

RMT Signature of the Rhineland Brown Coal

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I. Introduction

Cologne-based RWE Rheinbraun AG is responsible for mining of lignite, or brown coal, in Rhineland with an annual production of around 100 million metric tons. Rhineland brown coal accounts for around 16% of German's electricity supply. Growing competition from other sources of energy, such as imported hard coal, made it essential to minimize costs, especially in field-work functions like expensive drilling and direct-sampling. Here the geophysics enters the picture. Since electromagnetic (EM) methods have become more popular in surface-mining applications, EM survey in advance of the drilling could help design the future drilling (or direct-sampling) pattern. A total number of 86 radiomagnetotelluric (RMT) and 33 transient electromagnetic (TEM) soundings (five separate profiles) were carried out over the shallow coal seams at the "Garzweiler I" mining district, west of Cologne (Fig. 1), to image the vertical electrical resistivity structure of those seams. To determine what can be interpreted reliably from EM measurements, 16 rock samples for different lithologies were collected from the surface outcrops in the area and their direct current (DC) and alternating current (AC) resistivities were measured in the laboratory. We present here the one- and two-dimensional RMT inversion results for three profiles conducted over a coal-covered area (Fig. 2).



Figure 1: Field-panorama of the "Garzweiler I" mining district, west of Cologne.

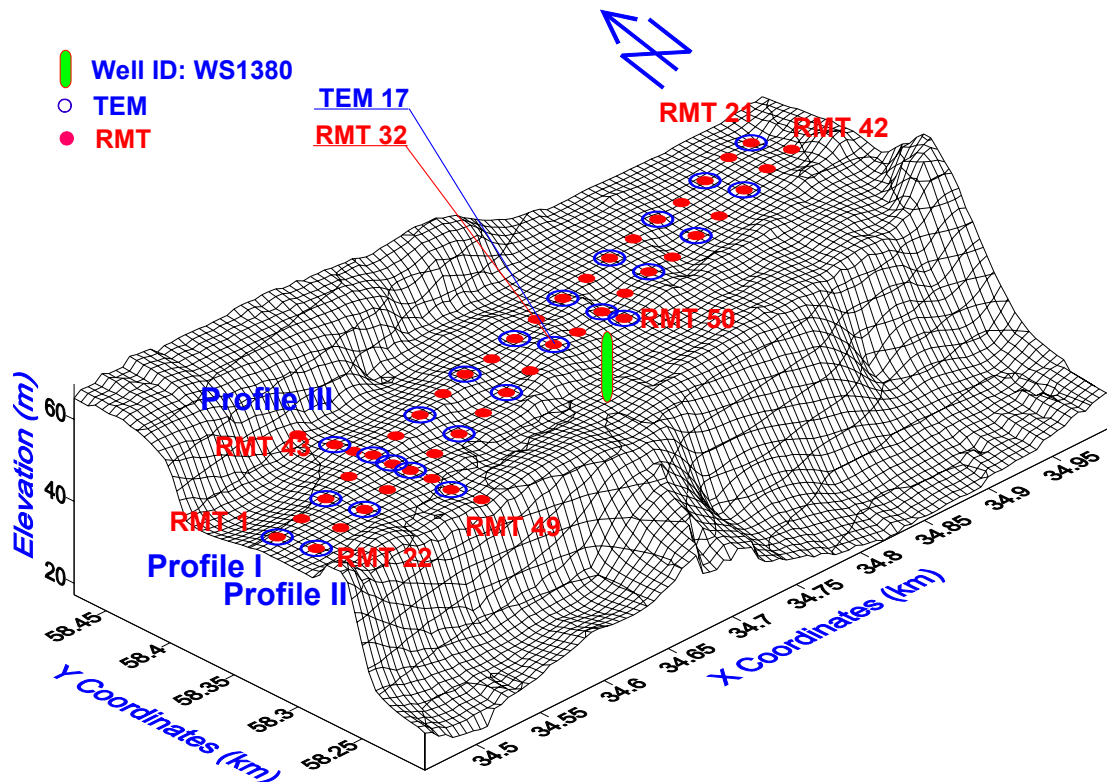


Figure 2: The topography and locations of RMT soundings over the coal-covered area.

II. Radiomagnetotellurics (RMT)

Methods utilize EM radiation generated in the low frequency band by remote powerful military (10-30 kHz) and civilian broad-casting (30-300 kHz) radiostations which transmit continuously either an unmodulated carrier wave or wave with superimposed "Morse Code." When the receiver locations are located at least seven "skin-depths" away from these transmitters, EM waves are essentially planar and horizontal. If the waves are polarized in the xy-plane and travel downward in the z-direction. In this case, simultaneous measurements of two orthogonal components of the time-varying electric (E_x) and magnetic (H_y) fields, for selected frequencies, using two ground potential-electrodes and a vertical coil respectively can be easily done. Analogous to magnetotellurics (MT), data analysis commences with calculation of the apparent resistivity $\rho_a(\omega)$ and the impedance-phase $\phi(\omega)$ using the well-known "Cagniard formulae" of MT.

For our field measurements, the RMT instrument was developed from a prototype built at the Hydrogeological Institute of the University of Neuchâtel, Switzerland. The data can only be acquired in scalar mode. Since the strike direction was often unknown, the measurements were made at 6 different orthogonal azimuths, namely at 0° , 30° , 60° , 80° , 120° and 150° N (Fig. 3). Due to the large number of distant transmitters in the Garzweiler region, it was easily possible to cover the entire RMT spectrum using only the best-observed frequencies (19.6, 21.7, 23.4, 24, 61.9, 65.8, 75, 118.7, 153, 162, 177, 183, 198, 207, 216, 225, 234, 243 and 252 kHz).

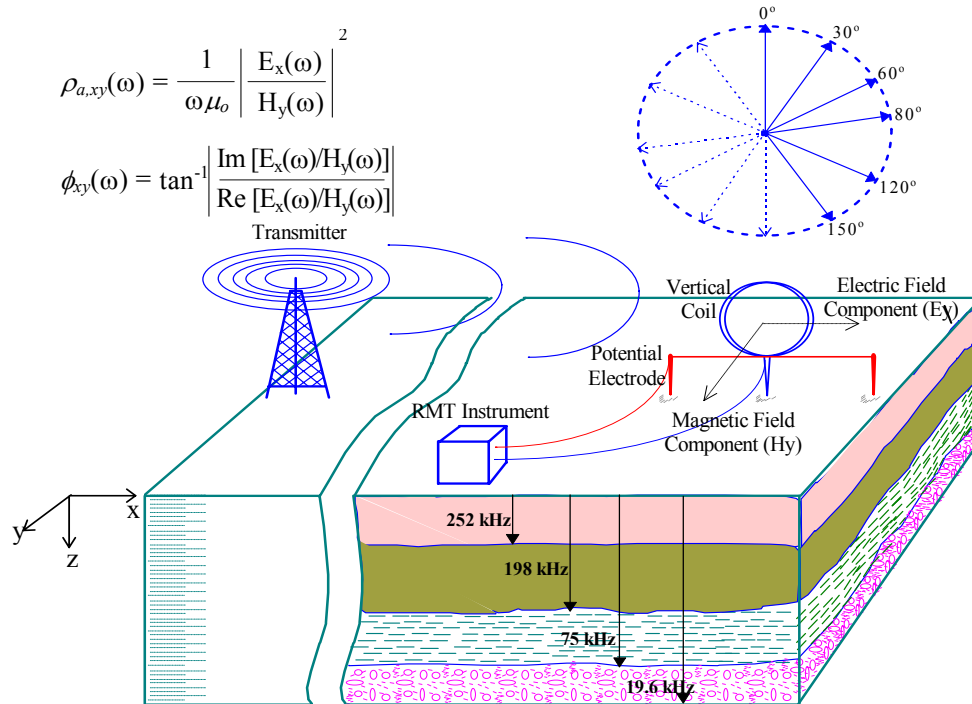


Figure 3: Multi-frequency RMT field-setup over a horizontally-layered earth.

III. Interpretation of RMT Data

The interpretation of RMT data at the IGM is currently carried out using a standard scheme of successive techniques as follows;

a. Viewing Resistivity and Impedance-phase

Plotting of apparent resistivity and phase values versus measuring distance (Fig. 4-a) showed a slight increase for apparent resistivity and decrease for phase values throughout the profiles from SW to NE. All apparent resistivity curves showed a descending behavior with increasing the frequency. While phase curves showed a change from about 25° to 50° with increasing the frequency (Fig. 4-b). This can roughly be explained by an upper conductor overlying a resistive medium. Plotting of apparent resistivity and phase values versus measuring azimuth, for every RMT-frequency band, (Fig. 4-c) showed that the change of either resistivity or phase is quite small (i.e. they are independent of the transmitter's azimuth). This may assume that the data are almost consistent with the one-dimensional (1-D) resistivity model.

b. ρ^* - z^* Transformation

Theoretically, observed RMT data can be interpreted according to the $\rho^*(z^*)$ transformation (Schmucker, 1987) which allows estimates of the conductivity depth distribution using modified (or substitute) resistivity values for phases ranging from 0° to 45° or from 45° to 90°. The $\rho^*(z^*)$ depth sections below the three profiles (see as example, Fig. 5) showed a monotonic increase of ρ^* values downwards with decreasing frequencies indicating an upper conductor overlying a resistive medium, the z^* values are scattered at the lowest frequencies. This

is interpreted as thin coal seam overlying a sand layer. The coal seam has a gradual thickness decrease from SW to NE. In the sense of $\rho^*(z^*)$ transformation, the maximum investigation depth was about 12 m. As Ziebell (1997) pointed out, in the case of an upper conductor overlying a resistive medium (e.g. a waste mass overlying an undisturbed resistive-geology), $2z^*$ can be used as a maximum investigation depth for 2-D RMT interpretation. We found that $2.5z^*$ is quite satisfactory in our case, either for one- or two-dimensional (2-D) interpretation (see Sections III-c and III-d).

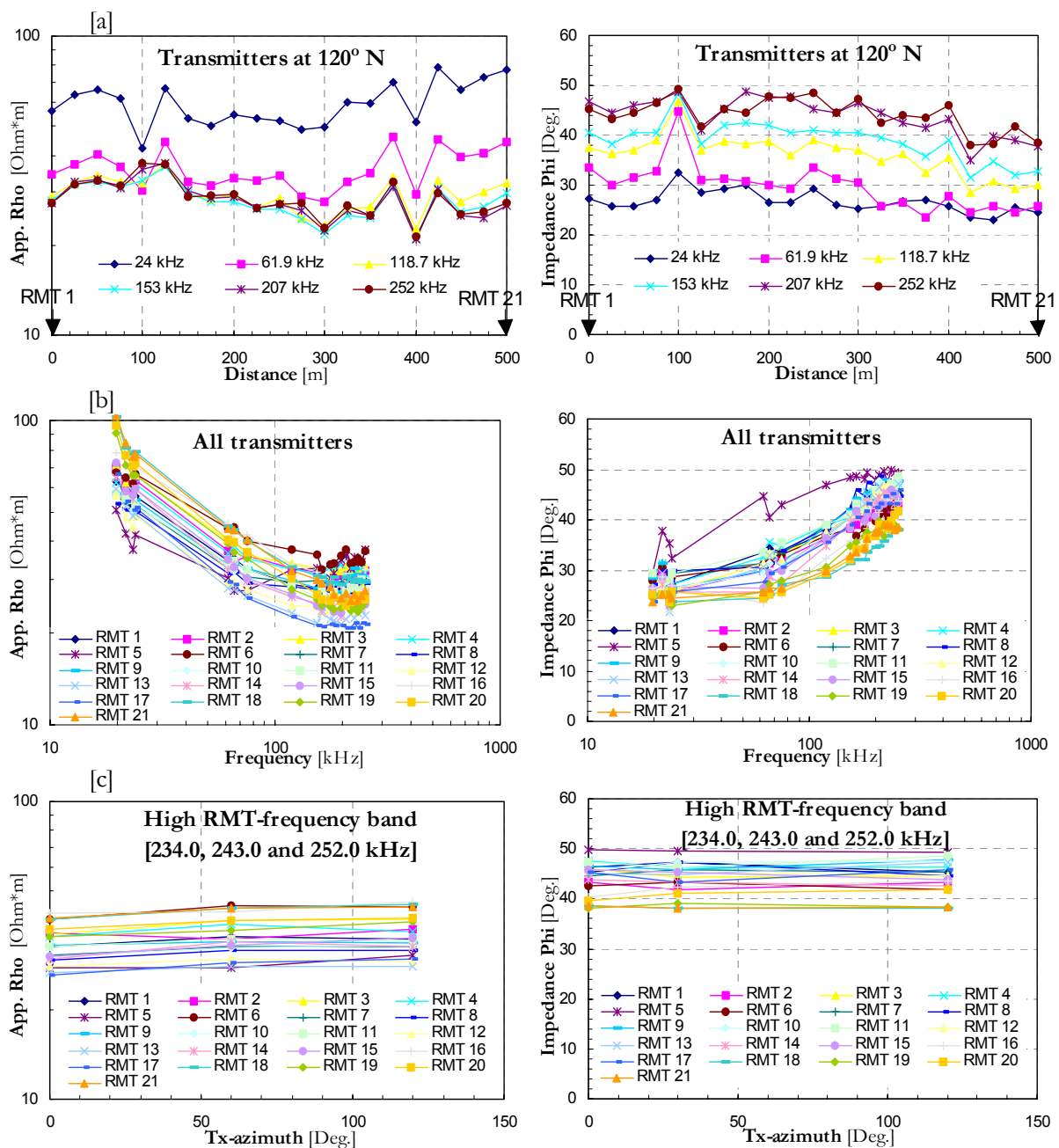


Figure 4: Apparent resistivity and phase versus measuring distance (a), frequency (b), and azimuth-direction (c), profile I.

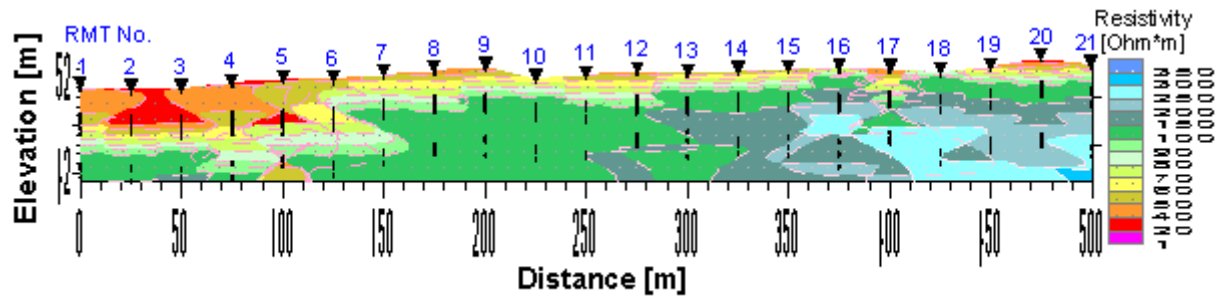


Figure 5: $\rho^*(z^*)$ depth section below profile I.

c. One-dimensional (1-D) Inversion

Models for different RMS obtained from Occam's inversion (Constable, 1987) of the sounding RMT 32, close to the stratigraphic-control borehole "WS 1380", (Fig. 6-a) showed smoothing curves exhibiting an upper conductor (Garzweiler coal seam) overlying a resistive medium (sand). The coal-sand boundary is not quite clear as the RMS threshold increases. Because the RMT data are skin-depth limited, only the first two layers (i.e. Garzweiler coal and the underlying sand) are needed to explain the data. Throughout each profile, Occam's results were quite consistent (Fig. 7-a). Only for profile III, we had to skip up to 50 % from its data before inversion. The blocked-layer thicknesses, after adjusting from the borehole-geology, and their average resistivity obtained from smoothed-earth model were used to formulate a good starting model for the full non-linear inversion to drive the layered-earth model (Inman, 1975) at the sounding RMT 32. Beginning from this reference sounding and using a kind of recursive starting modeling (which means the inversion results for the previous sounding is used as starting model for the present one), the inverted sections could be driven reasonably (Fig. 7-b) with a resolution depth up to 30 m.

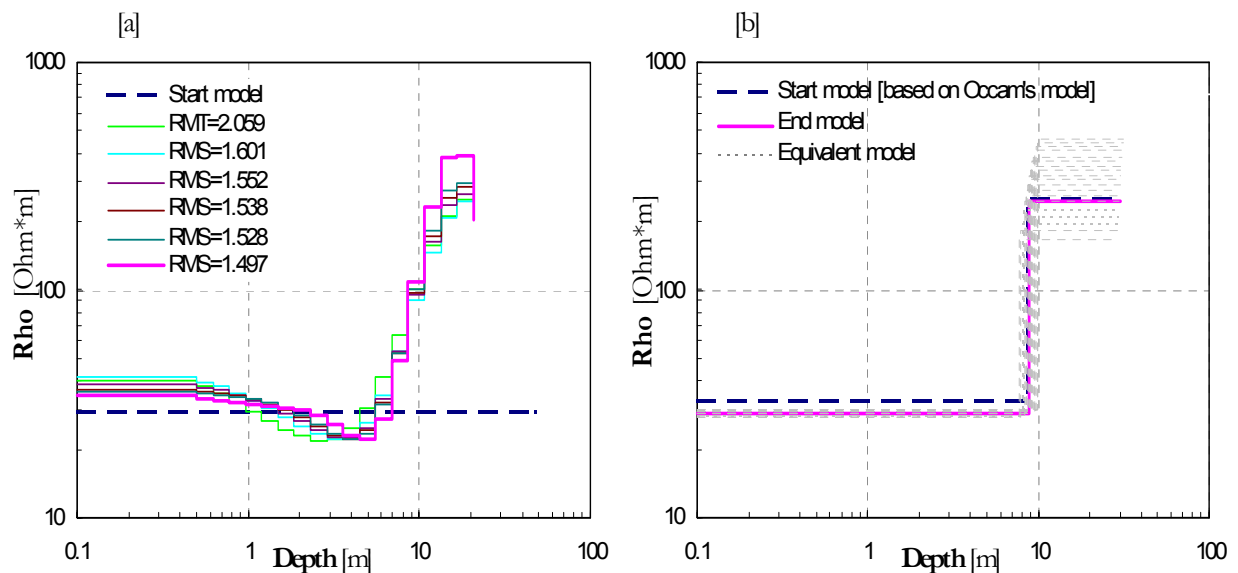


Figure 6: 1-D smoothed-earth (a) and layered-earth (b) models, sounding RMT 32, profile II.

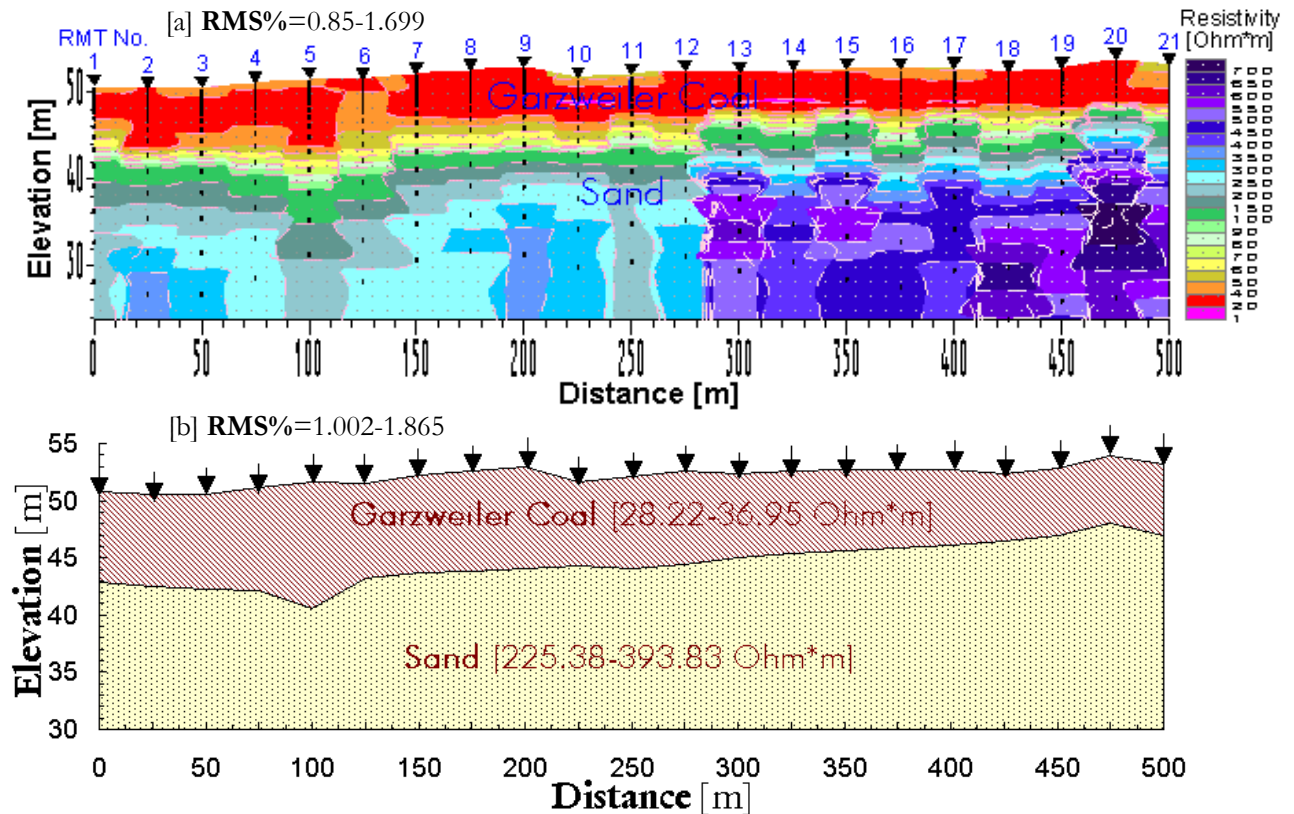


Figure 7: 1-D smoothed-earth (a) and layered-earth (b) inverted section below profile I.

d. Two-dimensional (2-D) Inversion

Using "Tikhonov regularization", non-linear conjugate gradients (NLGG) algorithm (Rodi and Mackie, 2001) finds a regularized solution of the 2-D inverse problem for RMT data. The inversion procedure uses the predicted impedances from the forward calculation, using a finite-difference algorithm, to modify the model parameters that minimize the objective function. To begin, one must develop an initial guess (start model) of the electric structure of the subsurface. The earth is broken down into discrete blocks for solving the problem. Because the calculation is extremely sensitive to the geometry of the mesh, during the course of discretizing the 2-D earth-mesh, four meshing parameters should be well-adjusted to aid in the design: (1) the "skin-depth limit", (2) the "size-delta limit", (3) the "mesh extension", and (4) the "topographic inputs". The L-curve criterion (Hansen, 1999) provides a means of estimating an appropriate value of the trade-off parameter (τ) between the size of the regularized solution and the quality of the fit that it provides the given data. If the model norm is plotted against the misfit for a wide range of τ , the resulting curve tends to have a characteristic "L-shape", especially when plotted on double-logarithmic axes (Fig. 8). The corner (i.e. the point of maximum curvature) of this L-curve corresponding to a roughly equal balance of the two terms.

The 2-D inverted section below profile I, as an example, is shown in Figure 9, with a resolution depth up to 30 m. Figure 10 shows the inversion models in comparison with the borehole-geology at the sounding RMT 32, one can see a smooth resistivity change in the case of 2-D model at the layer-boundary whereas the transition to the lower sand is more sharp in the case of 1-D models.

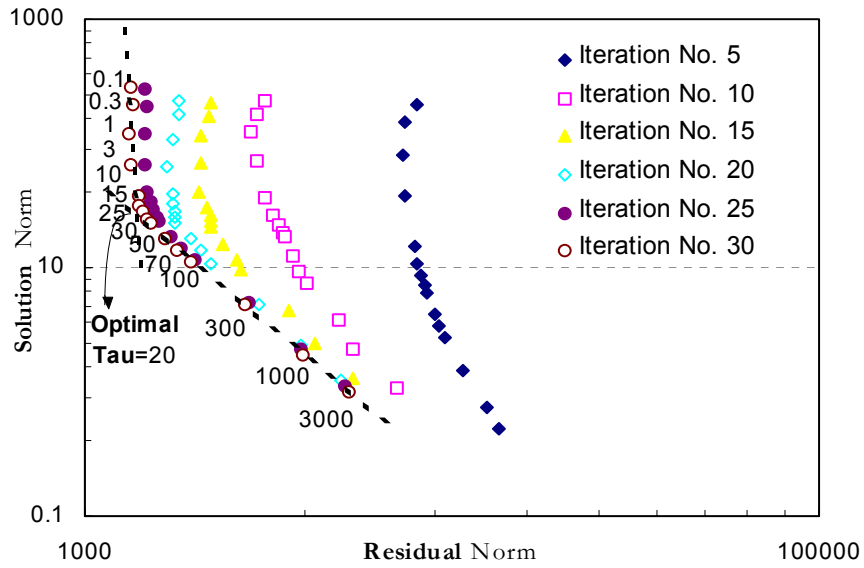


Figure 8: The L-curves at different iterations and the optimal regularization parameter, profile I.

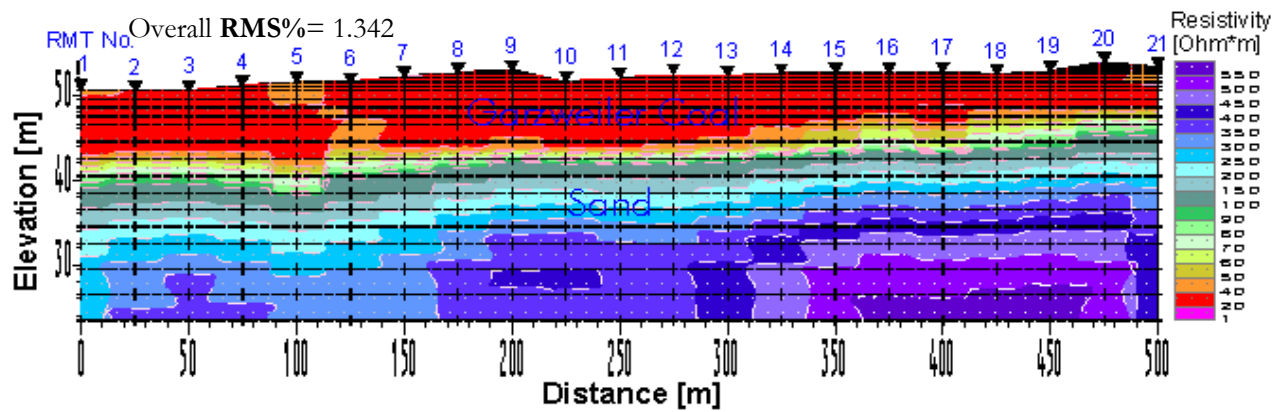


Figure 9: 2-D smoothed-earth inverted sections below profile I.

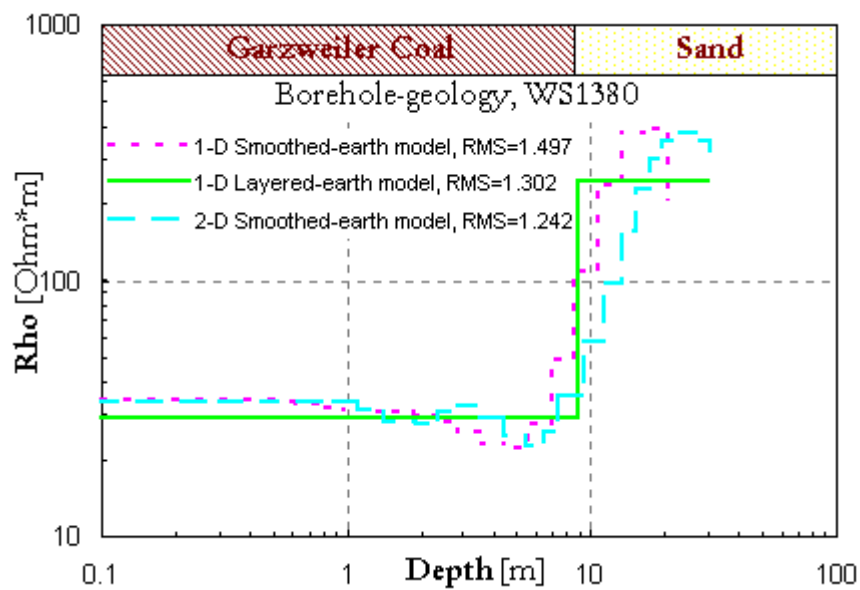


Figure 10: Comparison of the RMTE inverted models with the borehole-geology, sounding RMT 32, profile II.

IV. Concluding Remarks

Over the coal-covered area, the specially designed field setup (i.e. the multi-directional, multi-frequency RMT survey) enabled the data to be interpreted extensively by 1-D and 2-D resistivity models. Comparison of the inversion techniques showed that 1-D smoothed- and layered-models represent the coal-sand boundary very clearly and accurately where the geology and the model are reasonably matched, while the 2-D smoothed-earth model shows a less distinct boundary. One of the best uses of the 2-D inversion was to confirm that 1-D inversion is quite valid for all soundings. The simplicity of 1-D inversion can provide sometimes an interpretation with much resolution and more detail, with no aid of a complex 2-D inversion.

V. Acknowledgment

We would like to thank Mr. B. Becker and Mr. K. Schneider from RWE Rheinbraun AG for providing the filed support during the measurements at the "Garzweiler I" mine and allowing us to use the stratigraphical, topographical and well logging data.

VI. References

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