Applicability of RMT, VES and Dual Loop EM for the mapping of a Quaternary buried valley in the area "Heiliges Feld" (NRW, Germany)

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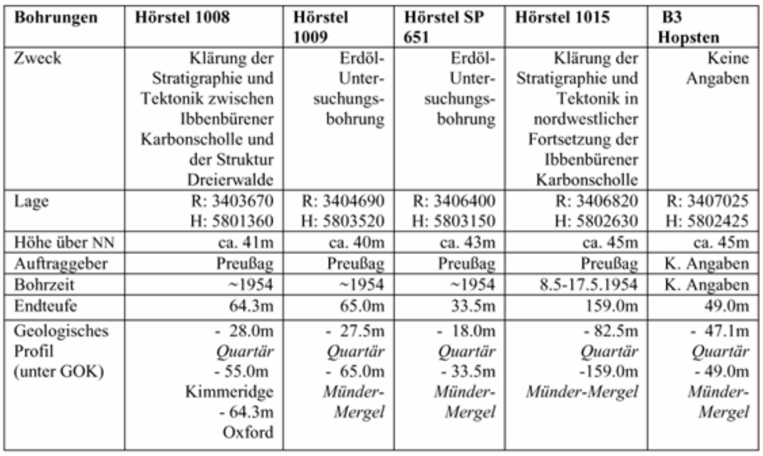
Introduction

Investigating aquifer systems of glacial buried valleys as potential sources for groundwater catchment areas is of actual interest in several scientific projects in northern Europe (Huuse et al. 2003) including northern Germany (Gabriel et al. 2003). This paper presents first results of a recent geophysical survey carried out by the Institute for Geophysics of the University of Münster (Germany) in an area called “Heiliges Feld” northwest of Ibbenbüren (North-Rhine-Westphalia, Germany).

Table 1: Borehole information in the area "Heiliges Feld" (from Thiermann (1975))



Bohrungen	Hörstel 1008	Hörstel 1009	Hörstel SP 651	Hörstel 1015	B3 Hopsten
Zweck	Klärung der Stratigraphie und Tektonik zwischen Ibbenbürener Karbonscholle und der Struktur Dreierwalde	Erdöl-Unter-suchungs-bohrung	Erdöl-Unter-suchungs-bohrung	Klärung der Stratigraphie und Tektonik in nordwestlicher Fortsetzung der Ibbenbürener Karbonscholle	Keine Angaben
Lage	R: 3403670 H: 5801360	R: 3404690 H: 5803520	R: 3406400 H: 5803150	R: 3406820 H: 5802630	R: 3407025 H: 5802425
Höhe über NN	ca. 41m	ca. 40m	ca. 43m	ca. 45m	ca. 45m
Auftraggeber	Preußag	Preußag	Preußag	Preußag	K. Angaben
Bohrzeit	~1954	~1954	~1954	8.5-17.5.1954	K. Angaben
Endteufe	64.3m	65.0m	33.5m	159.0m	49.0m
Geologisches Profil (unter GOK)	- 28.0m *Quartär* - 55.0m Kimmeridge - 64.3m Oxford	- 27.5m *Quartär* - 65.0m *Münder-Mergel*	- 18.0m *Quartär* - 33.5m *Münder-Mergel*	- 82.5m *Quartär* -159.0m *Münder-Mergel*	- 47.1m *Quartär* - 49.0m *Münder-Mergel*

In this area, Quaternary deposits (sands and silts) cover lower Cretaceous/ Jurassian marls (“Münder Mergel”), a sequence of marl- and clay stones with interlaced anhydrite and gypsum benches followed by rock salt (Lotze 1956; Thiermann 1975; Weinert 1999). A particularity of this region is a number of several lakes oriented on a NE-SW striking axis. These lakes were caused by subsurface collapses due to dissolution processes in the Jurassian layers. Some collapses occurred in quite recent times i.e. the so called “Erdfallsee” in the year 1913.

This survey aims to estimate the applicability of several electromagnetic geophysical methods to successfully map the subsurface with regard to the following general geological/ hydrogeological points of interest:

- Mapping of the Quaternary basis (QB) to delineate the dimension of the porous aquifer system
- Estimating the possibilities of groundwater quality mapping (brines)
- Delineation of future collapse regions

The current map of the QB extension (Figure 1) is based on some few drill holes (Table 1) showing a varying QB depth from 25 to 83 m beneath the surface

(Thiermann 1975). The punctual in-situ information from the wells is extensively distributed on a large area. To provide additional useful geophysical information, the applied methods have to be both able to survey quickly large areas and to investigate the QB at least to a depth of about 90 m.

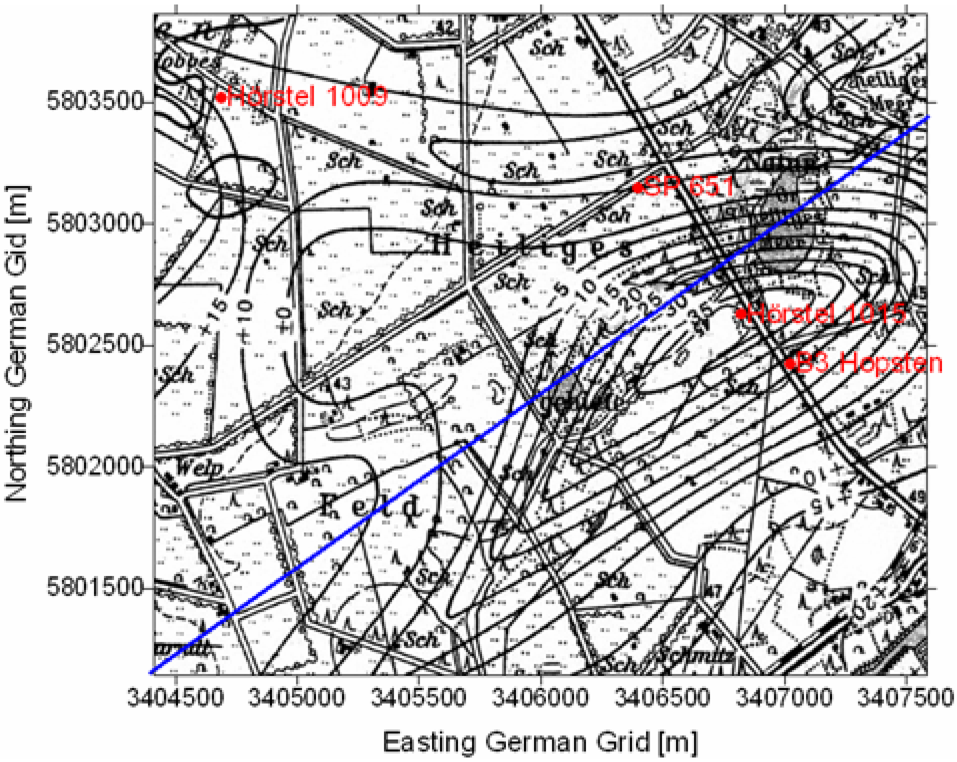


Figure 1: Depth of Quaternary basis in meter below sea level (normal null) after Thiermann (1975). The blue line indicates the "lake axis".

Applied methods and equipment

The drillings show a significant change in the electrical resistivity at the QB. Furthermore, the degree of the groundwater mineralization varies in the different parts of the survey area (Weinert 1999). Therefore, DC and AC electromagnetic methods have been chosen to investigate this area.

Vertical Electric Sounding (VES) has been applied in order to reach the QB at greater depth in the centre of the buried valley. An ABEM Terrameter SAS 300 (3 W, 320 V) with optional use of the SAS 2000 Booster (40 W, 800 V) was used, which enables to induce currents between 0.2–20 mA or 50-500 mA respectively. Schlumberger configuration with maximum current electrode spacing of 1000 m was applied. Twenty-one soundings have been carried out in the area along distinct profiles (Figure 2). Results from two NW-SE profiles with a station interval of about 1000 m are displayed in Figure 3. The apparent resistivities have been inverted with Bobachev's 1D-inversion Program IPI2Win (Bobachev 2002).

The ***Radiomagnetotelluric (RMT)*** method was additionally applied in order to use a resistivity sounding method which provides very quick measurement progress. An investigation depth of about 50 m has been expected in that survey area.

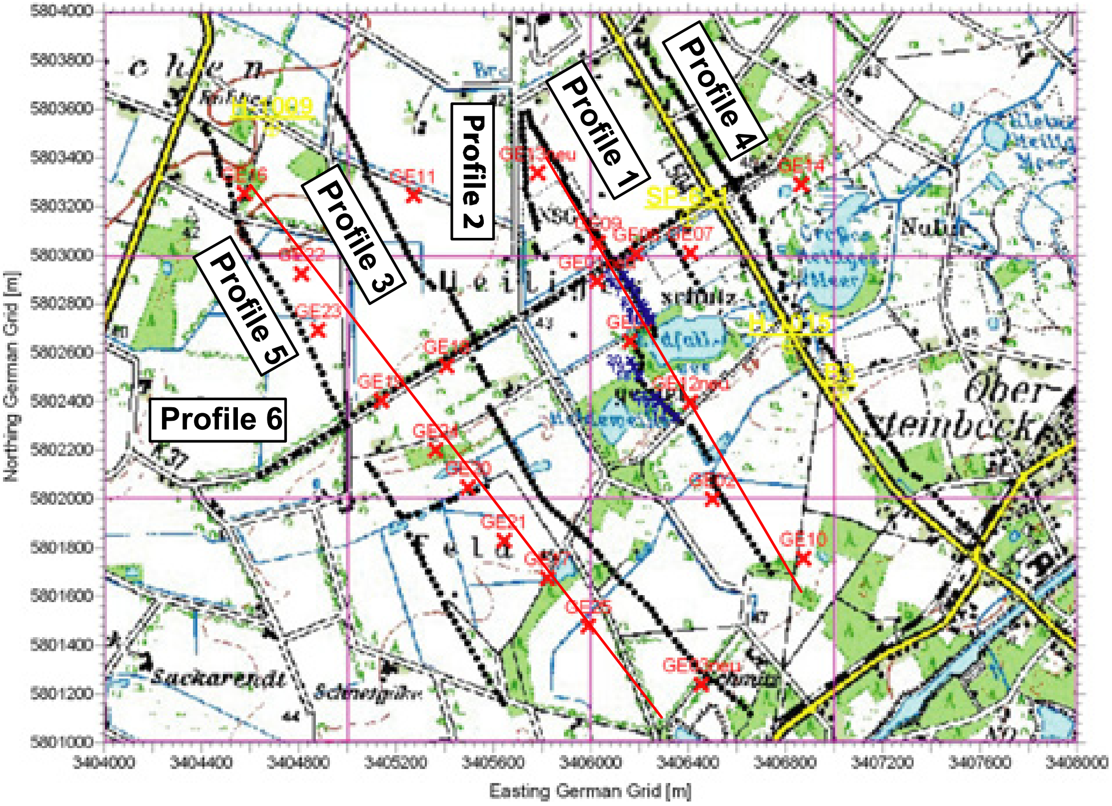


Figure 2: Locations of the different surveys: Red crosses with labels indicate the VES soundings along the East- and West-profile, black dots indicate the RMT sites (profile 1-6) and blue crosses indicate the HLEM stations. The borehole locations are labeled in yellow.

482 RMT soundings have been carried out (Figure 2) during seven days of field work using a scalar prototype device (Bosch & Müller 2005) developed at the Centre of Hydrogelogy Neuchâtel (CHYN, University of Neuchâtel, Switzerland). Four radio-transmitters sending from northwestern directions were used: 207 kHz (130°N), 81 kHz (105°N), 37.5 kHz (130°N) and 19.6 kHz (115°N). The station interval is about 50 m and was sometimes reduced down to about 25 m. The sounding curves have been inverted with Bobachev's 1D-inversion program IPI2Win(MT).

A ***horizontal loop electromagnetic (HLEM)*** prototype system developed at the CHYN was tested as a faster alternative to VES in order to provide comparable investigation depths while using much smaller setup geometry in the field.

The system provides Inphase and Quadrature component of the vertical secondary to primary field ratio for 9 frequencies between 7040–27.5 Hz. Parametric and geometric soundings are possible. For 9 frequency/ distance pairs, the device provides directly apparent conductivity according to the low induction number case (McNeill 1980).

We present a profile of 16 frequency soundings with a transmitter-receiver separation of 56.57 m. The station interval is about 50 m. The sounding curves have been inverted with the 1D-inversion program EMMIX MMp from Interpex.

Main Results

Vertical electrical soundings (VES)

Figure 3 shows the pseudo cross sections and the inverted resistivity cross sections of the two VES profiles. The fit of the inversions varies between 0.4 % and 5 %. The "East-Profile" might indicate some kind of valley structure

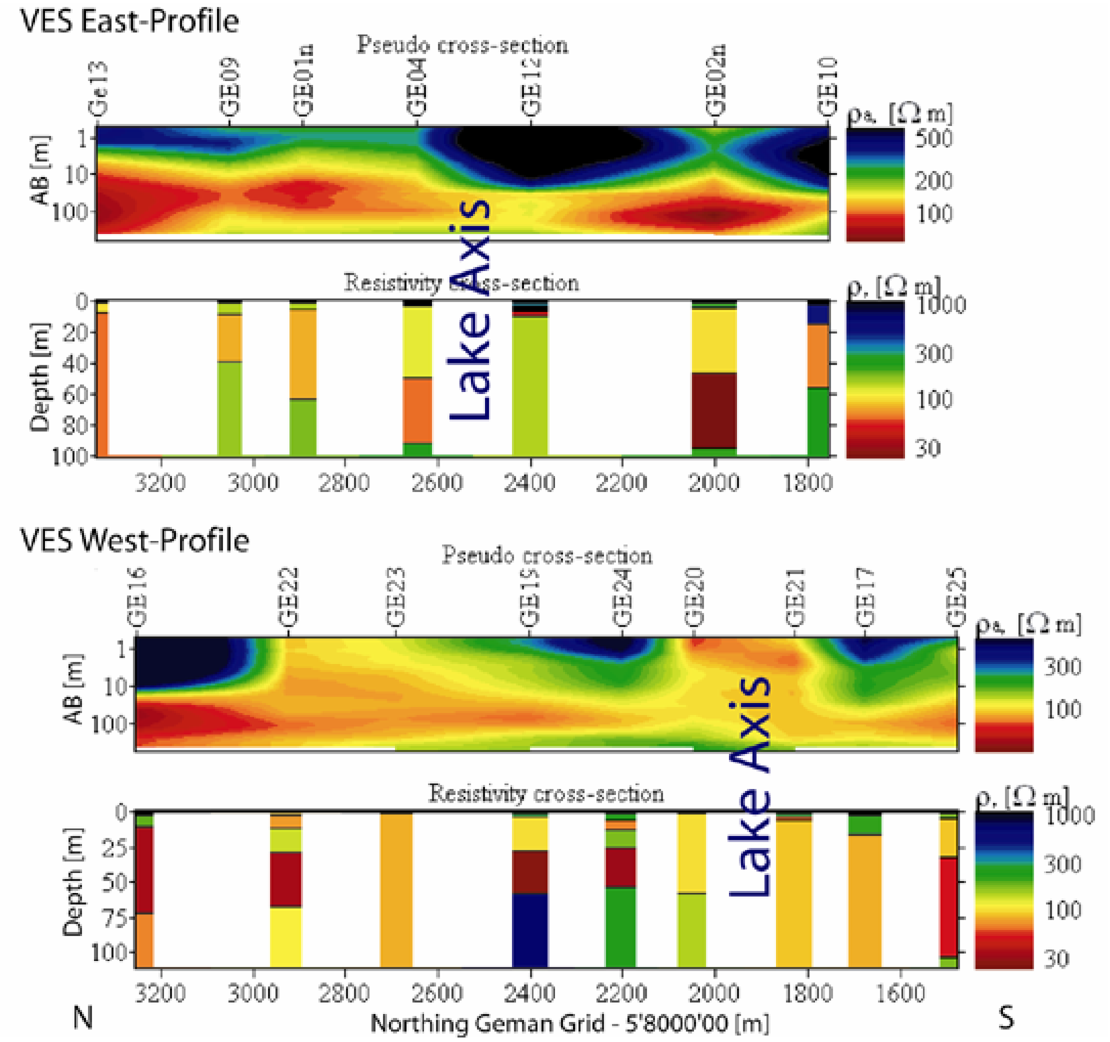


Figure 3: VES results: pseudo sections (left corner North) of apparent resistivity against current electrode spacing and 1D inversion models. Depth scale is in depth beneath surface.

marked by the increasing thickness of the resistive top layers (100-100 Ωm) over a prominent conductive layer (30-50 Ωm) from north towards the "lake axis". Under the conductive layer a more resistive half space (200-300 Ωm) is visible. According to the available borehole data in Table 1 this conductive layer might represent the change from the Quaternary sediments to the "Münder Mergel" (lower Cretaceous/Jurassian marls). Therefore, the top of the conductive layer can indicate the basis of the Quaternary sediments. South of the "lake axis", the thickness of the resistive top layers decreases and therefore the depth of the conductive layer. If a specific symmetry of the buried valley is assumed, then VES-station GE12 is located somewhere in the centre of the valley. This station does not show this conductive layer. That might either be due to the fact, that this layer is simply too deep to be detected at this location or the stratigraphic properties are different in that region.

According to the latter, one has to consider, that the area of the lake axis is the zone of subsurface collapses, which produced the lakes.

The inverted data of the "West-Profile" do not show a valley structure evidently. The most prominent feature of this profile is the missing of the conductive layer at VES-station GE23 and at the three stations around the lake axis. Unfortunately, it was not possible to place VES-stations in the vicinity of a drilling for calibration purposes.

Radiomagnetotelluric (RMT)

The four resistivity cross-sections (Figure 4) gained from the inversion of the RMT data (apparent resistivity and phase) provide a consistent image for the different profiles. All profiles feature a resistive top layer of about 100 to 200 Ωm with varying thickness covering a more conductive half space with a specific resistivity of ≤ 50 Ωm, while this interface is interpret as the QB. Therefore, the RMT results show the same general behavior as the VES results at the comparable depth scale, but with higher lateral resolution. The thickness variations of the top layer imply a valley structure. Due to the limited penetration depth, the RMT data cannot delineate another layer under the conductive one. In some regions, the interface of the two layers is not visible, but the resistive layer represents the half space. The interpretation is the same as for the VES data: either the conductive layer starts at depths, which are not reachable for the method anymore or it does not exist in that region.

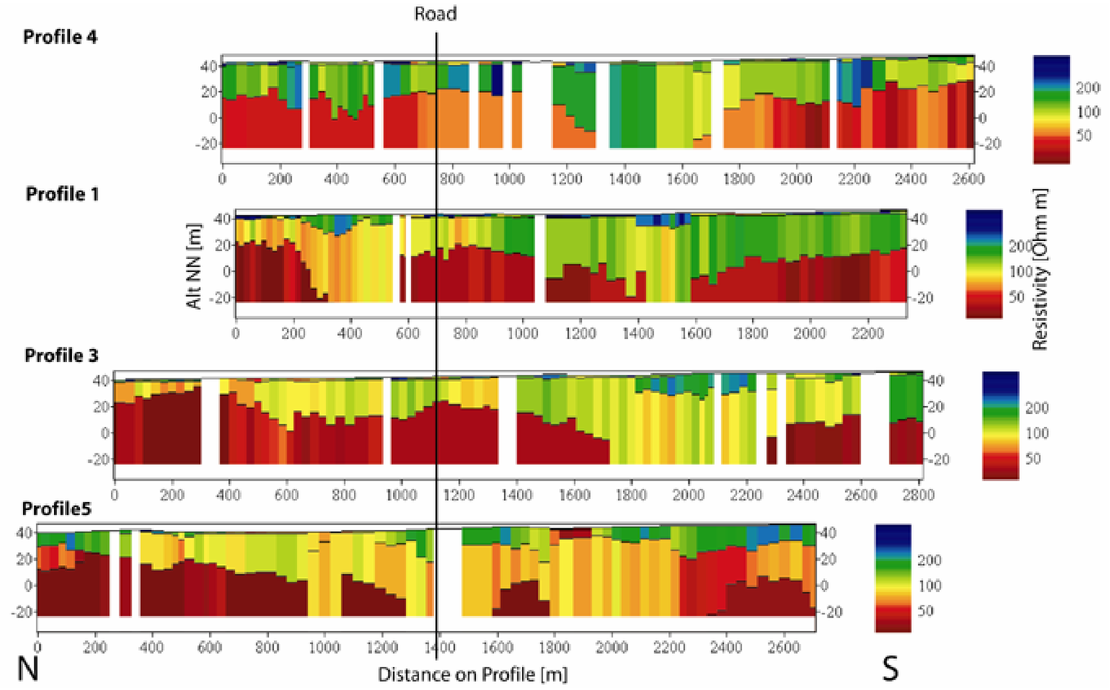


Figure 4: RMT resistivity cross sections obtained from 1D inversions. Depth scale is in "Altitude above sea level" (normal null).

As a matter of fact, all regions of increased resistive top layer thicknesses coincide with regions of observed collapses (Lotze 1956). Furthermore, the RMT inversion results can be compared with the borehole logs very well due to their vicinity to the profiles. The interface between the resistive top layer and the conductive half space at RMT stations near to boreholes coincide within ± 2 m with the depth of the drilled QB. Particularly, the steep slope on RMT-Profile 4 between profile meter 1400 and 1690 is validated by the boreholes H-1015 (-82.5 m beneath surface) and B3 (-47.1 m beneath surface) respectively (Figure 4, Figure 5 and Table 1). Figure 5 provides a map of the QB depths obtained from RMT inversion models. The depths are given in altitudes above sea level (ASL). Regions deeper than -20 m ASL are blanked because these depths have not been resolved by the RMT data in this case study.

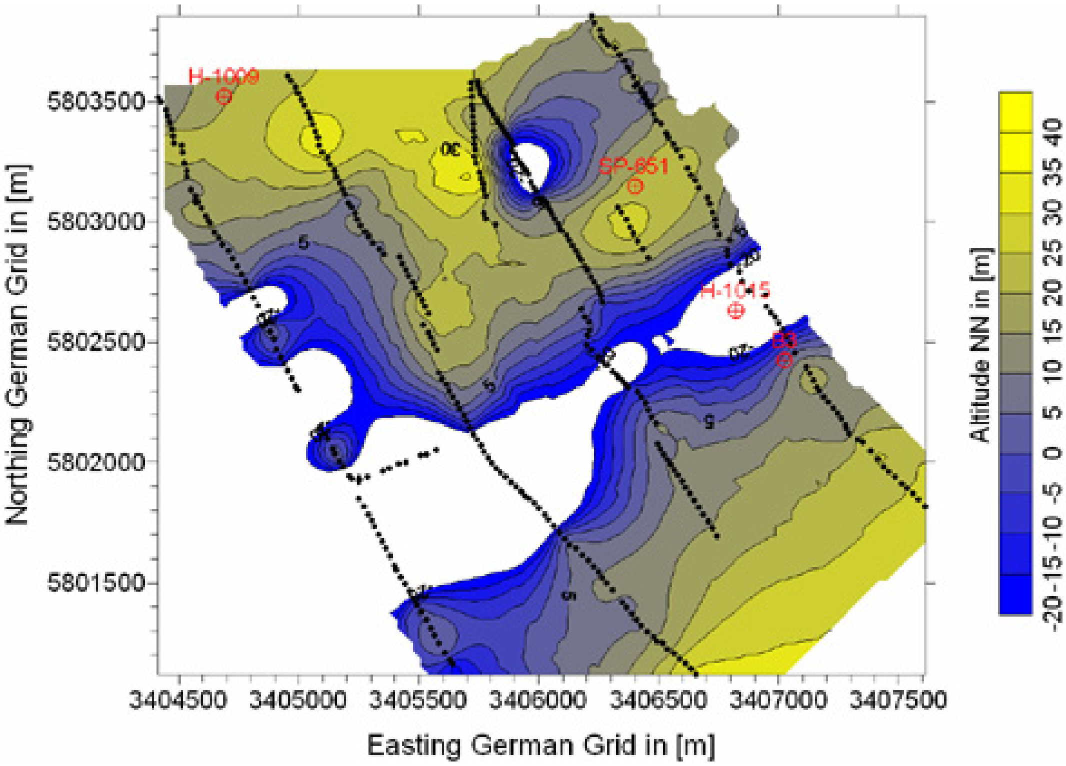


Figure 5: Map of Quaternary basis obtained from RMT inversions. Black dots indicate RMT station locations. Borehole locations are in red. Color code for depth is in altitude above sea level (normal null).

Horizontal Loop Electromagnetic (HLEM)

The HLEM data have been sampled on the central part of RMT-Profile1 in order to map the flanks and the central part of the buried valley (Figure 2). The inphase and quadrature raw data in Figure 6 show only significant lateral variations for the three highest frequencies. The resistivity cross section obtained from 1D inversions in Figure 7 shows models of the general type already obtained from VES and RMT data: a resistive top layer (500 - 1000 Ωm and varying thickness), a conductive layer (10 - 30 Ωm and generally about 10 m thick) and a resistive half space (100 - 250 Ωm).

From profile meter 800 to 1100, the increasing depth of the top of the conductive layer in the HLEM models coincides with the RMT models. Beyond 1100 meter they do not. Particularly remarkable is the fact that the conductive layer stays at about 20 meters depth beneath the surface in the central part of the buried valley, which definitely does not fit to the VES and RMT inversion models and the borehole information about the QB. This behavior might be due to the fact, that the chosen coil separation of 56.57 m is not adequate to the depth of the target in that region and must be greater instead. Furthermore, the HLEM inversion results are strongly depending on the starting model, which is not the case for VES and RMT. Therefore, in this case study HLEM cannot be considered as an alternative to VES in order to combine great information depth as obtained with VES and high lateral resolution due to short station distance as provided by RMT.

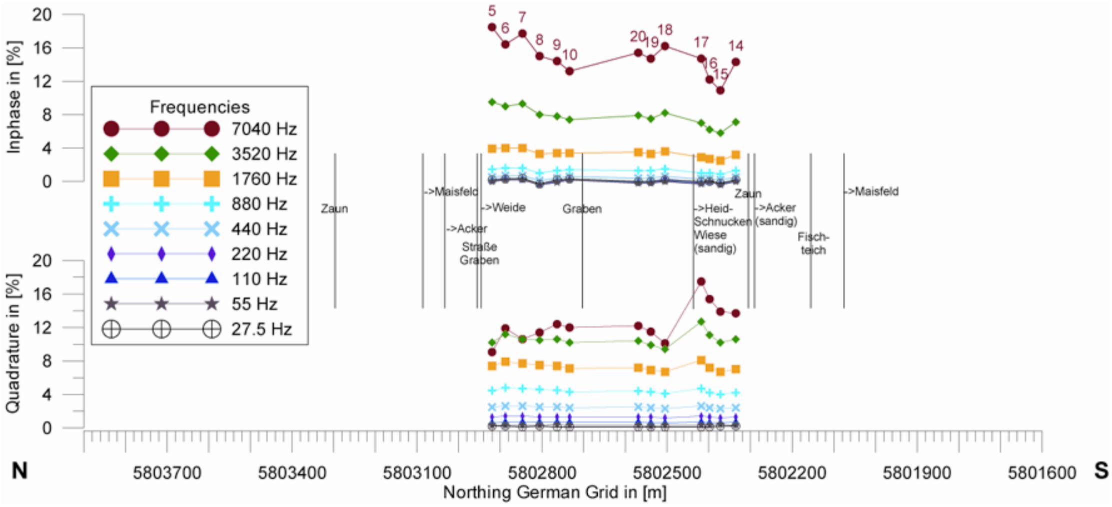


Figure 6: HLEM raw data: Iphase and Quadrature component for different frequencies.

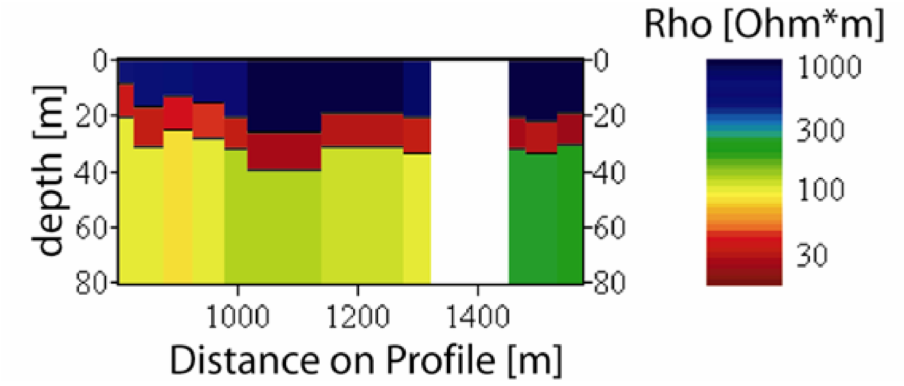


Figure 7: Resistivity cross section from 1D inversion of HLEM data on central part of Profile 1.

Summary and Conclusions

Compared to the geological map after Thiermann (1975) in Figure 1, the knowledge about the distribution of the Quaternary basis (QB) can be refined. The shape seems to be more complex than formerly known. Due to the RMT findings, the deepest extension follows along south of the "lake axis". An additional prominent deepening exists in the North. Further small QB depressions are located near to or at areas of geologically mapped collapses (Lotze 1956; Thiermann 1975). This might offer the possibility of delineating yet unknown collapses or even regions of risk for future collapses with RMT. Water quality mapping in terms of salinity was not done, yet.

The used maximum VES electrode separation of 1 km seems not to be sufficient in the centre of the buried valley to find the QB. Additionally, this large setup provides a logistic problem in choosing sounding locations. Consequently, no sounding is located near to a drilling. The location problem and furthermore the slow measurement progress hinders to achieve a necessary denser sounding location distance.

In this study, RMT was the most useful method to delineate the shape and the extension of the QB and therefore the buried valley so far. A large area has been covered in 7 days of field work. The QB depths coincide with borehole data, but the investigation depth is too small to detect the QB in the central part. At least the regions of greatest depth extension have been isolated. The maximum investigation depth has been about 60 m beneath the surface.

The results of testing the HLEM method as a fast alternative sounding and mapping method compared to VES was rather disappointing in this case. The inversion results have strongly been influenced by the starting model. The conductive layer used as marker for the QB is nearly everywhere at the same depth in the inversion models. Maybe keeping the coil separation fixed was not adequate for the whole profile or frequency sounding is not sensitive enough for the task? However, geometric sounding gives noisy inphase data and is much more time consuming. Another problem of the used HLEM system is that there was no chance for calibration because of missing high resistive ground of necessary thickness near to the survey area.

A better EM alternative to VES for deep sounding might be Transient Electromagnetic (TEM) and concerning high measurement progress airborne electromagnetic (AEM).

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