

Resistivity Sounding by Airborne Electromagnetics
and its Application to Groundwater Exploration

By

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ABSTRACT

New inversion techniques for multi-frequency airborne electromagnetic (AEM) survey data have led to a considerable improvement in determining the approximate resistivity distribution in the ground. This information can be represented either by coloured vertical resistivity sections along a flight line or by maps of the horizontal resistivity distribution at a preselected depth. With the available frequencies of EM-systems a depth range from the ground surface down to a maximum of 60 to 120 m can be explored. Examples are shown from a desert area where a large freshwater aquifer was detected and delineated on the basis of three-frequency AEM resistivity sounding results.

The vertical resolution obtained from only three frequencies is not always adequate to provide a true picture of the actual layering. This is one reason why the AEM survey was accompanied by ground d.c. resistivity soundings. Hydrogeological investigations and drilling results are always required for optimum interpretation of the resistivity pattern.

1. Introduction

Resistivity soundings at ground surface using direct current have long been a standard tool for solving hydrogeological problems.

The bulk resistivity ρ_t of a water-bearing formation is related to the resistivity ρ_w of the groundwater by Archie's formula

$$\rho_t = f \cdot \rho_w$$

where the formation factor f depends on the porosity, the water saturation, and the cementation of the geological formation. The groundwater resistivity ρ_w decreases with increasing salinity and varies typically

between 0.1 and	2 Ω m	for saline water
between 2 and	6 Ω m	for brackish water
between 6 and	150 Ω m	for fresh water.

If the ground formation consists of sandy or silty sediments, the formation factor varies within the range of 2.5 to 5. In desert or coastal areas we often encounter all the above types of groundwater in unconsolidated sediments. Consequently the formation resistivity ρ_t is essentially governed by the quality of the groundwater.

It is well known that the ground resistivity can also be determined by electromagnetic (EM) measurements. The equipment generally consists of a transmitter coil which produces an oscillating magnetic (dipole) field. This primary field penetrates into the ground and induces electric currents. For a given frequency, amplitude and phase of these currents depend on the resistivity distribution in the ground. The secondary magnetic field of these currents is picked up at a certain distance s from the transmitter by a receiver coil and is split into the inphase component

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R and the quadrature component Q. For measurements in the frequency domain and at ground surface the distance s should be of the order of 100 m for a parametric sounding, i.e. a sounding with a number of different frequencies. Due to the skin effect, the depth of penetration can be increased by decreasing frequencies, but this will decrease the signal amplitudes and the resolution.

Airborne EM equipment is operated according to the same principles, with one exception: the coil spacing s is only 6 to 8 m. At ground surface, such a small s would considerably reduce the depth of investigation. However, at normal flight altitudes of 30 to 40 m above ground, depths of more than 120 m can be reached with currently available equipment. The Federal Institute of Geosciences and Natural (BGR) uses a three-frequency DIGHEM EM system. Three horizontal, coplanar coil pairs are installed into a Kevlar bird which is towed 45 m below a helicopter and flown at a speed of 140 km/h. The measured R and Q values are stored on magnetic tape, together with the flight altitude, the positional data and data from other geophysical equipment.

2. Inversion of EM data into ground parameters

During a single survey flight, three-frequency measurements are taken at about 20,000 sites. It is not possible to apply conventional inversion techniques to all these data. Conventional inversion would require the input of an estimated model in order to calculate the parameters of a two or three layer ground. However, an approximate inversion algorithm (SENGPIEL, 1988) is now available, which transforms EM data for each frequency f into a pair of parameters $\rho^*(f)$ and $z^*(f)$, where the approximate resistivity ρ^* (equivalent to the apparent resistivity ρ_a) is assigned to the "centroid" depth z^* . The centroid of a current system near the axis of the inducing magnetic dipole was shown to be situated at depths $z^* \leq p/2$, where p is the conventional skin depth of a half-space. For a homogenous primary field, z^* equals $p/2$ (SCHMUCKER, 1970).

The approximation of a five-layer case by the $\rho_a(z^*)$ function can be seen in Fig. 1. The resistivities and thicknesses of the layers are given by the step-function $\rho(z)$. In the diagram ρ varies along the abscissa and the depth z along the ordinate. Based on this model, pairs of ρ_a and z^* values were calculated for 14 frequencies and shown in Fig. 1 as points on the $\rho_a(z^*)$ curve. The approximation of the model is quite satisfactory. From other model calculations we know (SENGPIEL, 1988) that good conducting layers come out much better in the $\rho_a(z^*)$ curve than resistive layers (unless the latter are thick), a fact which is common to all electromagnetic methods.

With the existing EM equipment only three frequencies out of the 14 of Fig. 1 are available. Actually we use $f_1 = 32893$ Hz, $f_2 = 3538$ Hz and $f_3 = 386$ Hz as indicated on the $\rho_a(z^*)$ curve by an open circle. Since the $\rho_a(z^*)$ curve is always smooth, we use a cubic spline interpolation through and in between the three available curve points and also for a limited extrapolation beyond the points of the highest and the lowest frequency.

Using the spline interpolation and extrapolation at a depth increment of 2 m, ranging from ground surface to 100 m depth, we obtain a vertical column of 50 resistivity values which give a smoothed representation of the true vertical resistivity distribution. This "electromagnetic sounding" is repeated for all measuring sites of the airborne survey.

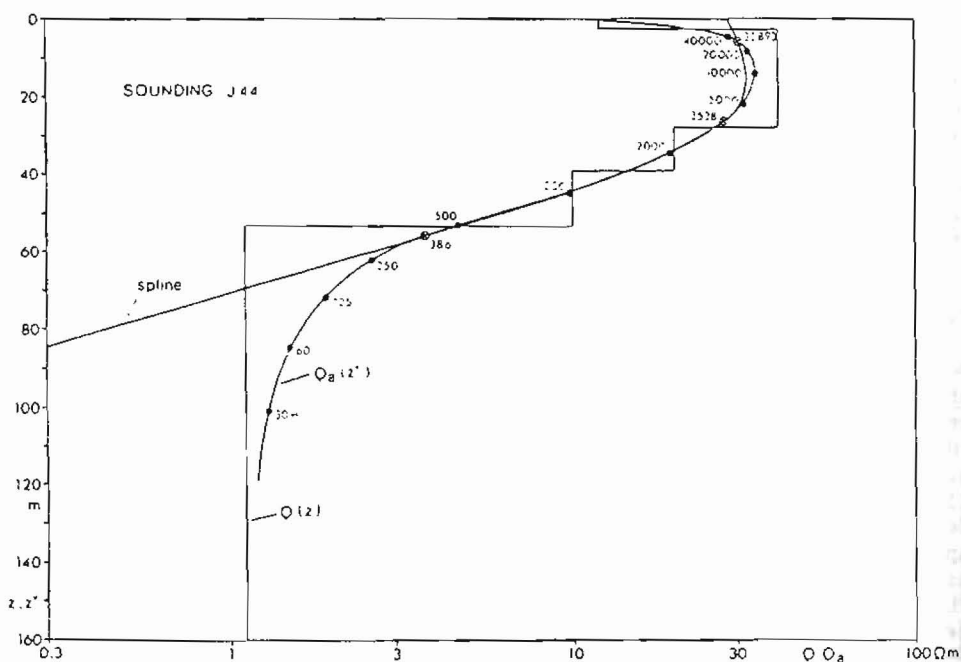


Fig. 1:

Plot of resistivity versus depth, where

- the step function $\rho(z)$ describes thicknesses and resistivities of a five-layer model,
- the function $\rho_a(z^*)$ is calculated for the above $\rho(z)$ model for 14 frequencies (points on the curve), yielding the approximate resistivity distribution,
- the spline interpolation function passes through the points for the available frequencies of the equipment: 386, 3538, and 32893 Hz.

3. Representation of the EM sounding results

Representation of the large amount of EM sounding results requires automatic plotting facilities including programs. These programs have been developed by the BGR helicopter-geophysics group.

The resistivity values are normally divided into 18 ranges of roughly equal logarithmic width. A certain colour is assigned to each range. Red colours are used for low, yellow-green for intermediate, and blue colours for higher resistivities. Since we have about 50 vertical resistivity columns per line-km, each coloured column has an average width of 0.8 mm when the horizontal scale is 1:25,000. The vertical scale is usually 10 m per cm. For this type of plot, which illustrates the resistivity distribution in a vertical section along a flight line, the term "Sengpiel Section" was introduced during the SEG meeting 1990. Fig. 2 shows an example of such a coloured resistivity section. The three thick lines (white, brown, black) indicate the values of z^* for the frequencies given in the caption of Fig. 1.

An interesting complement of the Sengpiel Section is achieved by adding results of an "exact" inversion of a few selected three-frequency data. In Fig. 2 such data were taken at fiducial points 30, 35, 40, 45, 50, and 55, and were inverted into parameters of a layered half-space using a new Marquardt-type inversion algorithm (FLUCHE, 1991). The results of the Fluche inversion are shown by the six coloured vertical columns in Fig. 2, centered at the above fiducial points. Here, the bars of constant colour represent the thicknesses as well as the resistivity ranges of the different layers (for two, three or four layers). This "composite resistivity section" combines the advantages of both inversion techniques yielding a high lateral resolution and the boundaries of a layered half-space. The hydrogeological interpretation of the resistivity section is given below.

Once the resistivity values are available at a depth increment of 2 m and for a number of flight lines, they can be sorted into an array of data for a selected depth z' . Using conventional gridding and contouring procedures the lateral resistivity distribution at depth z' can be represented by a coloured contour-line map. The colours correspond to the colour code of the vertical section plots. In addition to the horizontal section of resistivities, the plot contains the flight lines, the values of significant minima and maxima and their positions. This type of map we call a horizontal resistivity slice. Figure 3 is an example of a small scale, coloured resistivity slice, in this case without flight lines and extreme values. Further explanation is given in the next section.

4. Detection of a fresh water body in a saline environment

The three-dimensional resistivity distribution in the ground can be interpreted in terms of hydrogeology if additional information is available from the conventional methods of groundwater exploration. Often a few samples of such information are sufficient:

- The resistivities of the main formations and aquifers derived from ground d.c. soundings and borehole logs,
- the formation factor and the water resistivity ρ_w at different depths from water samplings and borehole logs,
- the depth to the water table in the whole survey area from investigations in dug wells and boreholes.

Plenty of this kind of data was collected in an area of the flat Cholistan Desert in Pakistan where BGR conducted the first systematic airborne EM survey for groundwater using three frequencies and applying the new evaluation techniques.

In the Cholistan area the average depth to the water table is 20 m (see Fig. 2) and varies only a few metres. The people of these regions regard brackish water down to a resistivity $\rho_w = 4 \Omega\text{m}$ ($\hat{=} 2500 \mu\text{S/cm}$) as "fresh", and water of less than $1.7 \Omega\text{m}$ as saline. The average formation factor of the fine-grained sediments is 3.4 (FIELITZ, 1987). Based on these and other data we can assign the apparent resistivities from the EM survey to the following formations below the water table:

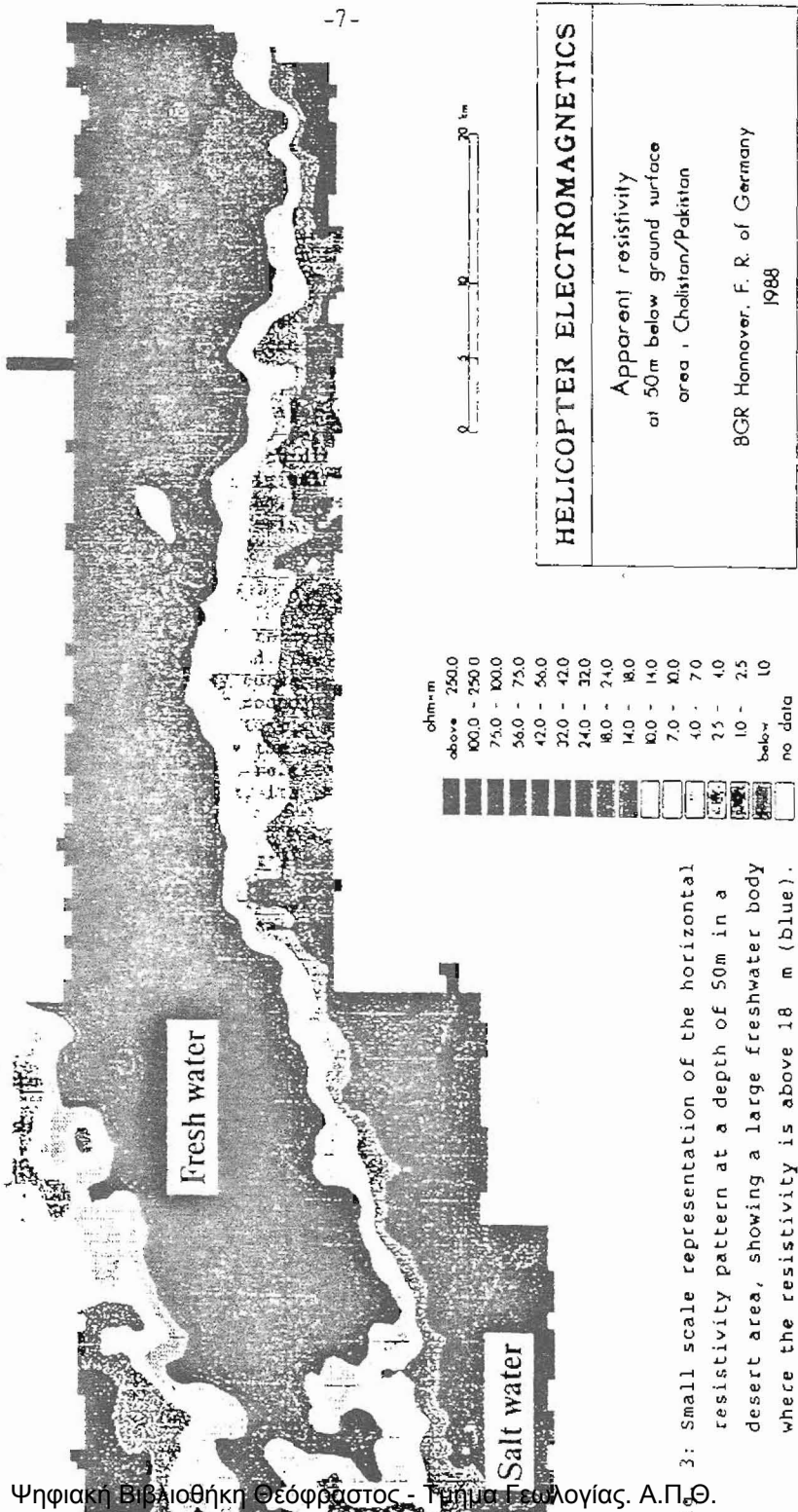
- 18 - 100 Ωm fresh water aquifer
- 7 - 18 Ωm brackish water aquifer
- < 7 Ωm salt water aquifer.

In the dry top layer the resistivity is related to the lithology of the sediments. Here, for example, we encounter clay pockets with low resistivities (less than $2.5 \Omega\text{m}$) and sand dunes with high resistivities (above $150 \Omega\text{m}$).

Figure 2 illustrates the resistivity section along the first 29 km of flight line 132.2 over the Cholistan Desert.

The lateral variation of the resistivity above the water table is much more irregular than below it. From the southern end of the line to UTM-km 238.5 we observe a thick zone with resistivities above $18 \Omega\text{m}$ and locally above $60 \Omega\text{m}$. There is an abrupt decrease of its thickness between line-km 235.5 and 237. Below the water table, the blue zone is interpreted to be a freshwater aquifer. North of km 238.5 the groundwater is most probably fresh at 20 to 35 m depth and saline below about 35 m. The results of the Fluche inversion confirm the rise of the conducting (saline) substratum north of km 236. The freshwater zone around km 235.5 is thicker than 100 m. However, for depths greater than $z^*(f_1)$, where $f_1 = 386 \text{ Hz}$, the information shown by the resistivity section is obtained by extrapolation and is only reliable within 10 to 20 m below $z^*(f_1)$. As can be derived from Fig. 2, e.g. at km 233.7, the depth of investigation is considerably reduced by a good conducting top layer in connection with a small decrease of the ρ_a values of the underlying layers. Furthermore, $z^*(f_1)$ is limited by the small skin depth within the conducting saline substratum (north of km 239).

The more resistive (blue) zone of Fig. 2, described above as a freshwater aquifer, is actually part of a huge freshwater body detected during this Technical Cooperation project carried out by BGR, Hannover, and the Water



3: Small scale representation of the horizontal resistivity pattern at a depth of 50m in a desert area, showing a large freshwater body where the resistivity is above 18 m (blue).

and Power Development Authority (WAPDA), Lahore. The lateral extent of this freshwater body is shown in Fig. 3 in the form of a horizontal slice for a depth of $z' = 50$ m. Again the fresh water can be assigned to resistivities greater than $18 \Omega\text{m}$ (blue). The length of the body mapped so far by the EM survey is 98 km, the average width 15 km and the mean thickness 70 m. 24 test-holes have already proved the quality of the water, which locally shows conductivities as low as to $1000 \mu\text{S/cm}$. The origin of the water and the recharge conditions are currently being investigated. It was surprising to find out that the position of the water body coincides with an old river course described by WILHELMY (1969). This river (Hakra or Ghaggar) was perennial up to 600 B.C. and later became a temporary flood channel which disappeared in the 16th century. Additional horizontal slices at an original scale of 1 : 100 000 have been produced (in colour) for other depths, namely 10, 30, 70, and 90 m, representing detailed pictures of the resistivity pattern in the survey area.

5. Conclusions

The parameters ρ_a and z^* are calculated on the basis of the model of uniformly conducting ground. The curve ρ_a versus z^* has some similarity to the apparent resistivity curve ρ_a versus $L/2$ ($L =$ electrode spacing) of ground d.c. Schlumberger soundings. It differs, however, in that z^* directly assigns a depth to ρ_a . Furthermore, in the EM method, ρ_a is essentially controlled by the more conducting parts of the ground. If a fresh-water aquifer (with relatively high resistivities) is to be detected above a saline substratum, its thickness must not be too small compared with its skin depth.

In general, the smooth $\rho_a(z^*)$ curve only provides limited vertical resolution even for more than three frequencies. It is therefore recommended that a selection of the EM data is interpreted in terms of a layered half-space by the Marquardt algorithm or the airborne EM survey should be accompanied by ground d.c. soundings at selected sites. The lack of vertical resolution is certainly compensated by the high lateral resolution as well as by the speed of the airborne measurement and the automated evaluation techniques.

6. Acknowledgements

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7. References

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