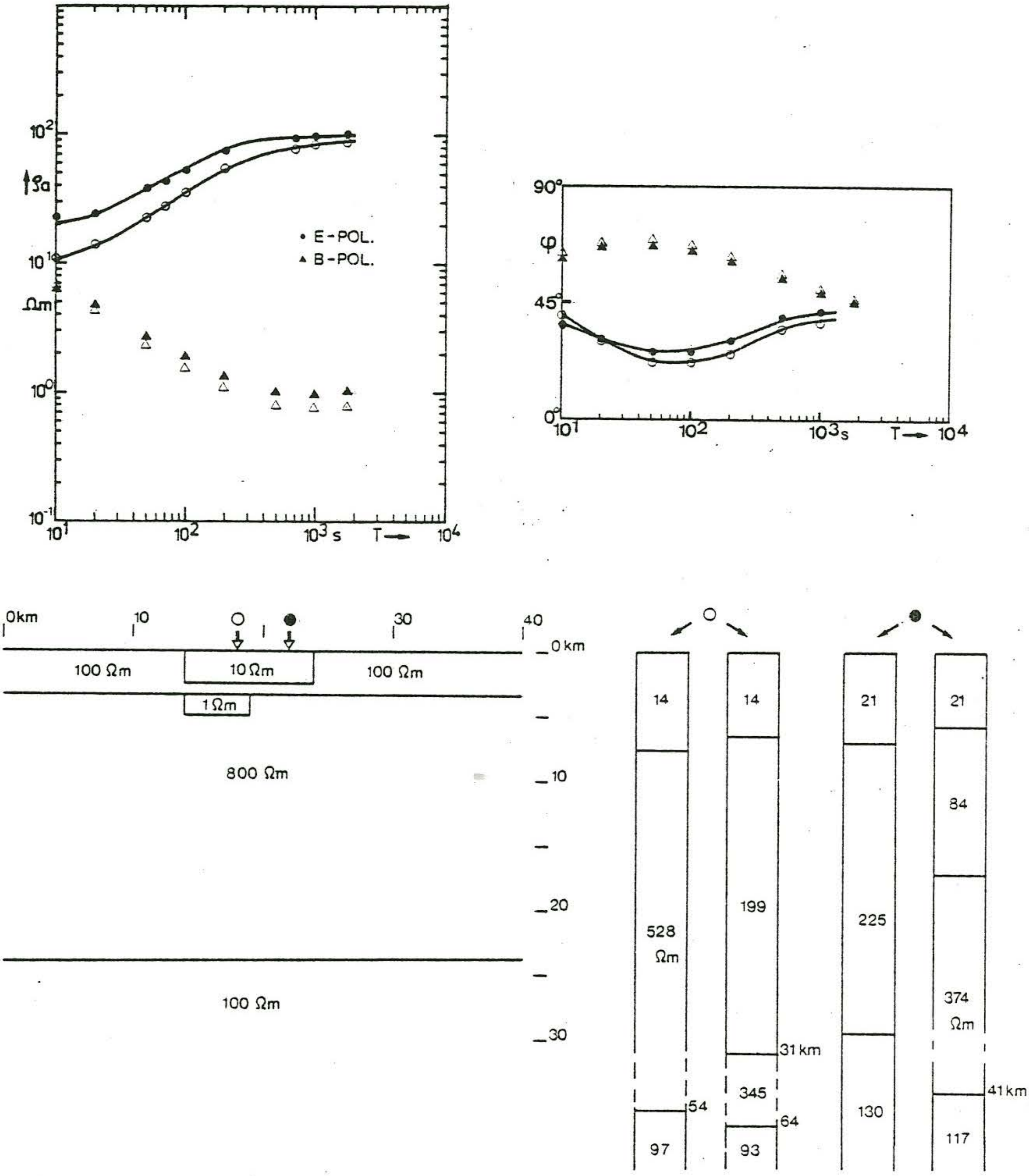

Fig. 6 : Shallow graben model with corresponding apparent resistivity curves of two sites in the middle of the graben. On the right: the apparent resistivity curves were interpreted by a 1D-inversion algorithm.

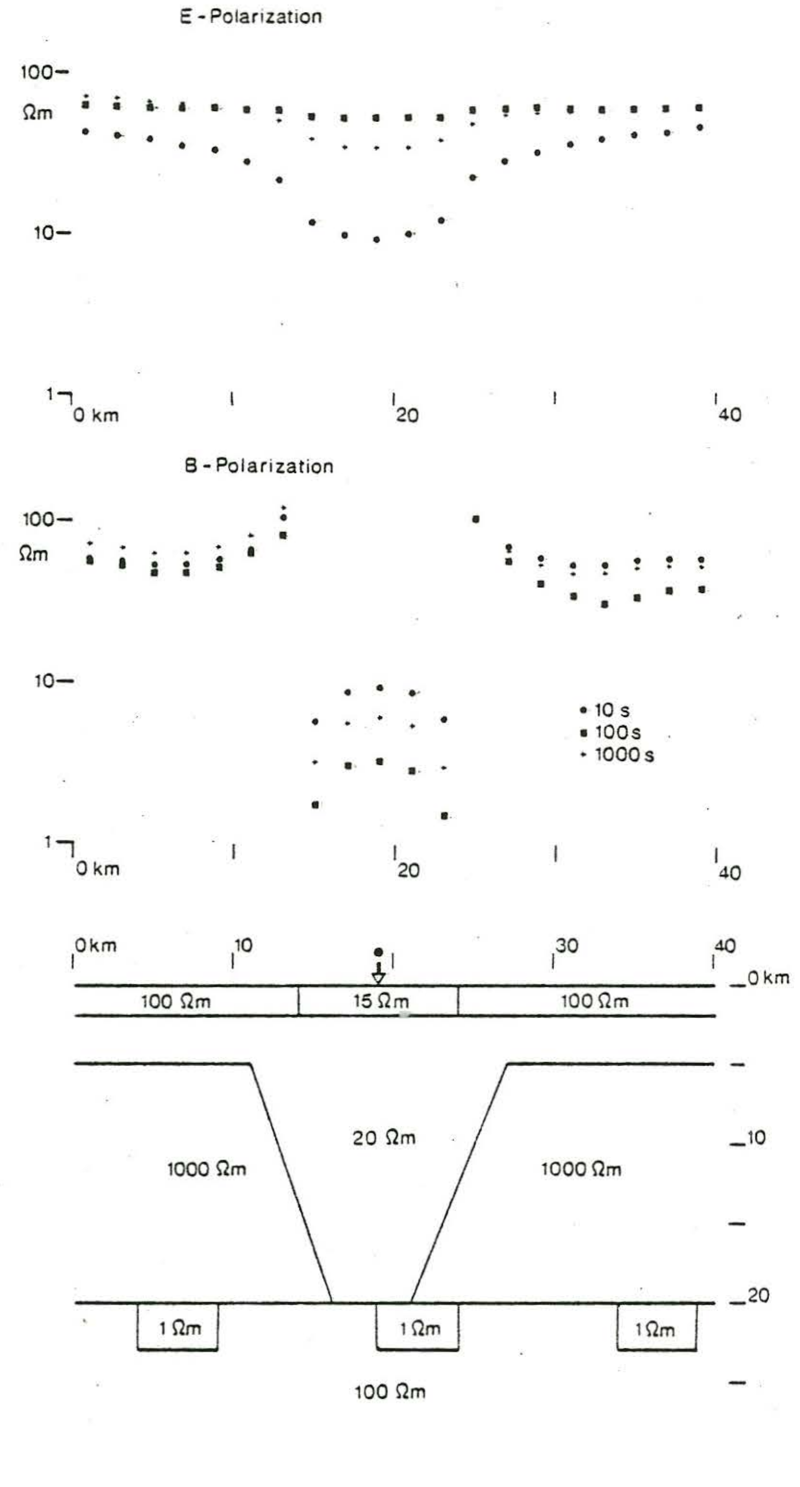

Fig. 7 : Apparent resistivities for the E- and B-mode calculated on a profile across the deep graben structure for the periods 10, 100 and 1000 s.

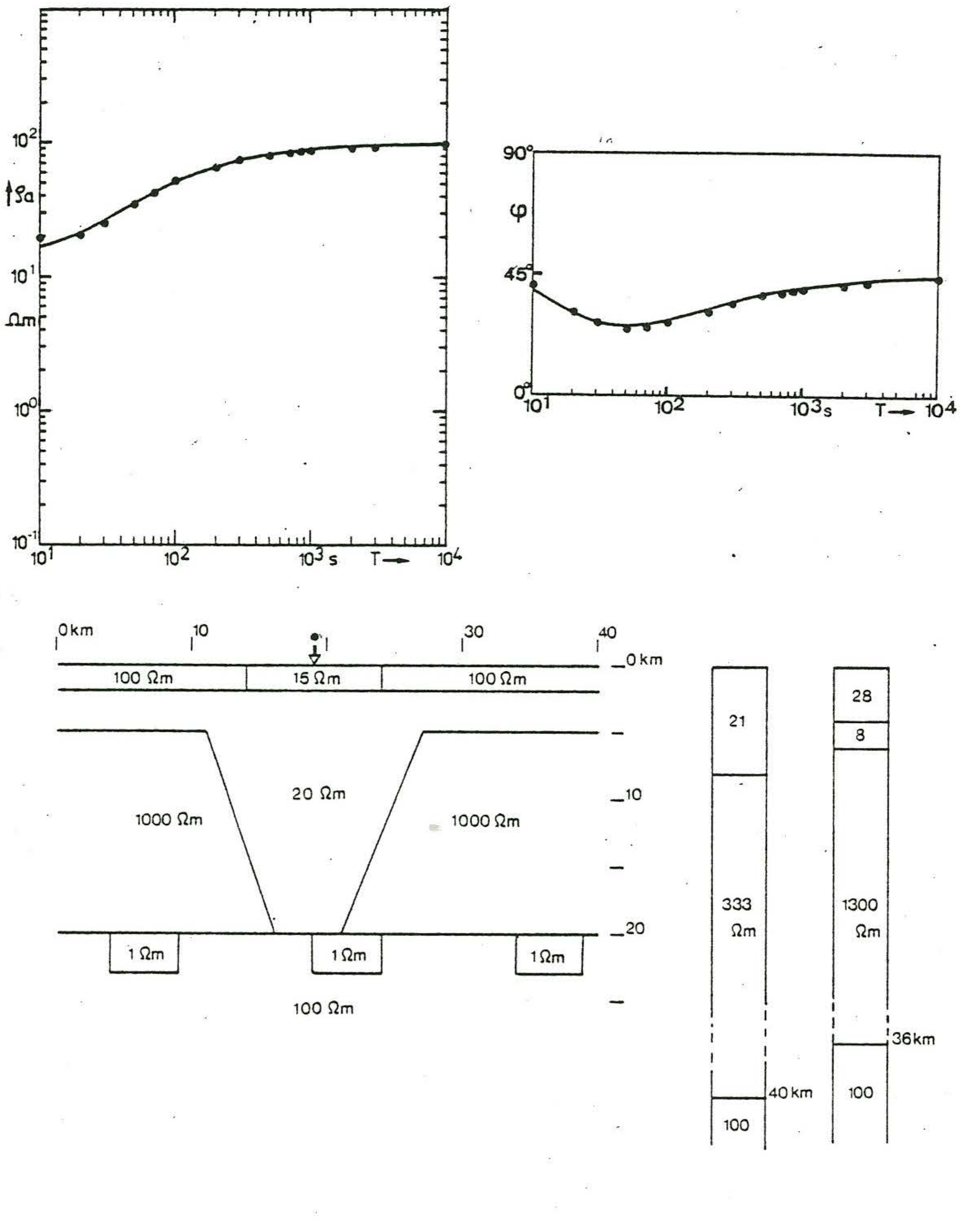

Fig. 8 : Deep graben model with corresponding apparent resistivity curve and phasedifferences of one site in the middle of the graben (marked by an arrow with full dot). On the right the 1D-inversion-models, deduced from the 2D-apparent resistivity curve.