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Near-surface resolution power of the Schlumberger sounding method: examples from Lake Fertő (Neusiedlersee) region, Austria-Hungary

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The near-surface layer-resolution power of geoelectric soundings is illustrated by means of direct comparison between the geoelectric and the core sample results. Three one-dimensional inversion techniques (classical least-squares interpretation, the Zohdy technique, and the stochastic Bayesian method) are used. All of them show more similarity with the measured core sample physical parameters (core resistivity, humidity and susceptibility) than with the drillhole lithology itself. Local inhomogeneities and very thin layers cannot be seen from the surface; in contrast, the robust layer boundaries and continuously changing layer transitions can be resolved by various geoelectric inversion methods.

Keywords: geoelectric sounding, inversion, near-surface, Neusiedlersee, Austria, Hungary

1. Introduction

The Schlumberger sounding technique (also known as 'vertical electrical sounding'), as all surface geophysical techniques, allows non-invasive insight into the electrical structure of the subsurface. In spite of its widespread application and of the increasing interest in the reliable imaging of near-surface geological structures, information about its performance for investigating very near-surface structure is very limited.

Such information can only be obtained by direct comparison of measurements of the actual resistivity profile with that obtained through inversion of the Schlumberger sounding curves. In the framework of French-Austrian and

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French-Hungarian cooperations, geophysical measurements, including very precise Schlumberger soundings, were carried out in 1997 in the region of Lake Fertő (Neusiedlersee). (For earlier geophysical studies of the region see KOHLBECK et al. [1993] and [1994].) As a part of this investigation, several shallow drillholes were deepened both in Austria and in Hungary. Continuous core sampling was carried out at each site, and Schlumberger soundings were performed at the core location along different (usually two perpendicular) directions.

In this paper the resolution power of near-surface Schlumberger sounding, utilizing the highest available precision in the field is discussed. The results obtained from different inversion techniques are directly compared with the subsurface rock physical properties. A summary is given of the techniques used and here we present the results for three sites, viz. Fertőújlak, Király-tó and Lébény. A detailed analysis of laboratory data together with the near-surface geology of the region is given elsewhere [JELINOWSKA et al. 2000].

2. Description of the techniques

Schlumberger sounding

With the advent of technological and computational development the resolution power of the Schlumberger sounding method (for a full description, see KOEFOED [1979]) has been significantly improved. Nowadays the main limitation of the method is the time requirement to implant the electrodes into the soil, with minimum geometrical error. In order to get very precise data within minutes, a special tool was employed. A wooden rod (made up of three lengths of 2.2 m, for ease of transportation) was prepared and perforated at preselected electrode locations. (The AB lengths were evenly distributed on a 20 holes/decade logarithmic scale between AB=500 mm and 6400 mm, and holes for three different MN distances, MN =100, 200 and 500 mm, were made, too.) At larger distances, traditional cable markers were used, still with 20 AB distances/length decade.

Soundings were carried out at different directions. Only a small difference was observed between the sounding curves, indicating that horizontally stratified layers can be assumed. Therefore we simply took the arithmetic mean of sounding curves measured in two perpendicular directions. Such sounding curves are shown for three sites (Fertőújlak, Király-tó and Lébény) in *Figure 1*.

Inversion techniques

Geoelectric inversion is inherently ambiguous for horizontally layered problems (i.e. in one-dimensional situations). It means that an infinite set of possible horizontally layered models can give equivalent responses and these responses are the same as the field response within very small or zero errors.

We applied three different one-dimensional inversion techniques:

(1) the Zohdy method, which is an automatic linear transformation of the apparent resistivity curves into the depth–resistivity domain, based on the morphological properties of apparent resistivity sounding curves [ZOHDY 1989]. Its main limitation comes from the fact that the layer thickness is assumed to increase logarithmically with increasing depth;

(2) a least-squares inversion technique, in which a small number of homogeneous layers are considered [JOHANSSON 1975]. From such an approach we

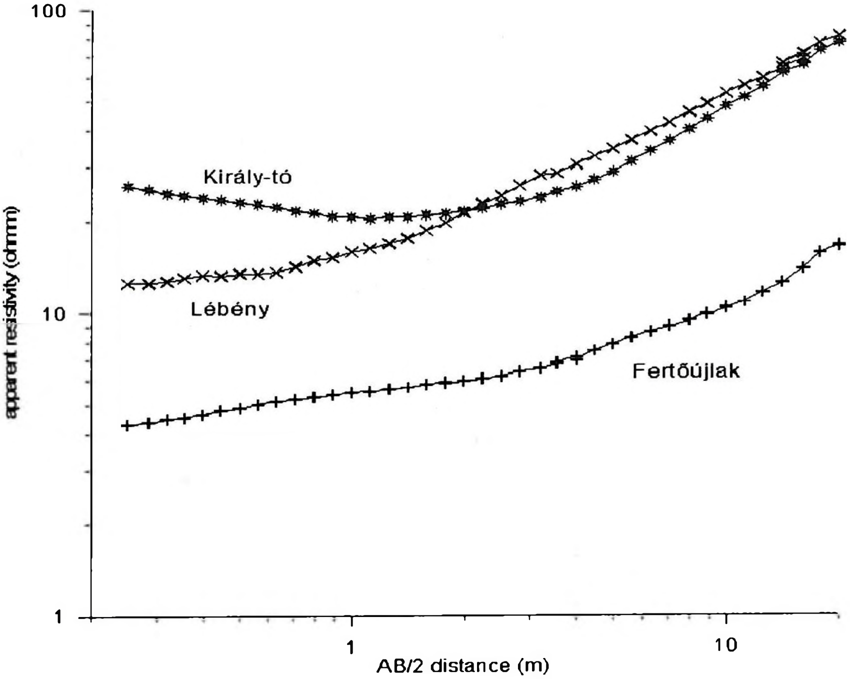

Fig. 1. Schlumberger resistivity sounding curves (mean values of two perpendicular directions, used in the geoelectric inversion) at Fertőújlak, Király-tó and Lébény

1. ábra Vertikális elektromos szondázás (azaz az inverzióhoz felhasznált, két merőleges irányban kapott szondázási görbe átlaga) Fertőújlakon, a Király-tónál és Lébény mellett can expect that the most pronounced layers, or layer-sets, can be distinguished from each other;

(3) the stochastic Bayesian inversion elaborated by SCHOTT et al. [1999], which considers smooth models, digitized over a large number of thin layers of fixed thickness; the variable parameters are the layer resistivities. The results are the a posteriori marginal laws of the parameters over a priori preselected resistivity ranges.

Laboratory measurements on the core samples

The drillholes were deepened by using a manual drilling set. The core samples with a diameter of 5 cm were collected in about 50 cm long sections. They were immediately sealed from the air and the measurements were carried out later in the laboratory of the University of Orsay. For further investigations 22 mm x 22 mm x 22 mm standard perspex cubes were pushed into the sediment. The susceptibility and the water content were measured using standard methods; for the susceptibility a Bartington MS–2 susceptibility meter was used. The electric resistivity of core samples was measured by using a new, self-made technique (a detailed description is given in the Appendix.)

3. Results

Figures 2, 3, and *4* present observed morphological and measured physical (susceptibility, water content, and electrical resistivity) core properties for the three sites, viz. Fertőújlak, Király-tó and Lébény. Results of the inversion

Fig. 2. Lithological and physical properties of near-surface layers at the Fertőújlak site. From left to right: (a) observed lithology of the core; measured variations of physical parameters along the core: (b) susceptibility, (c) water content, and (d) electrical resistivity; resistivity profiles deduced from the inversion of the Schlumberger sounding curves given in Figure 1 using three one-dimensional inversion techniques: (e) Zohdy [ZOHDY 1989], (f) least-square fitting with a few-layers model, and (g) stochastic Bayesian method [SCHOTT et al. 1999]

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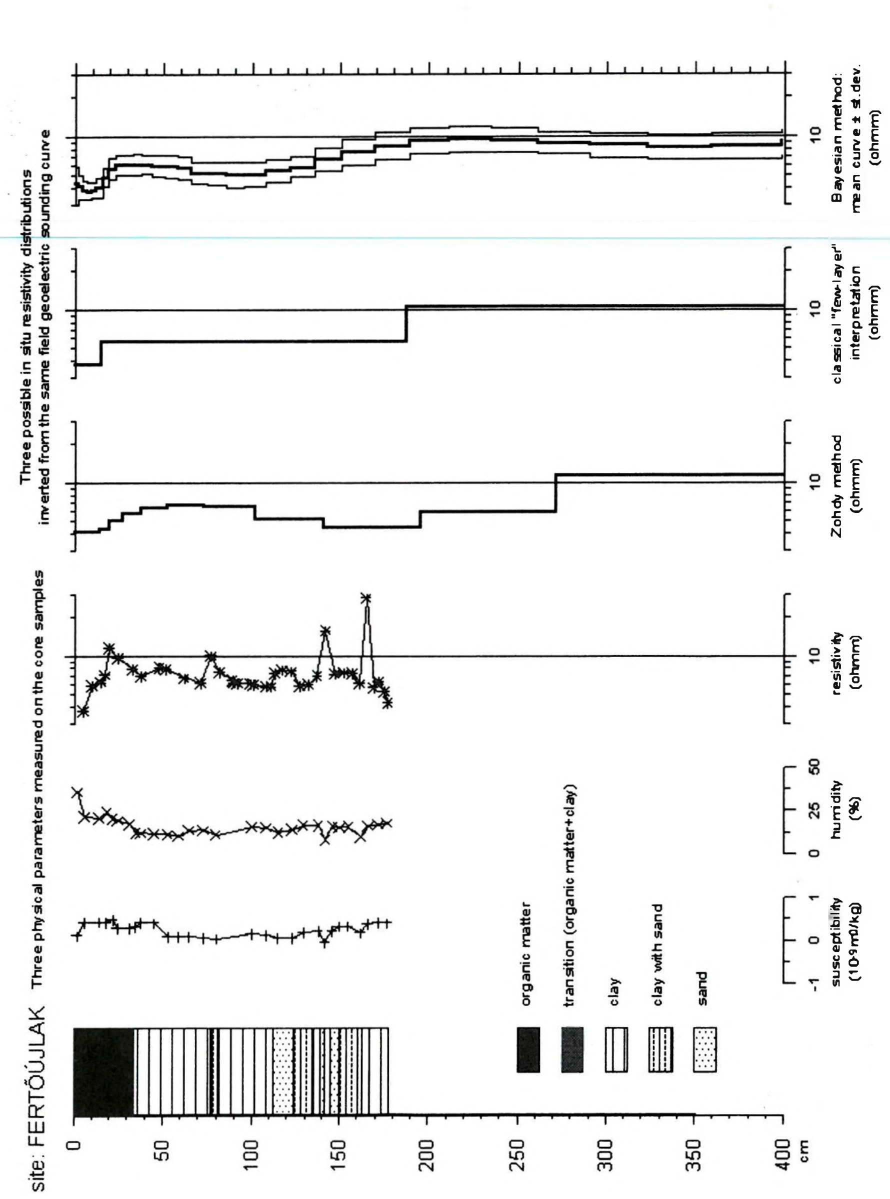
2. ábra. A fertőújlaki mérési hely felszínközeli rétegeinek litológiai és fizikai tulajdonságai. Balról jobbra: (a) fúrómag litológiai szelvénye; majd a fúrómagban mért három fizikai paraméter-szelvény: (b) szuszceptibilitás, (c) víztartalom, és (d) elektromos fajlagos ellenállás; s ezután az 1. ábrán bemutatott vertikális elektromos szondázási görbékből nyert fajlagos ellenállás-mélységszelvények, három egydimenziós inverziós eljárás alkalmazásával: (e) Zohdy-eljárás [ZOHDY 1989], (f) néhány réteges modellt szolgáltató legkisebb négyzetes illesztés, és (g) sztochasztikus Bayes inverzió [SCHOTT et al. 1999]


site: FERTŐÚJLAK
Three physical parameters measured on the core samples
Three possible in situ resistivity distributions inverted from the same field geoelectric sounding curve
0
50
100
150
200
250
300
350
400
cm
organic matter
transition (organic matter+clay)
clay
clay with sand
sand
-1
0
1
susceptibility (10-9 m3/kg)
0
25
50
humidity (%)
10
resistivity (ohmm)
10
Zohdy method (ohmm)
10
classical "few-layer" interpretation (ohmm)
10
Bayesian method: mean curve ± st.dev. (ohmm)

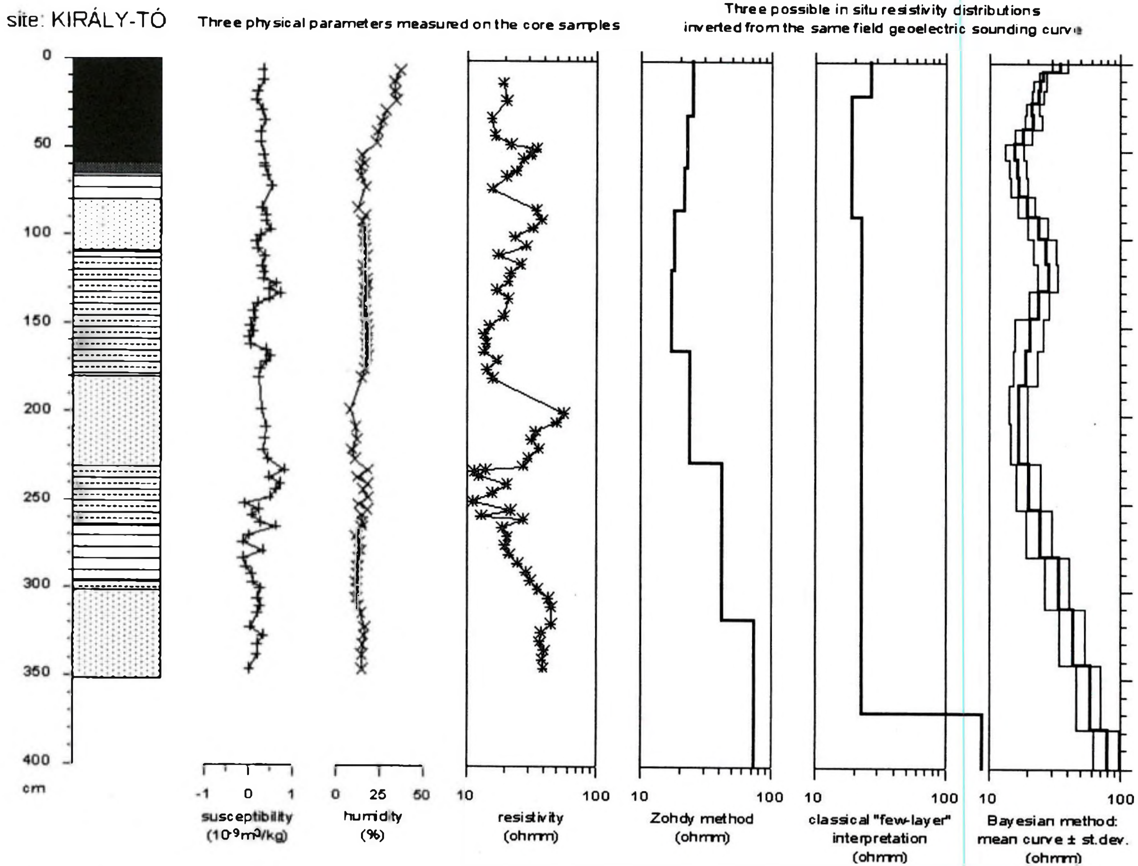


Fig. 3. Lithological and physical properties of near-surface layers at the Király-tó site (see Figure 2 for further details).
3. ábra. A Király-tavi mérési hely felszínközeli rétegeinek litológiai és fizikai tulajdonságai. (A részleteket ld. a 2. ábra aláírásában)

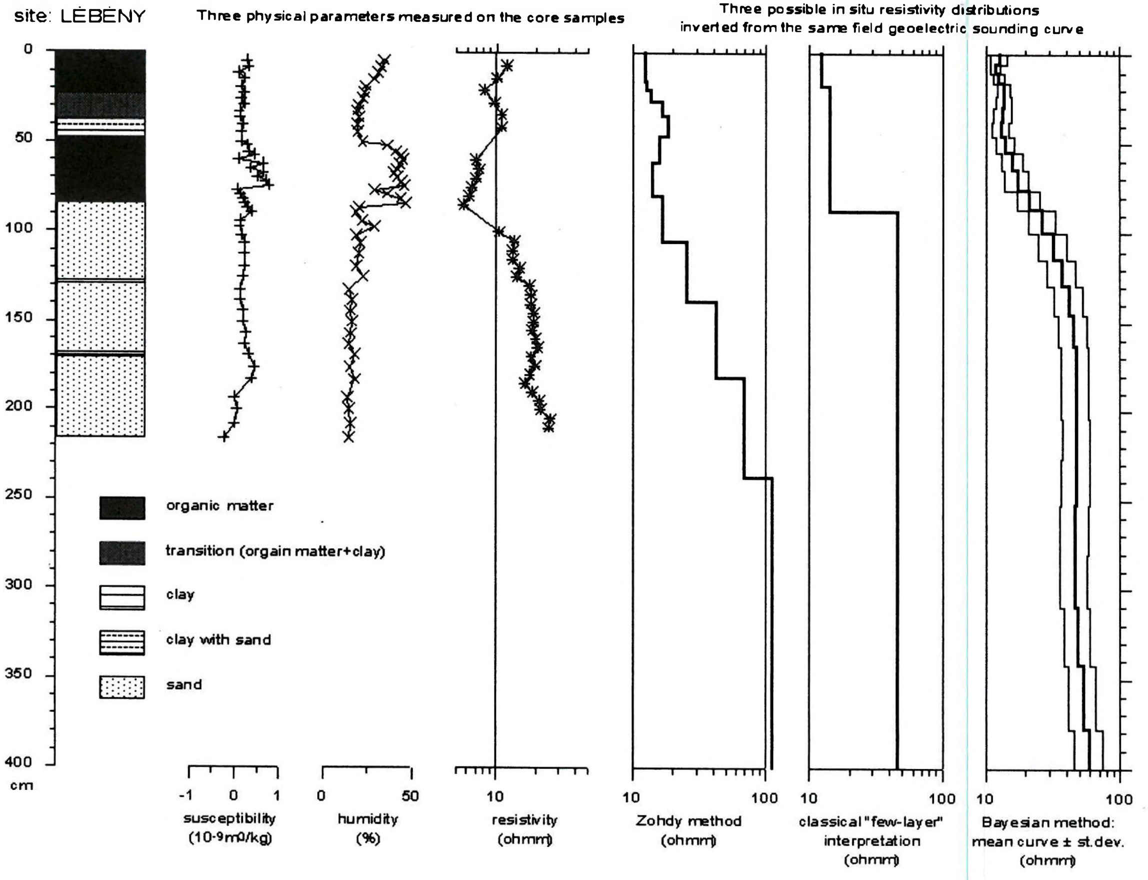


Fig. 4. Lithological and physical properties of near-surface layers at the Lébény site (see Figure 2 for further details).
4. ábra. A lébényi mérési hely felszínközeli rétegeinek litológiai és fizikai tulajdonságai. (A részleteket ld. a 2. ábra aláírásában)

of the Schlumberger sounding curves (shown in Figure 1), using the three aforementioned one-dimensional inversion techniques (Zohdy, least-squares fitting, and stochastic Bayesian methods), are also presented in these figures.

The inversion results are given to a depth of 4 m, which is greater than any of the drillhole depths. At each site, the three resistivity–depth profiles obtained are actually quite different, thereby giving a clear illustration of the non-uniqueness of the inverse problem. Their mean values are, however in good agreement with the measured core resistivity values, though all the details of the measured core resistivity profiles are not seen in the inverted profiles. This filtering out is expected either because the effect of very thin and relatively deep layers is too small to be observed, or because some changes in the core sample resistivity values might correspond to very local inhomogeneities and not to realistic layers.

For Fertőújlak the near-surface resistivity increase in the upper part of the layer of organic origin (between 0–25 cm) can be seen in all three inversion results, but the resistivity decrease observed just below it (between 25 cm and 50 cm) cannot be seen in any of them. The deeper and small resistivity changes are not detectable, either.

For Király-tó the detailed resistivity structure of the uppermost 100 cm cannot be seen from the Schlumberger sounding, though the resistivity decrease in the upper 50 cm, as well as the resistivity increase below 250 cm, is visible on all three inversion results.

For Lébény the core sample resistivity profile and the Zohdy resistivity profile run nearly parallel. A resistivity decrease between 30 and 40 cm, followed by a resistivity decrease between about 60 and 80 cm can be equally well seen. The classical inversion assuming a few layers does not allow one to detect it —, with the exception of some resistivity change at a depth of about 20 cm. The Bayesian inversion gives some weak indication about this resistivity change, but it takes place at somewhat shallower depths than where it was actually observed on the core. It is, however, worth noting that the uncertainty of the resistivity determination provided by the Bayesian inversion is of the same order as the measured resistivity variation, thus indicating that it is not possible to get clear evidence of it from inversion. At the same time, the organic matter/sand layer boundary at a depth of 85 cm can be seen perfectly in the classical interpretation. Given the already mentioned non-uniqueness of the solution of the inverse problem, this result would have been difficult to interpret in the absence of direct measurements on the core.

4. Conclusion

The results from the three sites dealt with allow one to discuss the subsurface resolution of high-precision Schlumberger soundings in conditions, in which there is no one-to-one correlation between the lithology and the physical parameters (magnetic susceptibility, water content, electric resistivity) of the core. It is evident that local resistivity heterogeneities and very thin layers cannot be resolved from the surface by using any geophysical methods. Nevertheless, significant changes in the resistivities of well-developed layers, or even progressive resistivity changes can be detected from the surface by using precise Schlumberger soundings. For the first problem (correlation of lithology and physical parameters) the classical few-layer inversion techniques are preferable whereas the latter problem (inability of geophysical methods to interpret resistivity heterogeneities) can only be resolved by inversion methods, allowing smooth layer transitions. A combination of different inversion techniques and sometimes direct comparison with measurements on the core provide a useful aid in understanding the subsurface resistivity distribution.

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Appendix
Core sample resistivity measurements

The electric measurements were carried out by using a special, small-sized, four-electrode (*AMNB*) system, connected to the field instrument and simulating a Wenner sounding on the centimetre scale. The *AM, MN*, and *NB* distances were equal to 2 cm, and — in order to have good contact with the matrix — each of the electrodes had a length of 20 mm and a diameter of 2 mm. The $R = \Delta U/I$ electric resistance values were measured along the cores at every 5 cm, applying the smallest possible current intensity. For the computation of apparent resistivities from these resistance values, instead of a theoretical determination of geometrical coefficient for electrodes penetrating into a cylinder, a physically-based correction factor was used as follows.

In the first step of the physical correction, detailed resistance measurements were carried out with the field equipment along three parallel profiles of a more or less homogeneous core sample. The arithmetic mean of all measurements was found to be 62.3 Ωm, with a standard deviation of 1.1 Ωm. In the second step of the correction, large sheet electrodes were connected to the ends of a 26 cm long section of the same core sample, and the potential differences due to the current flowing along the core sample were measured in the central section of the sample by using different *MN* distances. The measured resistance values ($R = \Delta U/I$) were found to be proportional to the *MN* lengths, as had been expected from the following form of the differential Ohm's law: $R = \rho_c\ MN\ /\ A$, where A is the cross section of the sample. In our case A was 15.9 cm^2. The specific resistivity of the core was then directly obtained from the above equation. For the selected core sample we found $\rho_c = 6.98$ Ωm. This means that to transform all $\Delta U/I$ resistance values into resistivity values the correction factor in our case was 6.98 Ωm / 62.3 Ω = 0.112 m (within 2 % of error). In order to avoid any confusion either with results of direct resistivity measurements or with apparent resistivity ρ_{app}, this transformed resistivity ρ_c is denoted as 'core resistivity' throughout the paper.

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A vertikális elektromos szondázás felbontóképesssége felszínközeli mérések esetén

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Nagy geometriai pontossággal (20 adat/dekáddal; az *AB*=6,4 m-nél kisebb tápelektróda távolság esetén mindössze mm-nagyságú geometriai hibával) végzett vertikális elektromos szondázás felszínközeli rétegekre vonatkozó felbontóképességét a felszíni geoelektromos- és a magminta-eredmények közvetlen összehasonlításával szemléltetjük. Három különböző egydimenziós inverziós eljárást használtunk: a klasszikus legkisebb négyzetes kiegyenlítés módszerével néhány vízszintes réteget szolgáltató megoldást, a Zohdy-eljárást és a sztochasztikus Bayes-módszert. Mindhárom eljárás eredménye nagyobb hasonlóságot mutat a folyamatosan vett fúrómagon mért fizikai paraméter-szelvényekkel (az elektromos fajlagos ellenállással, a víztartalommal és a mágneses szuszceptibilitással), mint a fúrómagon szemmel megfigyelhető litológiai változásokkal. Helyi inhomogenitások és nagyon vékony rétegek a felszínről nem mutathatók ki, de a jól kifejlett réteghatárok és a rétegződés folyamatos változásai megjelennek a különböző inverziós eredményekben.

ABOUT THE AUTHORS

Franz Kohlbeck (1943, Vienna) graduated Dipl.-Ing. (physics) from the Vienna University of Technology in 1969. He was then offered a post at the Institute of Mechanical Technology and Engineering Material Sciences. At the same time he started his dissertation work at the Reaktorzentrum Seibersdorf (now: Seibersdorf research centre). In 1974 he was awarded his Ph.D. for his work on calculating cell-dimensions from d-values of powder diffraction patterns. With a view to carrying out research on rock mechanics, in 1975 he returned to the Vienna University of Technology. He was appointed docent for Engineering Geophysics in 1981. Since then, he has worked mainly on environmental geophysics, particularly on geoelectrics. On two occasions, he was an invited Professor at the National University of Bogota, Colombia. From 1991 to 1993 he headed the department of Geophysics of the Institute of Theoretical Geodesy and Geophysics; he has been professor since 1994.

László Szarka (1954, Derecske) graduated in 1977 as geophysical engineer from Miskolc University. Since that time he has carried out research work in the field of electromagnetic geophysics at the Geodetic and Geophysical Research Institute of the Hungarian Academy of Sciences, in Sopron. Currently, he is scientific adviser and head of the electromagnetic department. He became D.Sc. (earth sciences) in 1997. After a habilitation at Miskolc University, he was nominated head of the Geoscience Institute of Sopron University (now: University of Western Hungary). Between 1997 and 1999 he worked as part-time associate professor at the University of Orsay (Université Paris Sud XI).

Alina Jelinowska, geologist-geophysicist, graduated in 1985 from the University of Warsaw (Poland); she was awarded her postgraduate diploma at the University of Orsay, in 1988. Her Ph.D. thesis dealing with the magnetic properties of lake sediments as indicators of palaeoclimatic and environmental evolution in continental Quaternary sections was awarded in 1995 by the same university. She holds the title Maitre de Conferences at University of Orsay; her major research interests cover magnetic mineralogy in sediments and its relationship with environmental parameters. Recent works of hers has dealt with Caspian and Black Seas sediments and east-European Upper Quaternary sequences.

Michel Menvielle (1951, Paris) graduated as an engineer at the Ecole Centrale de Paris, France, in 1974. He joined the Institut de Physique du Globe de Paris. In 1984, his These d'Etat was awarded for his work on electromagnetic induction. He is now a professor at the University of Orsay, and belongs to the C.E.T.P. (Centre d'étude des Environnements Terrestre et Planétaires, Saint Maur, France). His work deals with the study and characterization by indices of transient magnetic activity observed at the Earth's surface, and with the application of induction methods to determining the electric structure of the solid Earth using a Bayesian approach. More generally, he is interested in using surface magnetic measurements for understanding inner and outer planetary structure and dynamics; in particular, he is involved in magnetic experiments on board Mars landers.

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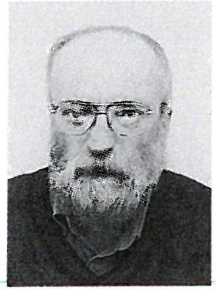

Piotr Tucholka graduated in 1970 at the Department of Geology, University of Warsaw (Poland), specializing in geophysical well-logging. He worked (1970–79) at the Polish Academy of Sciences in Warsaw, Poland, obtaining his Ph.D. for his work on the palaeomagnetic study of loess sequences. From 1979 to 1983 he was Leverhulme and N.E.R.C. Research Fellow at the University of Edinburgh (Scotland) where he worked on the magnetism of lake sediments and palaeosecular variation of the Earth's magnetic field. Since 1985, he has been professor at the University of Orsay, France. At present, his main research topics include palaeomagnetism and the palaeoenvironment, and the application of shallow geophysics to environmental problems.

Viktor Wesztergom (1959, Mosonmagyaróvár) studied geophysics at the Eötvös Loránd University in Budapest, graduating in 1983. From 1983 to 1986 he worked at the Eötvös Loránd Geophysical Institute. He also qualified at Budapest's University of Economics. In 1995, he was awarded his Ph.D. Since 1986 he has been at the Geodetic and Geophysical Research Institute of the Hungarian Academy of Sciences. His main research topics are the geomagnetic field of external origin and geomagnetic induction. In addition to his research work, he is the head of Geophysical Observatory István Széchenyi near Sopron and editor of Acta Geodaetica et Geophysica Hungarica.