Vertical Electrical Resistivity Structure of the Garzweiler and Frimmersdorf Coal Seams Inferred from Transient Electromagnetic Data

Karam S. I. Farag* and Bülent Tezkan*

E-mail: farag@geo.uni-koeln.de

* Institut für Geophysik und Meteorologie (IGM), Universität zu Köln, Albertus-Magnus-Platz, D-50923 Köln

I. Rhineland Brown Coal and Near-surface Electromagnetics

The largest single lignite, or brown coal, formation in Europe is found in Rhineland which covers an area of some 2,500 km^2 to the west of Cologne. RWE Rheinbraun AG operates four large open-cast mines, namely Inden I/II, Garzweiler I, Hambach I and Bergheim. The Garzweiler I mine accounted for one-third of total lignite output. The planned Garzweiler II mine will replace capacity from Bergheim mine, which is nearly worked out. The shallow stratigraphy at the "Garzweiler" region consists of a layered-cake sequence of Garzweiler, Frimmersdorf and Morken seams (built in the Miocene age, 26.60 Ma) embedded in a sand-background with different silt/clay contents (Fig. 1).

The present study was devoted to carry out transient electromagnetic (TEM) and radiomagnetotelluric (RMT) investigations along three profiles over a coal-covered area at the "Garzweiler I" mine (Fig. 2). It was hoped that such methods may image the vertical electrical resistivity structures of the shallow coal seams at the study area. To determine what can be interpreted reliably from the 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-dimensional TEM resistivity models below the profiles concerned.

II. Transient Electromagnetics (TEM)

Methods in which electromagnetic (EM) energy is introduced into the ground as transient pulses, instead of continuous waves, by a square transmitter-loop (50 m*50 m) carrying steady current and primary magnetic field. Immediately after the primary current and magnetic field are switched off suddenly, an induced secondary field, resulting from the induced currents for subsurface, is sensed by a centrally-placed square receiver-loop (20 m*20 m) and decays with time as the currents gradually dissipate. The whole process of the step-wise excitation of the current-loop is repeated many times and the data stacked. The direction in the transmitter is usually reversed for each pulse to avoid effects due to ground polarization. The loop is then moved, parallel to one of its sides, by a distance equal to the side. This geometry forms the basis of "in-loop" or "central loop" resistivity sounding and can be schematically shown in Figure 3.

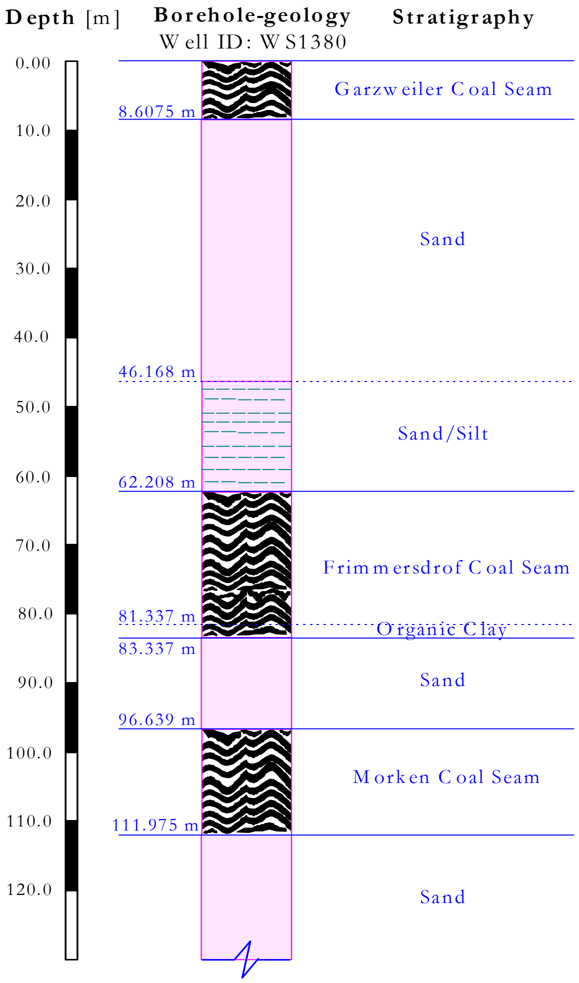

Figure 1: Borehole-geology at the "Garzweiler" mining district, west of Cologne.

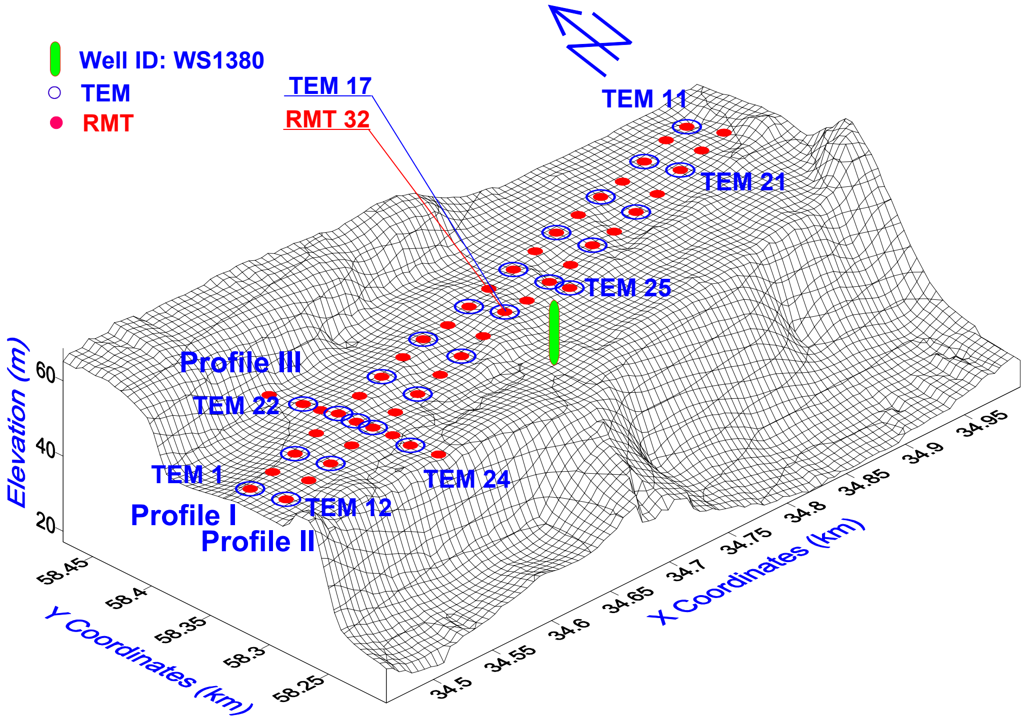

Figure 2: The topography and locations of TEM soundings over the coal-covered area.

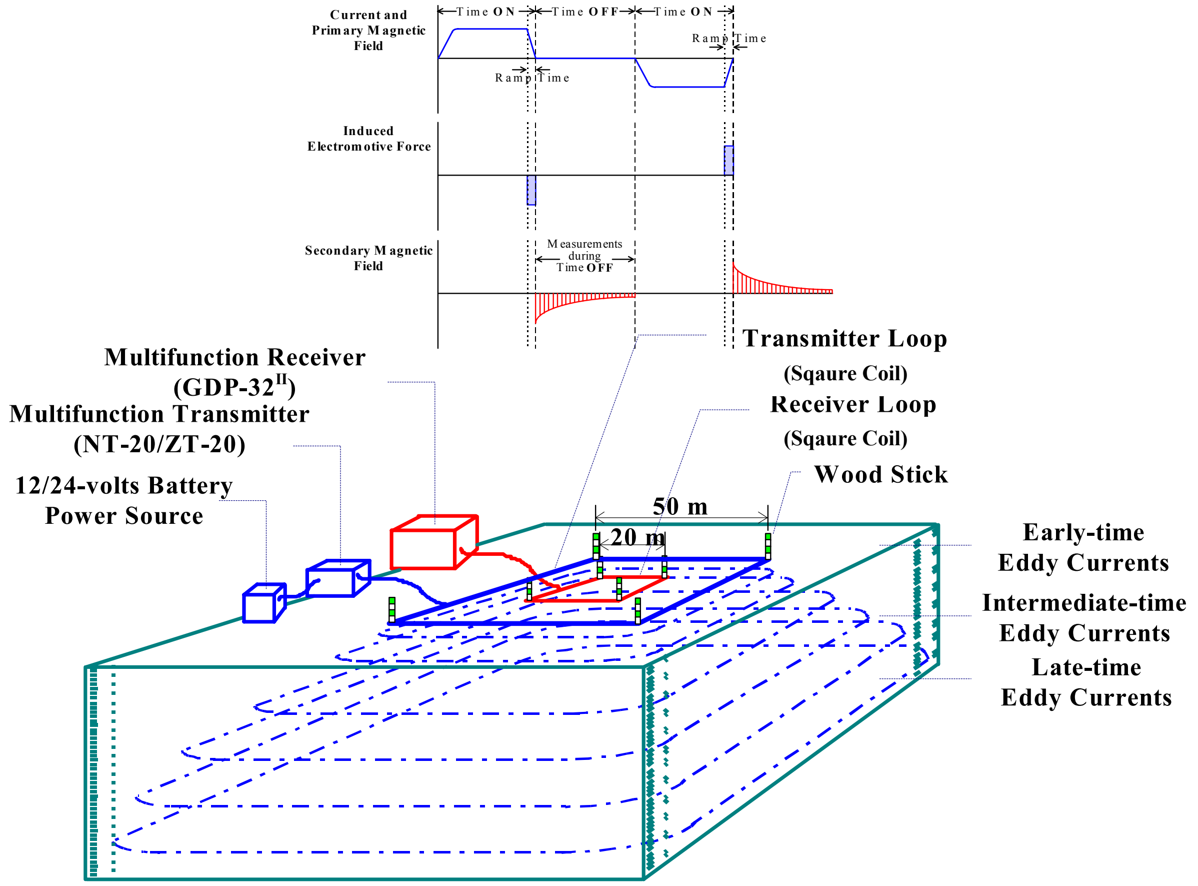

Figure 3: In-loop TEM field-setup and transmitted/received signals over a homogeneous earth.

For our field measurements, all TEM data were taken using Zonge manufactured TEM system. Routinely, the time derivative of the vertical magnetic field is recorded as a voltage, dB/dt, by a segmentation process using different transmitter-current waveforms (Fig. 4) and receiver sampling schemes. First, the very fast turn-off NanoTEM (i.e. shallow investigation mode) measurements were taken from about 0.3 μs to 2.5 ms with manual low-gain settings and low transmitter-current (about 0.5 amps) and then with high-gain settings and high transmitter-current (from 2.60 to 3 amps) using 12 volts, 64 Hz repetition frequency, 3 μs turn-off ramp and 1.6 μs sampling rate to cover the narrow very-early/early time gates to the wider intermediate time gates. Later on, the slow turn-off ZeroTEM (i.e. deep investigation mode) measurements were taken from about 31 μs to 6 ms with automatic-gain settings and relatively high transmitter-current (from 8.0 to 9.0 amps) using 24 volts, 32 Hz repetition frequency, 50-55 μs turn-off ramp and 30 μs sampling rate to cover the narrow intermediate time gates to the wider late time gates. Background noise measurements were done with the same sampling scheme while the transmitter was turned-off. Some data points must be eliminated from the measured curves, either for early or late times due to the over-gain or noise content respectively, to avoid misinterpretation. Figure 5 (-a and -b) shows the ground response and its background noise measured at the sounding TEM 17 using the segmentation recording.

Although the combined-NanoTEM and ZeroTEM transients can be jointly interpreted, TEM inversion could be more efficiently undertaken if the data were converted to an unique form. This is can be done by deconvolving the system response, the turn-off ramp in our case, out of the measured signal based on the simplifying assumption that it is approximately a linear function (Helwig et al., 2003). Afterwards, one representative transient can be obtained and will be ready for further interpretation (Fig. 5-c).

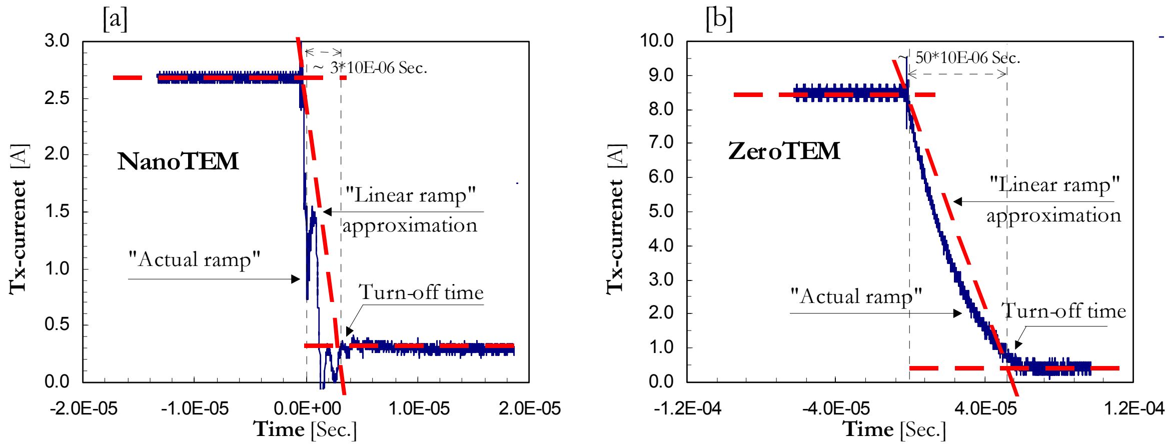

Figure 4: The actual transmitter-current waveforms for NanoTEM (a) and ZeroTEM (b) measuring modes at the sounding TEM 17, profile II.

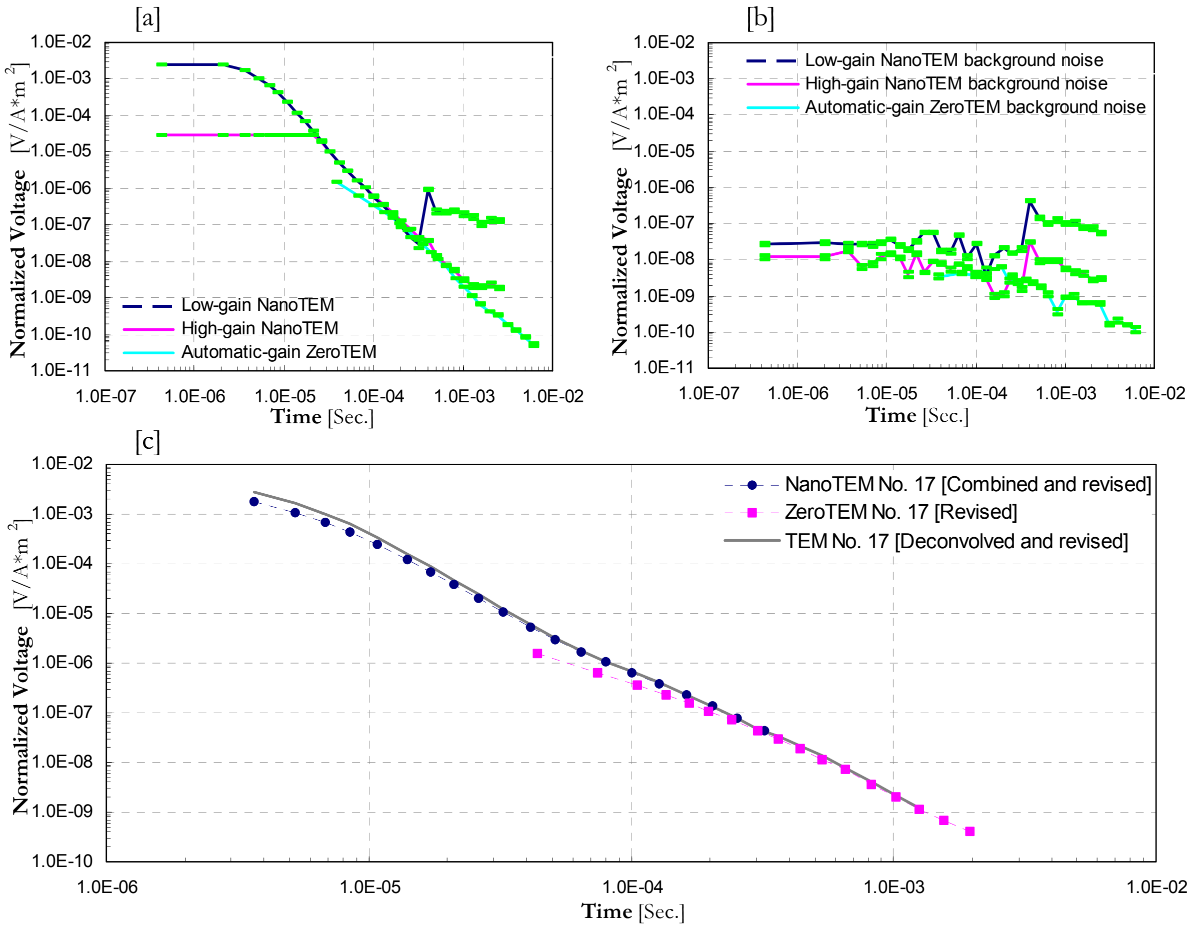

Figure 5: The segmentation recording scheme for the in-loop Zonge manufactured TEM system; the ground response segments (a), the back-ground noise segments (b) and the revised form of the deconvolved response (c) at the sounding TEM 17, profile II.

Models for different RMS obtained from Occam's inversion (Constable, 1987) of the sounding TEM 17, close to the stratigraphic-control borehole "WS1380", along profile II (Figs. 2

and 6-a) showed smoothing curves exhibiting two conductors (Garzweiler and Frimmersdrof coal seams) embedded in a resistive medium (sand-background). The coal-sand boundary is not quite clear as the RMS threshold increases. The first four layers (i.e. Garzweiler and Frimmersdorf coal seams within the sand background) are needed to explain the data. Throughout each profile, Occam's results were quite consistence (Fig. 7-a). 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 TEM 17 (Fig. 6-b). 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 section could be driven reasonably (Fig. 7-b) with a resolution depth up to 90 m.

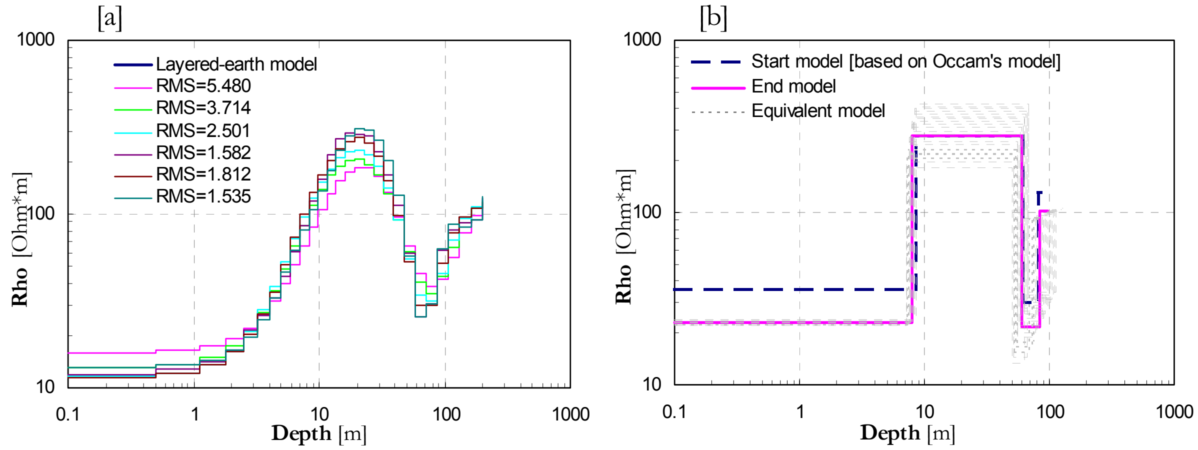

Figure 6: 1-D smoothed-earth (a) and layered-earth (b) models, sounding TEM 17, profile II.

To evaluate the reliability of the inversion results, we examine the normalized Jacobian (sensitivity) matrix. The Jacobian gives an idea of each data point's sensitivity to a change of an individual parameter in the solution and qualitatively displays the parameter correlation. The values of the Jacobian show whether a parameter is to be seen in the measured data at all and how the data are influenced by every parameter relative to the other (Lines and Treitel, 1984; Jupp and Vozoff, 1975). Figure 8-a displays the Jacobian for the inverted parameters throughout the time range of the sounding TEM 17. The first layer (Garzweiler coal) parameters dominate the data strongest in the very early time and their influence decays sharply. The derivatives with respect to ρ_1 (first resistivity) and h_1 (first thickness) change simultaneously in different direction, a high negative correlation has to be expected. This means just a combination of the first layer parameters could be resolved and neither of them independently. The second layer (sand) parameters are positively correlated throughout all the time. h_2 influences the signal very well in the early and intermediate time, beyond this the absolute values of ρ_2 are mush smaller than all other derivatives. Later on, from intermediate to late time, the third layer (Frimmersdorf coal) parameters dominate the data strongest with a high negative correlation. This means again just a combination of the third layer parameters could be resolved and neither of them independently. Finally, the last detected layer (sand) is resolved in the later data points with moderate absolute values. Figure 8-b shows that, for all TEM data, all layer thicknesses and coal resistivities are well resolved (i.e. important), while the sand resistivities are moderately to poorly resolved and, therefore, do not contribute to the data very much.

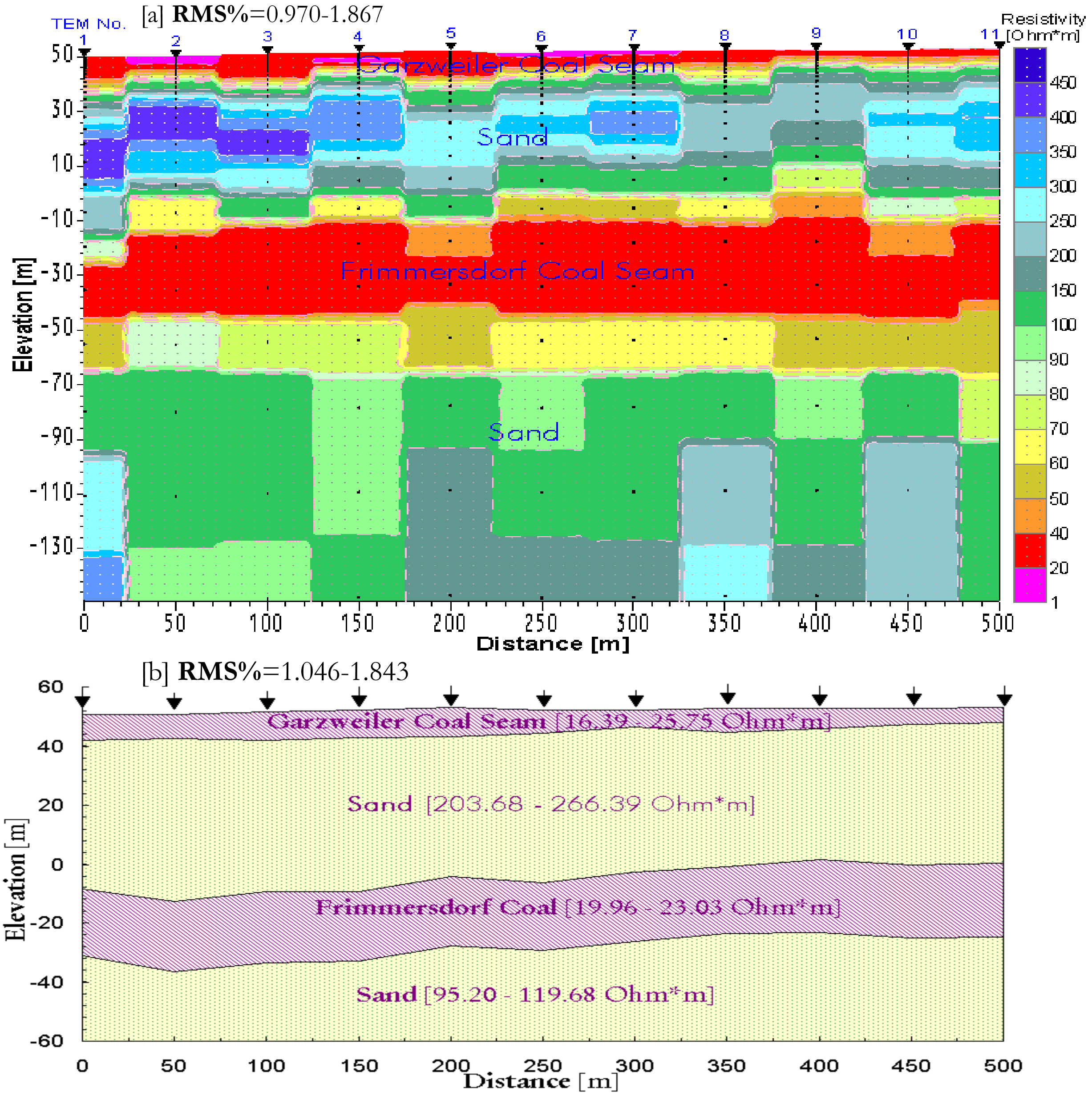

Figure 7: 1-D smoothed-earth (a) and layered-earth (b) inverted sections below profile I.

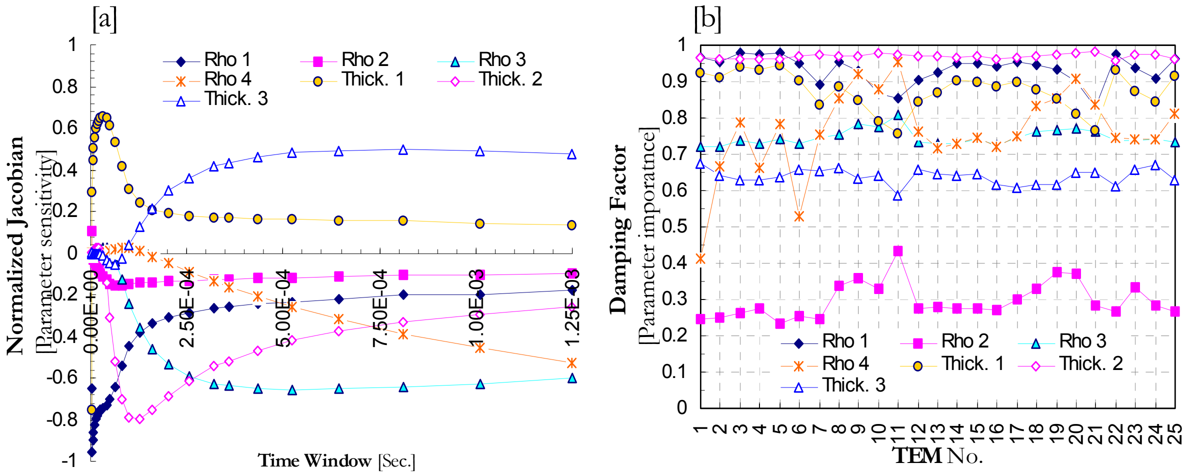

Figure 8: Sensitivity analysis; Jacobian values for the layer parameters at the sounding TEM 17 (a), and damping factors for the layer parameters at all TEM's (b)

III. Correlation of Resistivity Models with the Borehole-geology

Comparing the inversion results with Rheinbraun borehole-geology at the soundings RMT 32 (Farag and Tezkan, 2003) and TEM 17 showed that the joint-application of RMT and TEM techniques were successful in identifying the major stratigraphic units, i.e. Garzweiler and Frimmersdorf coal seams within the sand back-ground, but could not discriminate between the sand and silty sand or between Frimmersdorf coal and the underlying organic-clay. The coal-sand boundaries could be resolved very clearly and accurately where the geology and models are reasonably matched (Fig. 9). Beyond this the absolute resistivity values derived from the RMT and TEM inversion averaged well around the values obtained from the four-electrode DC and AC laboratory measurements for sand/silty sand and coal/clay.

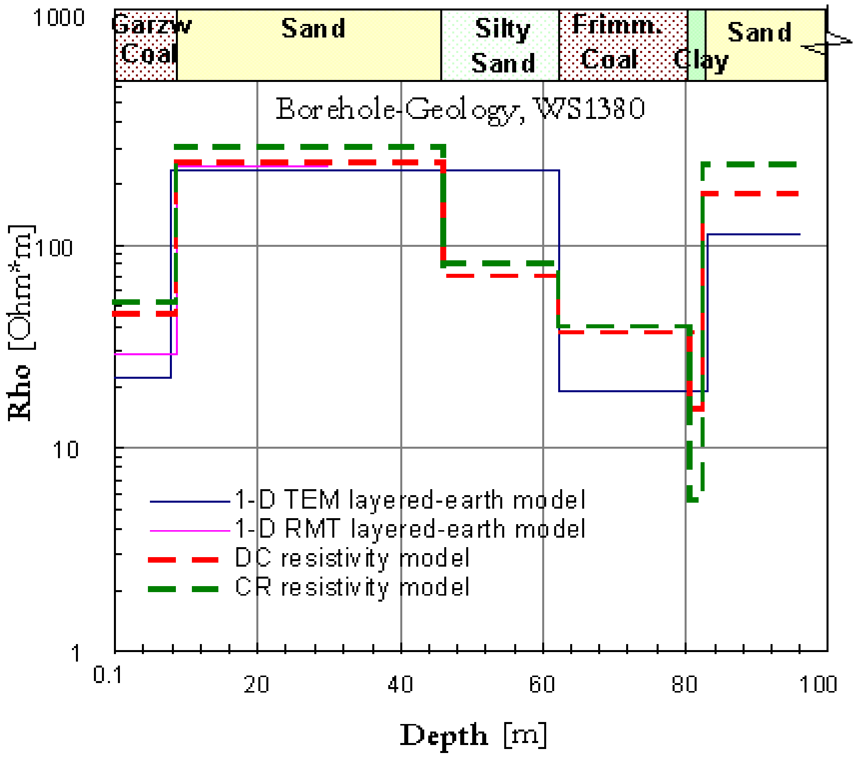

Figure 9: Comparison of the TEM and RMT resistivity models with the borehole-geology, soundings TEM 17/RMT 32, profile II.

IV. 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.

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