Evaluation of Ground Penetrating Radar and Vertical Electrical Sounding Methods to Determine Soil Horizons and Bedrock at the Locality Dehtáře

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Abstract

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Recently, geophysical methods have been widely used in many fields including pedology. Two of them, ground penetrating radar (GPR) and vertical electrical sounding (VES) were employed at the Dehtáře experimental site with the aim to evaluate their application in the Cambisol and Stagnosol soil types and crystalline bedrock survey in Czech conditions. These measurements were complemented by the classical soil survey using a gouge auger. As a result, interpreted soil and rock environment profiles were obtained, with the identification of boundaries of Bg, C, and R soil horizons and bedrock at various degrees of weathering. The interpretation of measurement records demonstrated suitability of the VES and GPR method application, using GPR for imaging the soil profile and the top of bedrock, while the VES method gave better results in imaging greater depths. The research demonstrated advantages of the geophysical methods such as instancy, continuous imaging, and no disturbance of the subsurface. In spite of needing classical survey data for interpretation of the results obtained by the geophysical methods, their usage can bring better quality to the soil profile imaging.

Keywords: geophysical method; parent rock; soil layer; soil survey

Traditional pedological survey is based on an invasive point method at selected intervals using a gauge auger and dug soil probes. In both cases, only a limited part of the soil profile is observed and, in addition, the soil is disturbed. Assessing a larger area, the obtained data must be interpolated. For this reason, geophysical methods, which provide continuous soil profile imaging, have recently gained worldwide interest (Metje *et al.* 2007; Allred *et al.* 2008). They have extensively been used e.g. in precision agriculture in recent years (Freeland *et al.* 1996; Lambot *et al.* 2008).

Soil horizons differ in their properties, both physical and chemical. The physical properties include electrical properties, and the change in electrical conductivity and permittivity of soil is the basis of the ground penetrating radar (GPR) method. This method has become more popular since the beginning of the 1960s, when GPR instruments were successfully employed during investigations in the Arctic and Antarctic (Bailey *et al.* 1964; Annan 2002). Ice was the first natural material to be explored. In the 1970s geological material started to be investigated and the method was used in the Apollo lunar program. For soil survey, the GPR was first used in Florida by Benson and Glaccum in 1979 (Doolittle & Collins 1995). Since then, the GPR has been applied in a number of disciplines such as archaeology, sedimentology, and geotechnical engineering (Mellett 1995; Collins 2008). The GPR has effectively contributed e.g. to soil classification by mapping the presence, depth, lateral dimension, and variability of subsurface horizons (Doolittle & Butnor 2009). Single soil layers differing in texture were successfully identified e.g. by Dominic *et al.* (1995) or by Boll *et al.* (1996) and Andre *et al.* (2012).

Bedrock is identifiable also using the GPR (Collins *et al.* 1989; Breiner *et al.* 2011), but it brings about more difficulties. Bedrock is rather a subject of research of geologists who often employ the geophysical method of vertical electrical sounding (VES). This method does not allow continual mapping, but measuring is in points and the continual image is created by interpretation and interpolation. Principles of this method were defined already at the beginning of the 20th century (Stefanesco *et al.* 1930; Parasnis 1972; Telford *et al.* 1976) and are based on electrical resistivity of soils and rocks, as described below. The VES method was used for determination of stratigraphy (Balkaya *et al.* 2009; Yadav *et al.* 2010), for mapping fractures and faults (da Silva *et al.* 2004) or groundwater (Batte *et al.* 2008; Rai *et al.* 2011).

Because the GPR method needs sufficient contrast of electromagnetic properties between layers (Daniels 2004), the aim of our study was to verify this method in the Czech conditions of Cambisols and Stagnosols to identify soil horizons and their spatial position, and using the VES method to detect bedrock and assess its degree of weathering.

MATERIAL AND METHODS

Site description. The locality Dehtáře (Figure 1) is an experimental catchment located in the southwest part of the Bohemian-Moravian Highlands. It spreads out over an area of 59.6 ha at the altitude of 497.0–549.8 m a.s.l. The bedrock is formed of partially migmatized paragneiss (cordieritic paragneiss), which is weathered to sandy loams to great depths (Zajíček *et al.* 2011). Soil survey was done by Duffková *et al.* (2011). According to the World Reference Base for soil resources (WRB 2006), the main soil types are Haplic Cambisols, Stagnic Cambisols, and Haplic Stagnosols, with small areas of Haplic Gleysol and Fibric Histosol.

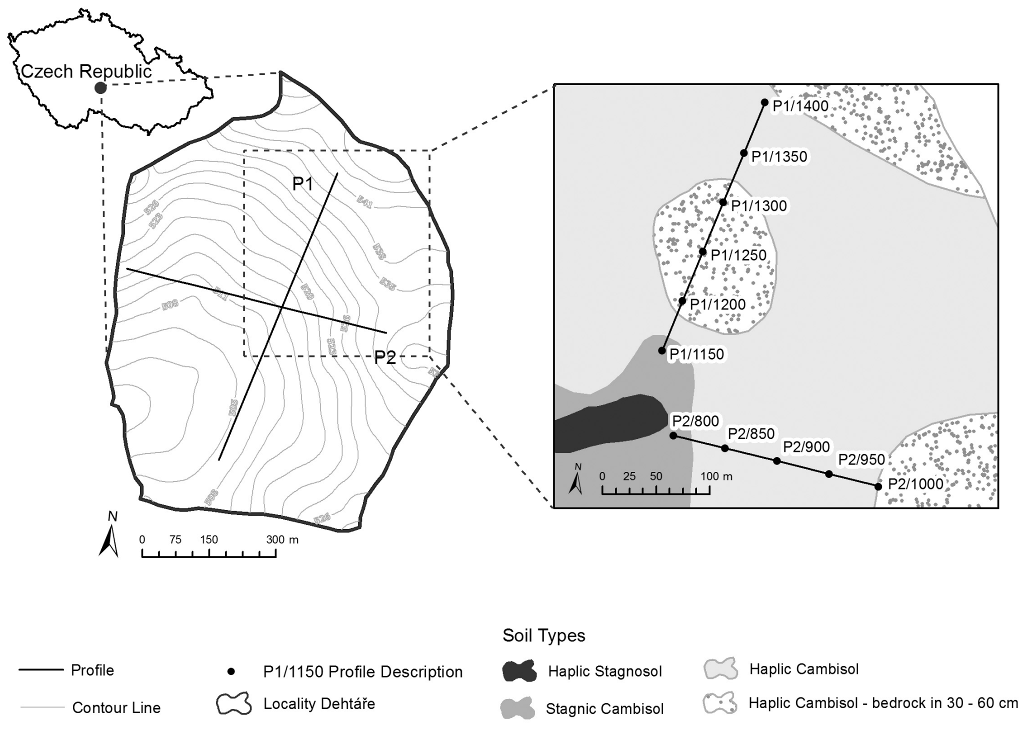

Figure 1. Map of the locality Dehtáře with soil types and investigated profiles; modified according to Duffková *et al.* (2011)

In this paper, we present only parts of two straight profiles (P1, SW-NE orientation and P2, W-E orientation), which were demarcated in the area of interest using the tape and GPS navigation (with ± 3 m accuracy) (Figure 1). The GPR survey was done by continuous dragging the antennas on the earth surface and the VES survey was used in the step of 25 m (P1) and 50 m (P2). Data from these two methods were then processed in special software programs, compared, and interpreted. Soil samples for the classical survey were taken by gauge auger at 50 m intervals, and in apparently interesting locations the distances were shortened. Maximum depth of the probes was 85 cm and basic soil characteristics (depth of soil horizons, texture, structure, colour) were determined. Information yielded from these probes supported the interpretation of the GPR data.

GPR. The GPR method is based on transmitting a high-frequency electromagnetic pulse (signal in MHz) (radio waves) from a transmitting antenna to the subsurface to probe lossy dielectric material and recording of the pulse responses reflected from the interfaces and objects below the earth surface, e.g. soil/bedrock interface (Annan 2002; Allred *et al.* 2008). The system measures the time which takes the electromagnetic energy to travel from the antenna to the interface and back. Typically, GPR produces a time-distance record of the subsurface. The vertical scale represents the two-way travel time of the radar pulse through the subsurface.

When an electromagnetic wave propagates through the ground and encounters a surface where the dielectric properties of the ground change, part of its energy is reflected and part of it is transmitted. The propagation velocity of an electromagnetic wave in a medium is determined by the electric permittivity (ε), while the part of the kinetic energy that is irreversibly converted into heat is determined by the electric conductivity (σ). Factors influencing dielectric properties include the type of salts in the soil water and their concentrations, the degree of water saturation, and the clay content. Material with higher conductivity rapidly reduces the signal and limits the depth of penetration.

For the vast majority of natural materials relative permittivity ε_r (= permittivity of the material ε_m/ permittivity of free space or vacuum ε_0) ranges between 5 and 15. An extreme value, about 80, is attained practically only by water (Cassidy 2009). Permittivity influences the conversion of time profiles to depth profiles. Their relationship is given in the following formula:

$$v_m = \frac{v_0}{\sqrt{\dfrac{\varepsilon_m}{\varepsilon_0}}}$$

where:

v_m – velocity of the wave propagation through any material

v_0 – speed of light in air

ε_m – permittivity of the material

ε_0 – permittivity of free space or vacuum (Allred *et al.* 2008)

The depth of signal penetration depends on these parameters as well as on the signal frequency used. At lower frequency, the depth of signal penetration increases, but the resolution decreases, and vice versa. For instance, using the frequency of 1 GHz, several cm resolution can be obtained (to only a small depth of around 0.25 m), while using the antenna frequency of 10 MHz, the depth of 10 m can be reached, but with a 1 m resolution. Details on the GPR method can be found e.g. in van der Kruk *et al.* (1999), Jol (2009).

For the research, numerous commercially available instruments can be applied. In our project, the RAMAC GPR equipment (Malå GeoScience, Malå, Sweden) was used with shaded antennas transmitting the central frequency of 250 MHz. For data collection the reflection method of survey called single-fold common-offset was used. The antennas were firmly fixed at a particular distance and the data collection was done by continuous dragging the antennas on the earth surface. The distance was measured by a survey wheel towed behind the antenna. The measurement step was set at 0.05 m, stacks at 16 and time window at 201 ns. The data obtained were then processed using the REFLEXW program (Sandmeier Software, Karlsruhe, Germany).

Vertical electrical sounding. The vertical electrical sounding (VES) is based on measurements of apparent resistivity ρ_z (Ωm). To monitor the changes of resistivity with depth, we use the so-called vertical electrical sounding, in which two earthed metal poles (current electrodes A, B) introduce electric current I (A) into the earth. After that, the resulting potential difference ΔV (V) is measured between a pair of potential electrodes M, N. Based on these values, apparent resistivity is calculated. Current electrodes are gradually moved still further from the fixed centre, thus increasing the anticipated depth range of the measurement. With growing depth, the changes of apparent resistivity are determined (Reynolds 2005).

For the VES measurements at the Dehtáře locality, the so-called Schlumberger's configuration was selected with the electrode separation AMNB/2 = 0.2–5 m. In this configuration, the potential electrodes are placed in central position. The current ones are symmetrically placed in the outer sides and are moved to the next position after each apparent resistivity measurement. The measuring interval was 25 m along transect P1 and 50 m along transect P2. The measurements were performed using the apparatus GEVY 100/MIMI II (Geofyzika Brno, Brno, Czech Republic). The measured curves of apparent resistivity were interpreted using the inverse task resolution by the iterative PC program VES 2 based on algorithm of Nyman and Landisman (1977). By interpreting the VES curves, changes in resistivity of the soil and rock environment at the depth below the configuration centre AMNB were found.

RESULTS AND DISCUSSION

The results of the measurements represent interpreted soil and rock profiles. Only the most interesting and representative soil profiles investigated at the locality at the hill slope are presented here. On transect P1 the 1150–1400 m section is interpreted in Figures 2 and 3 and on transect P2 the 800–1000 m section is interpreted in Figures 4 and 5.

Profile P1

Figure 2 shows an interpreted GPR record of profile P1. Darker colour on the radar record shows places of a reflection interface. Typical strong reflection is usually produced at the interface of two contrasting materials. As reported by Doolittle and Butnor (2009), this contrast can be the result of differences in soil moisture, physical properties (texture, volumetric mass), and/or chemical properties (soil organic carbon, calcium carbonate, sesquioxides). However, to determine the exact significance of the reflections we must compare the radar record with the description obtained by conventional survey (by the soil probe). At this locality, the radar record shows the soil profile only to the depth of 2–4 m, deeper it shows only noise. The first 25–30 cm of the profile could not be interpreted, because the direct wave between the antennas drowned the signal from shallow depths. However, the depth of the record is only approximate because it is recalculated according to the mean velocity of the electromagnetic signal in the soil, which, of course, in actual conditions differs from layer to layer (Daniels 2004).

In Figure 2 we delineated soil horizons (by black lines) which were interpreted based on visible interfaces in the radar record and specification of the horizons was made by comparison with soil probes. Bg horizon with redoximorphic features of the soil type Stagnic Cambisol was delimited at the distance of ca. 1160 m and R horizon (solid rock = bedrock) of Haplic Cambisol at the interval of 1240–1280 m. R horizon onset at the depth of 45 cm was detected by the soil probe. C horizon was identified, too, which was an unexpected positive result. As presented by Doolittle and Butnor (2009), under suitable conditions the GPR is able to determine the contrast horizons B, C, and R, because they are often sharply delineated. Redoximorphic features and R horizon were contrasting enough, but we did not know whether horizon C would be identifiable in these conditions of Cambisol. Indeed, the GPR is not capable of recording small changes in the soil properties and transition horizons (AB, AC, BC).

Figure 3 shows an interpreted resistivity section obtained by the VES method. In this profile, the apparent electrical resistivity was measured to the depth of up to 12 m. The legend to Figure 3 was prepared based on the well-known physical properties for this rock type, corresponding to the given resistivity values (Keller 1986). The solid compact rock (Fresh Rock in the legend) is indicated by resistivity values exceeding 1000 Ωm, which were found at the distance of 1200 m 4 m deep, at the distance of

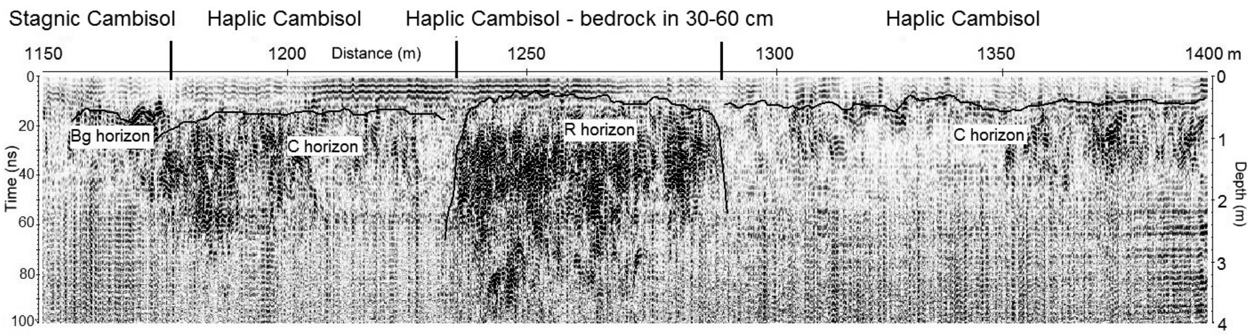

Figure 2. Profile P1 – ground penetrating radar (GPR) record interpretation with marked horizons and soil types

1325 m at 6 m, and at the distance of 1400 m this high resistivity value of compact rock rose almost to the surface. Between this compact rock and the surface the rock exhibited various degrees of weathering. An interesting section was localized at the distance of ca. 1250 m, where resistivity values exceeding 2000 Ωm suddenly occurred near the surface. However, about 1.5 m beneath the surface there was a sharp boundary and resistivity values declined to 500 Ωm. This rock with resistivity values of 2000 Ωm is probably weathered to the same degree like the rock at depth with resistivity around 500 Ωm (slightly weathered, but without groundwater). This sharp interface would probably mark the groundwater level. As can be seen from Figure 3, the upper parts of the profile show more sections with higher resistivity values. These should represent dry sections. Groundwater is a good electric conductor, its conductivity depends on its mineral and salt content. When soil moisture and its mineralization are high, the electric conductivity is higher and electrical resistivity is lower. As the rock is more compact (its porosity is lower and therefore it contains less water), resistivity rises again.

When we compare the VES image with the GPR image, we can see that the location of 2000 Ωm resistivity values corresponds to the marked R horizon in the GPR. On the GPR record we can see the exact border of R horizon (bedrock), but from the VES information we assume that the rock is in fact not solid (fresh rock), but it is slightly weathered. On the GPR record in the section between ca. 1170–1200 m, C horizon also displays larger reflections. As shown by the VES image, there should be a moderately weathered rock. However, this part is potentially influenced by groundwater and its exact description is difficult. Some reflection can be seen in the section of 1350–1400 m corresponding to bedrock on the VES image. In this part the soil probe did not provide information on R horizon. No reflections were observed in the 1320–1350 m section below 1 m, which corresponds to the VES image and indicates the presence of a fault in this part.

In the section of 1180–1320 m the GPR record allowed to precise the conventional soil survey. According to this survey (Duffková *et al.* 2011) here the soil type is Arenic Cambisol (Czech classification system, Němeček *et al.* 2011) determined by sand and loamy sand texture at the depths reaching to 60 cm. Nevertheless, in the GPR record we could mark bedrock at the depth of 30–60 cm located from 1234 to 1286 m with great precision, which is, of course, different from the sand texture. Although according to the Czech classification the soil type was determined properly, the GPR record enabled us to better specify the depth of bedrock as shown in Figure 2. (The soil type is denoted as Haplic Cambisol – bedrock at 30–60 cm, because Arenic Cambisol is not specified in the WRB classification).

Profile P2

In profile P2 at the distance of around 800 m, the GPR showed reflections according to the soil probe

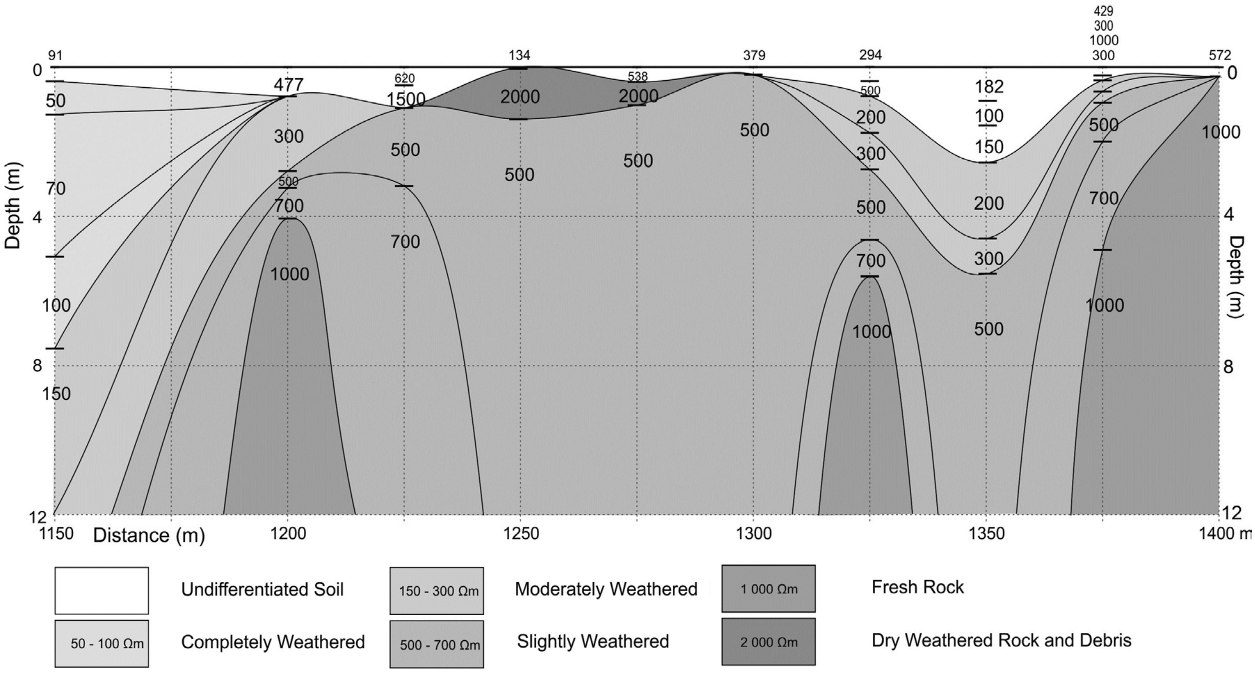

Figure 3. Profile P1 – vertical electrical sounding (VES) method interpretation based on resistivity

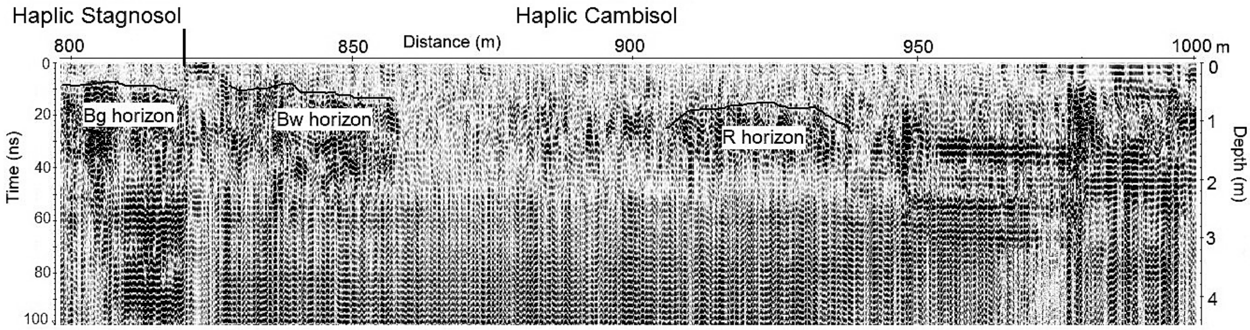

Figure 4. Profile P2 – ground penetrating radar (GPR) record interpretation with marked horizons and soil types

interpreted as mottled Bg horizon of the Haplic Stagnosol soil type (Figure 4). The VES method showed resistivity of 50 Ωm at the depth of ca. 3 m in this point (Figure 5), indicating sandy clay material (Karous 1977). According to the map of soil types (Figure 1), this area should contain Stagnic Cambisol. However, we corrected it to Haplic Stagnosol.

The GPR record in the section of 825–860 m showed other distinct reflections interpreted as an area of accumulated slope sediments – alternating rough and fine particles, lying close to the surface. The soil probe documented sandy-loamy and loamy-sandy texture in Bw1 (23–60 cm) and Bw2 (60 cm and deeper) horizons. The depth of this probe was only 85 cm.

Other significant reflections shown by the GPR occurred in the section of 900–940 m. The soil probe did not record this situation because the reflections were at a depth exceeding 1 m. The VES data recorded directly under the surface did not point to any relatively compact rock according to the resistivity, but at greater depths (around 8 m) values of 1000 Ωm indicating such a rock started to appear (Figure 4). Unfortunately, just at this profile (P2) the VES measurement was made at 50 m intervals and the method VES was not able to record this. We may presume that the radar only recorded more solid rock in this section, but we cannot validate it.

In the section of 860–900 m, no significant reflections were found in the GPR record and the resistivity values from the VES survey were low in this part. Both these data correlate and mean that this section should contain sandy texture (the soil probes confirmed sand texture from the depth of 60 cm and more, with the substrate (rock) strongly weathered into large depths). No interface between

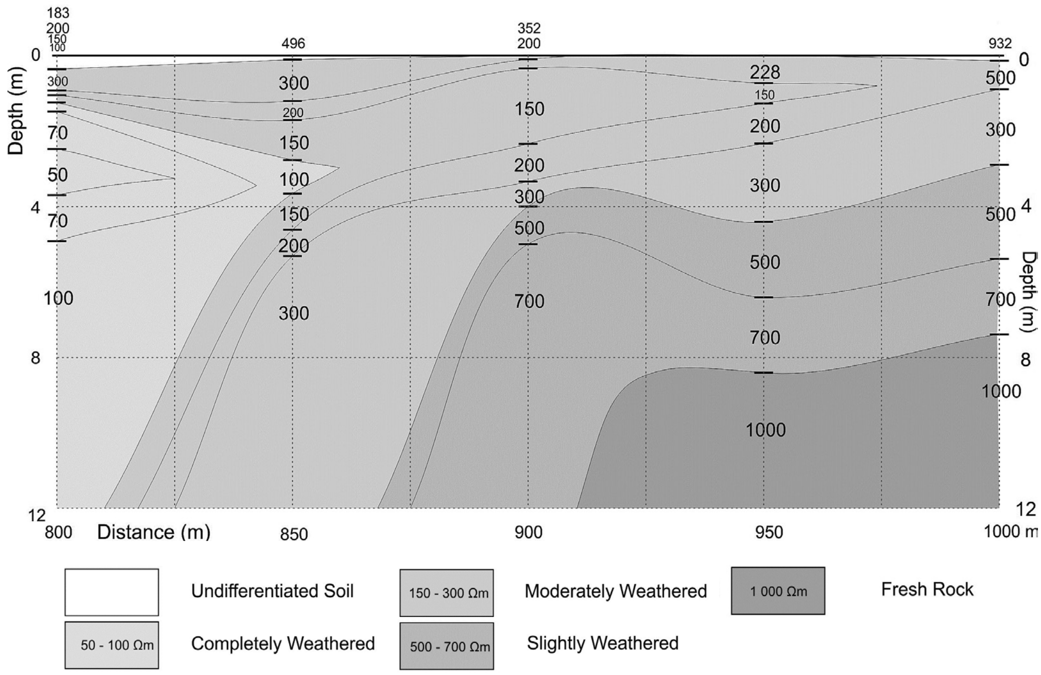

Figure 5. Profile P2 – vertical electrical sounding (VES) method interpretation based on resistivity

horizons B and C was identified in the profile P2. It was not sharp enough to be noticed by the GPR at this location. Some other reflections could be seen in the 950–1000 m section, but we were not able to interpret them.

CONCLUSION

In this study, geophysical methods GPR and VES were used together with conventional soil survey and images and overview of the profiles reaching to the depth of about 12 m were obtained. At the locality Dehtáře, where Cambisol and Stagnosol soil types cover the crystalline bedrock, some boundaries of horizons and also bedrock could be detected. The GPR yielded images (maps) of continuous profiles with apparent spatial distribution of boundaries between the horizons and soil types. The VES survey provided data for creating a map of resistivity values indicating the degree of weathering and thus the image of substrates and compact bedrock could be completed.

An advantage of using the GPR method is the speed of obtaining the data, continuous image, and the rather good possibility to identify zones with markedly different texture and moisture (as these two properties are related). Different textures show different field capacities and different reflections in the radar record (Gerber *et al*. 2010). A disadvantage is that to determine the meaning of the radar record a classical soil sampling record is still necessary, but locations of the sampling points can be specified more precisely. Another disadvantage of the GPR record is that it deals only with a relative depth. To get information about the exact depth, another type of antenna (Annan 2009) could be used, but this measurement would be more time-consuming and more difficult to interpret.

In combination with the VES method we have learned about the depth of the individual geological layers but not of the soil horizons as was expected, because the soil horizons are mostly too thin for the VES survey. Geophysical measurements may sometimes be limited by bad weather and field conditions (intensive rains before the measurements, overgrown vegetation). To achieve better quality of the future measurements, some parameters of measuring instruments that influence the resulting images should be changed, e.g. the step of the measurement, type of antenna of the GPR, or the method of computer processing.

To conclude, the geophysical measurement provided us with good spatial information. The GPR method was useful in measuring the first 2–3 m of subsurface and the VES method worked well in the geological material. Both methods working together gave us a description of the studied profiles from pedological as well as geological viewpoints.

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