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CHARACTERIZATION OF NEAR-SURFACE SEDIMENTS BASED ON COMBINED GEOELECTRIC STUDIES AT STARUNIA PALAEONTOLOGICAL SITE AND VICINITY (CARPATHIAN REGION, UKRAINE)

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Abstract: Combined geoelectric research was performed in the Starunia area, where the specimens of woolly rhinoceros were discovered at the beginning of the 20th century. The work included: DC resistivity soundings, electromagnetic terrain conductivity measurements, resistivity imaging and penetrometer-based resistivity profiling. The main purpose of the survey was to give geoelectric characterization of near-to-surface sediments and estimate their variability (extent, thickness and electric resistivity). Generally, resistivity of geological strata is low and decreases with depth but its spatial distribution is locally complex. This complexity reflects joint effects caused by the presence of salty underground water outflows from the salt-bearing Miocene Vorotyshcha beds into the Quaternary sediments, distinct transformations of the geological medium by former ozokerite and oil exploitation and current activity of the natural geological processes in the area.

Key words: geoelectric survey, DC resistivity soundings, electromagnetic terrain conductivity measurements, resistivity imaging, penetrometer-based resistivity profiling, Starunia, Ukraine.

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INTRODUCTION

Geoelectric survey was a part of an interdisciplinary research project focused on study of the Starunia area. In the years 2006–2009 interdisciplinary studies were carried out in an abandoned ozokerite (earth wax) mine at Starunia (Kotarba, 2009), about 130 kilometres southeast of Lviv, Ukraine (Fig. 1), where remnants of a mammoth and three woolly rhinoceroses , and one nearly completely preserved rhinoceros were found in 1907 and 1929. The discovery of large Pleistocene mammals in the Starunia ozokerite mine was a spectacular scientific event on a world scale. A unique combination of oil and brine within the Pleistocene clayey mud, into which the animal had sunk, resulted in near-perfect preservation of this specimen.

General information covering history of the area and details about geology and results of the earlier research works conducted in this region (including reconnaissance resistivity research; Mościcki, 2005) are described in a special monograph devoted to Starunia (Kotarba, *ed*., 2005) and recent works (Sokołowski *et al.*, 2009; Sokołowski & Stachowicz-Rybka, 2009; Stachowicz-Rybka *et al.*, 2009).

The field area was partly transformed due to the 19th and 20th century's shallow mining activity, focused on ozokerite and oil. As a result there are many dumps, remnants of old shafts and occurrences of oil seeps ("eyes") and mud volcanoes on the terrain surface. Salt water outflows in the area were also noticed. The area is also influenced by neotectonic activity resulting in frequent changes of the Velyky Lukavets River bed and banks.

The main targets for the geoelectric survey were near-to-surface Miocene strata and Quaternary sediments and their variability (extent, thickness and electric resistivity).

Various types of the Quaternary deposits are described for the Starunia area: loess and loess-like sediments, loam, mud, peat, sand, gravel, and others (Alexandrowicz *et al.*, 2005; Sokołowski *et al.*, 2009; Sokołowski & Stachowicz-Rybka, 2009). The underlying rocks are mostly represented by the clayey Miocene salt-bearing Vorotyshcha beds (Korin, 2005). Considering such diversity, it was hoped that appropriate resistivity contrast favourable for geoelectric methods should also exist.

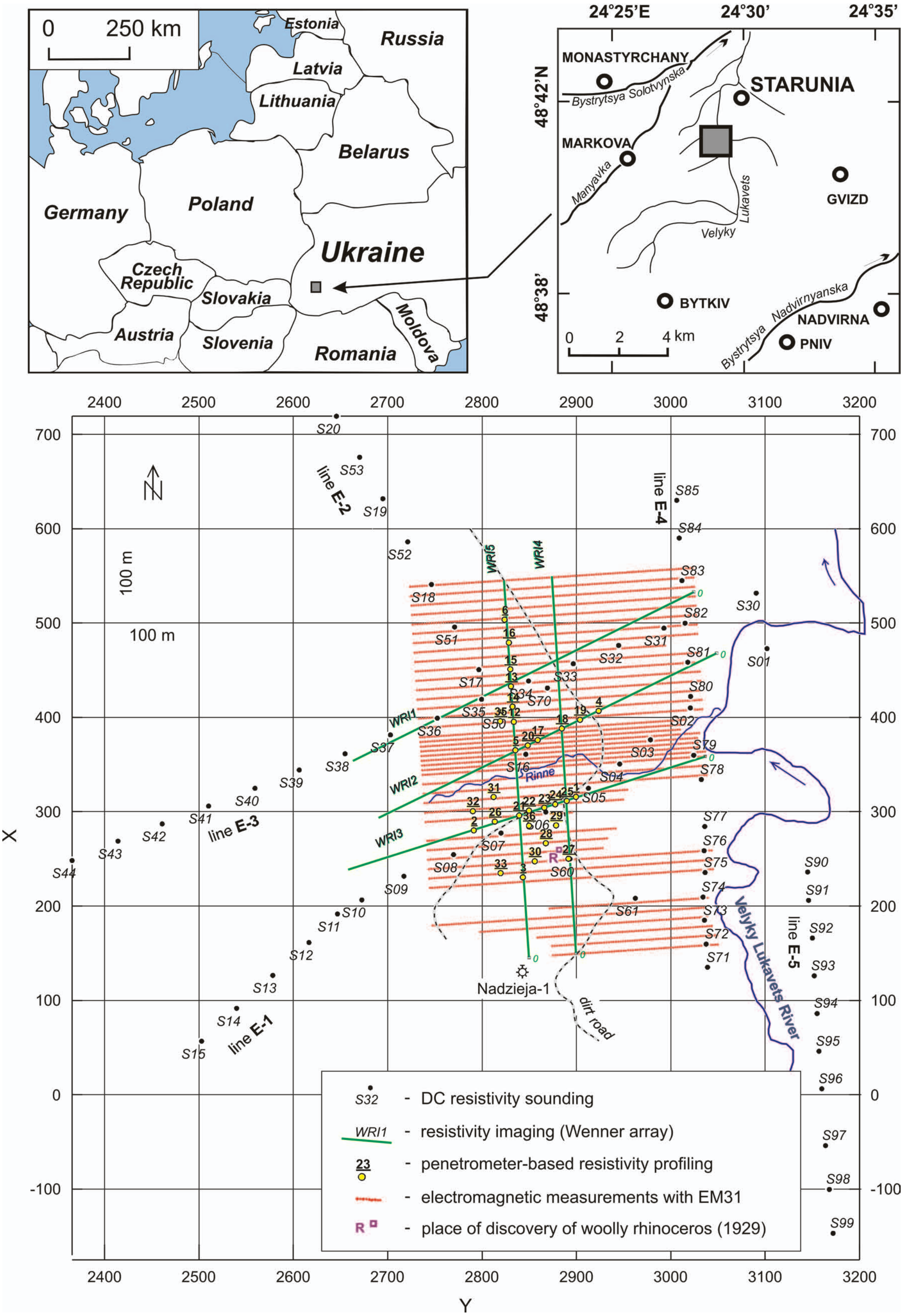

Fig. 1. Sketch map of the Starunia palaeontological site and surrounding area (Carpathian region, Ukraine) showing the location of geoelectric survey. Nadzieja-1 – old oil well

METHODS

The following geoelectric methods were applied: DC resistivity soundings, resistivity imaging (sometimes referred to ERT – electric resistivity tomography), electromagnetic terrain conductivity measurements, and penetrometer-based resistivity profiling. Detailed location for the completed research is given in Fig. 1.

DC resistivity sounding is known also as Vertical Electrical Sounding – VES (Keller & Frischknecht, 1966; Koefoed, 1979). A four electrode Schlumberger array AMNB with 12 spacings: AB/2 = 1.47, 2.15, … , 68.1, 100 m (six points per decade) and MN/2 = 0.4, 2.0 and 10.0 m was used. Soundings were grouped in five survey lines (Fig. 1). Three of the lines: E1, E2, E3 were studied during the first reconnaissance field campaign in 2004 (Mościcki, 2005), and the next two, E4 and E5, were added in 2007–2008 for broader recognition. Additional few VES were done in individual places. Soundings were performed at 68 sites, in total.

Resistivity imaging (Dahlin, 1996; Loke, 2003) was made with the use of the LUND SAS 4000 system. The Wenner alfa array was applied and the smallest electrode separation was 5 m. The method was applied along five research lines, each 400 m long. WRI1, WRI2 and WRI3 were oriented generally west-east, and WRI4 and WRI5 were directed to the north. The position of survey lines was chosen according to the results of VES. Resistivity imaging was aimed at 2D quantitative recognition of near-surface structures/properties to a depth of 20 m.

Electromagnetic terrain conductivity measurements (ETCM) make use of EM induction in fairly conductive geological media. The method is recognized as a valuable geophysical tool in studying underground polluted (mineralized) water problems (*e.g.*, Mościcki & Antoniuk, 2002). In this study, the Geonics EM31 (www.geonics.com) equipment was used with two modes of coils orientation: HD (horizontal dipole) and VD (vertical dipole) what enables an estimation of mean conductivity of sediments to the approximate depths of 3 to 6 metres. The upper limit of the measuring range of the equipment is 1000 mS/m (which corresponds to a resistivity of 1 Ωm). Data were collected along 42 lines oriented east-west, most of them 300 m long and separated from each other by 5 to 10 m. Measuring step along lines was 2.5 m. This method was chosen on the basis of the former resistivity results, which revealed high conductivity zones requiring much more detailed research of their surface extent.

Penetrometer-based resistivity profiling is an invasive method used for a very detailed study of the vertical distribution of loose sediment resistivity (*e.g.*, Antoniuk & Mościcki, 1994). A special geoelectric probe is pushed (or hammered) into the ground for measuring changes of electrical resistivity with depth. The GEOPROBE (www.geoprobe.com) system with small size Wenner array (76 mm total length) was used in this study. High vertical resolution can be achieved as measuring step is less than 2 cm. The method was applied at 30 sites selected after analysis of the results of surface geoelectric surveys and following suggestions inferred from the geological and geochemical studies. The penetration depth depended on local conditions. In most sites it was of about 14–16 m.

RESULTS AND INTERPRETATION

All the above mentioned methods utilise electrical resistivity of rocks as a characteristic physical property. Unfortunately, the resistivity determined in the field measurement is not true resistivity of the rock, but rather a complex quantity called *apparent resistivity* (or apparent conductivity). The value of apparent resistivity depends on the distribution of true resistivity within the medium and on the type and size of measuring array (and specificity of the method applied). Information on actual resistivity may by derived only after interpretation of the field data. It is not an easy task as interpretation suffers from inherent ambiguity (for the VES case it was demonstrated with details by Mościcki, 2005). Therefore, the values of resistivity obtained from geophysical interpretation should be treated rather as *interpreted* than *real* and *exact*. What is more, there is no simple correlation between resistivity and lithology. That is due to the fact that electrical resistivity of rocks depends on many factors: mineral composition, porosity, water/gas content in pores and voids, pore-fluid chemistry, temperature, structure, etc. (Keller & Frischknecht, 1966; McNeil, 1980; Kobranova, 1989). For loose rocks, the most important factors influencing resistivity are state and fill of the voids and pores and clay minerals content. Chemical composition of the water/humidity present in pore spaces can modify resistivity to a high degree (rise in water mineralization lowers resistivity). The presence of air (or gas/oil) in pore spaces may increase resistivity due to air's insulating properties. The presence of clay particles in sediments distinctly lowers resistivity.

The reconnaissance DC resistivity soundings in the Starunia area enabled general characterization of shallow sediments (Mościcki, 2005). Apparent resistivities vary in a relatively wide range, but their values are rather low. The lowest values < 0.4 Ωm were observed in the vicinity of the main mud volcano, whereas the highest, about 200 Ωm, were near the banks of the Velyky Lukavets River. On the basis of qualitative analysis and quantitative interpretation of VES curves, a few conclusions were drawn (Mościcki, 2005). First – sediments resistivity visibly decreases with depth, and may be caused by increasing salinity/clay content in deeper strata. Second – the top interpreted layer (in some areas two layers) with a resistivity higher than 10–15 Ωm forms an overburden over deeper low-resistivity formation. The thickness of that overburden (mainly the Quaternary sediments and mine dumps) ranges from 2–3 to 10 metres. Third – in the central part of the area a distinct low-resistivity-pattern (LRP) was observed. It may be caused by underground outflow of salty water into the more permeable Quaternary sediments resulting in a remarkable lowering of resistivity. The general distribution of apparent resistivity and its surface/depth variations are well visible on apparent resistivity maps (ARM) for the whole set of VES data (Figs 2, 3). On these maps the presence of LRP is clearly reflected.

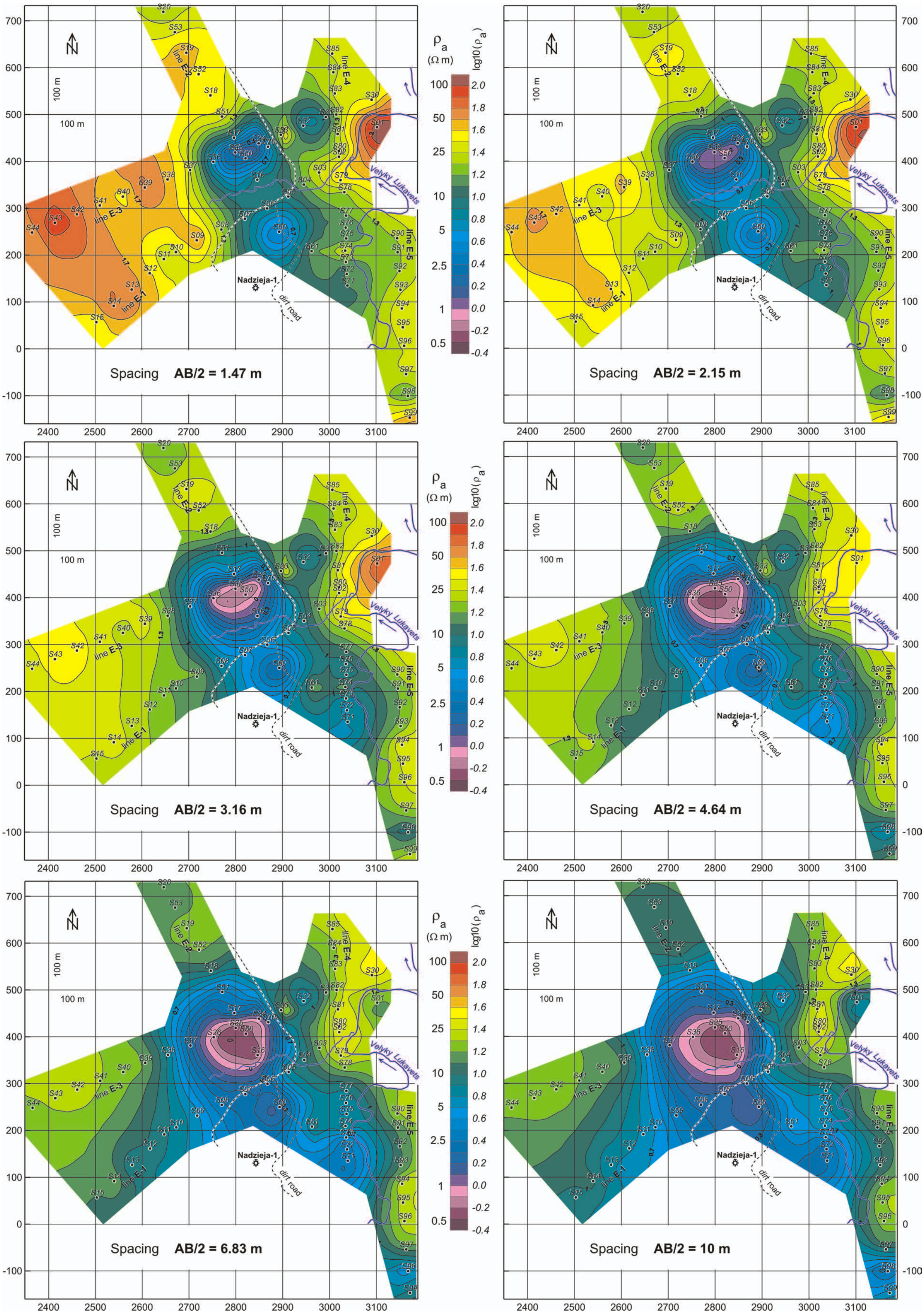

Fig. 2. Contours of apparent resistivity based on DC resistivity soundings data. Maps constructed for spacings AB/2 from 1.47 to 10 m of the Schlumberger array. Contours in logarithms of resistivity given in Ωm

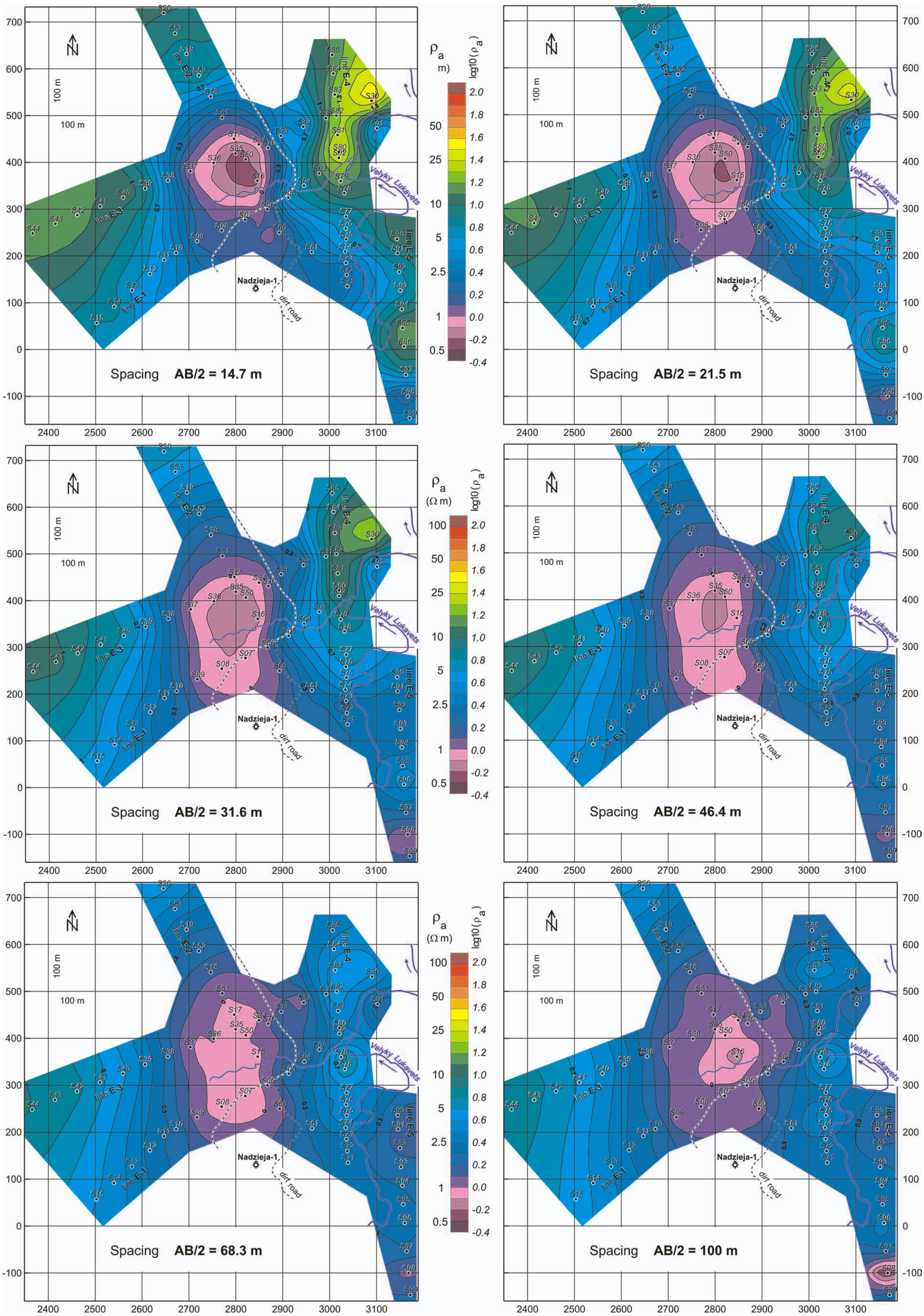

Fig. 3. Contours of apparent resistivity based on DC resistivity soundings data. Maps constructed for spacings AB/2 from 14.7 to 100 m of the Schlumberger array. Contours in logarithms of resistivity given in Ωm

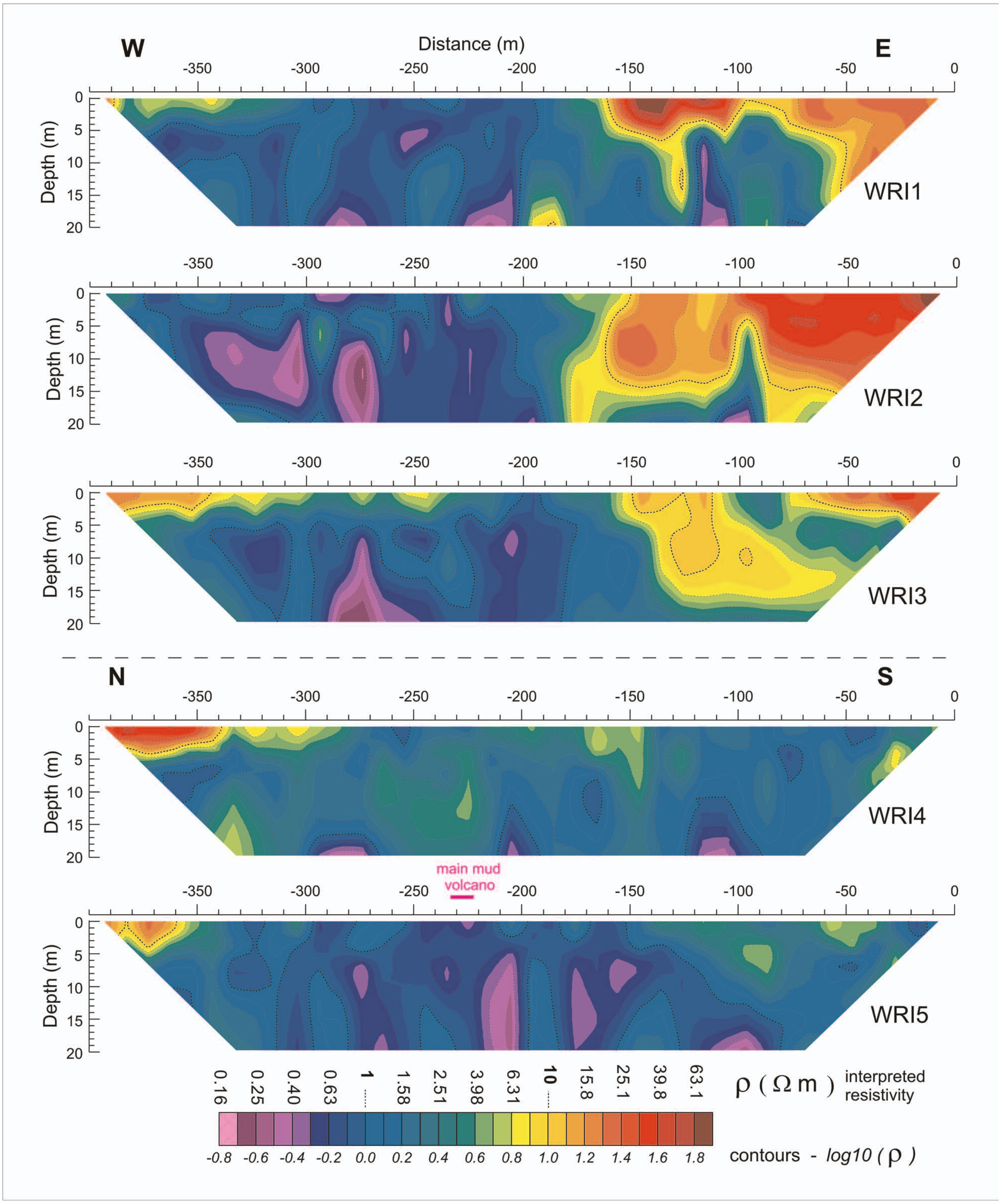

Fig. 4. Interpretation of the 2D resistivity imaging dta. Vertical axis – interpreted depth below the terrain level

For better recognition of depth character of the LRP, the resistivity imaging survey along five lines was conducted (Fig. 1). The field data were inverted with RES2DINV software (Loke, 2003). As the inversion results depend on many factors (Loke *et al.*, 2003), several inversion options (normal, robust, and combined) were applied and carefully analysed. Final inversion results are shown in Fig. 4. Presented here are 2D "mean" models (calculated by averaging the results of different options). Sections show distribution of interpreted resistivity with depth. For lines WRI1,

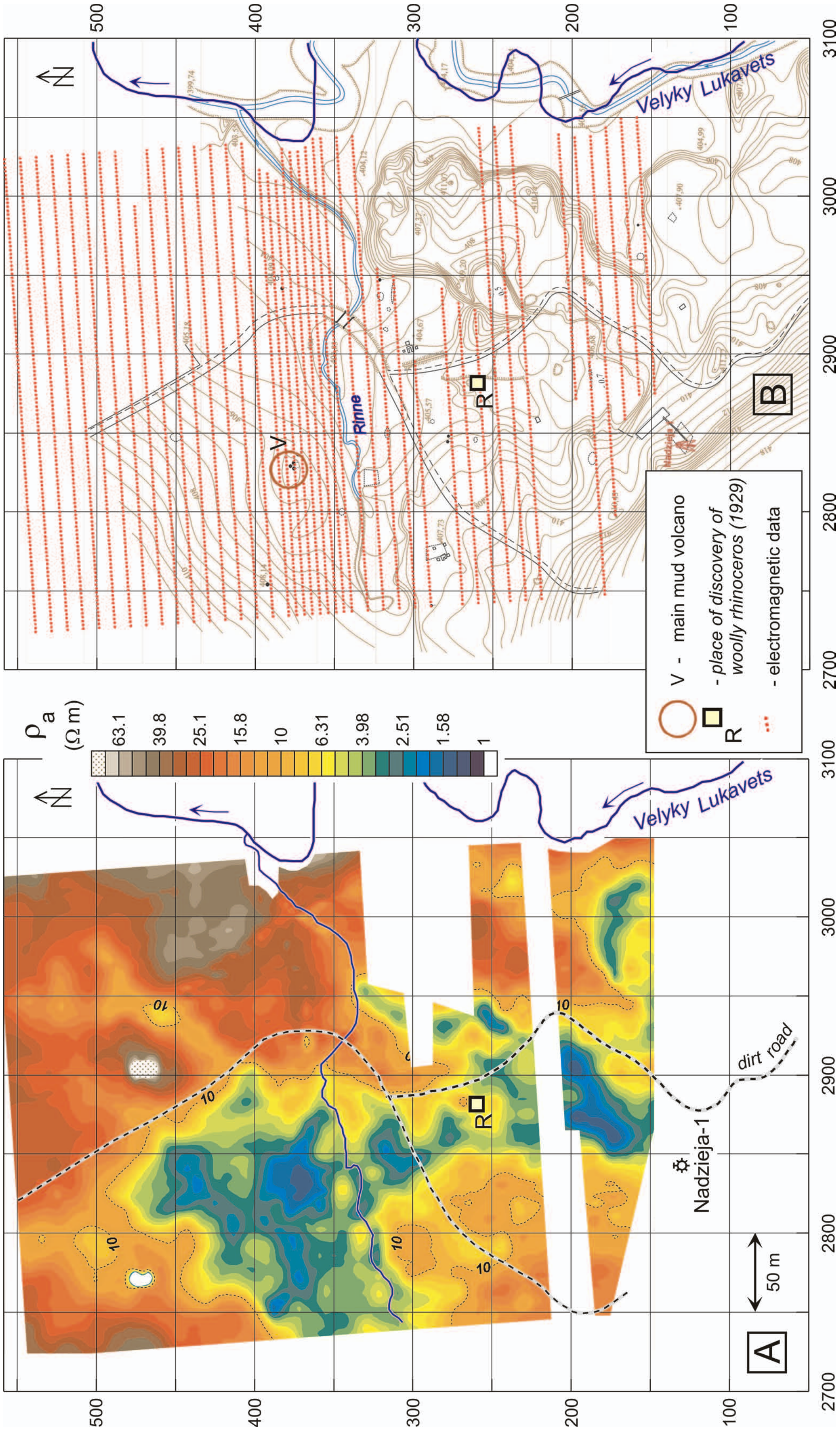

Fig. 5. **(A)** Contours of apparent resistivity calculated from apparent conductivity EM data measured with Geonics EM31, HD array, and **(B)** map of morphology of the terrain with measuring points marked. Present (fat, blue line) and older traces of Velyky Lukavets River superimposed

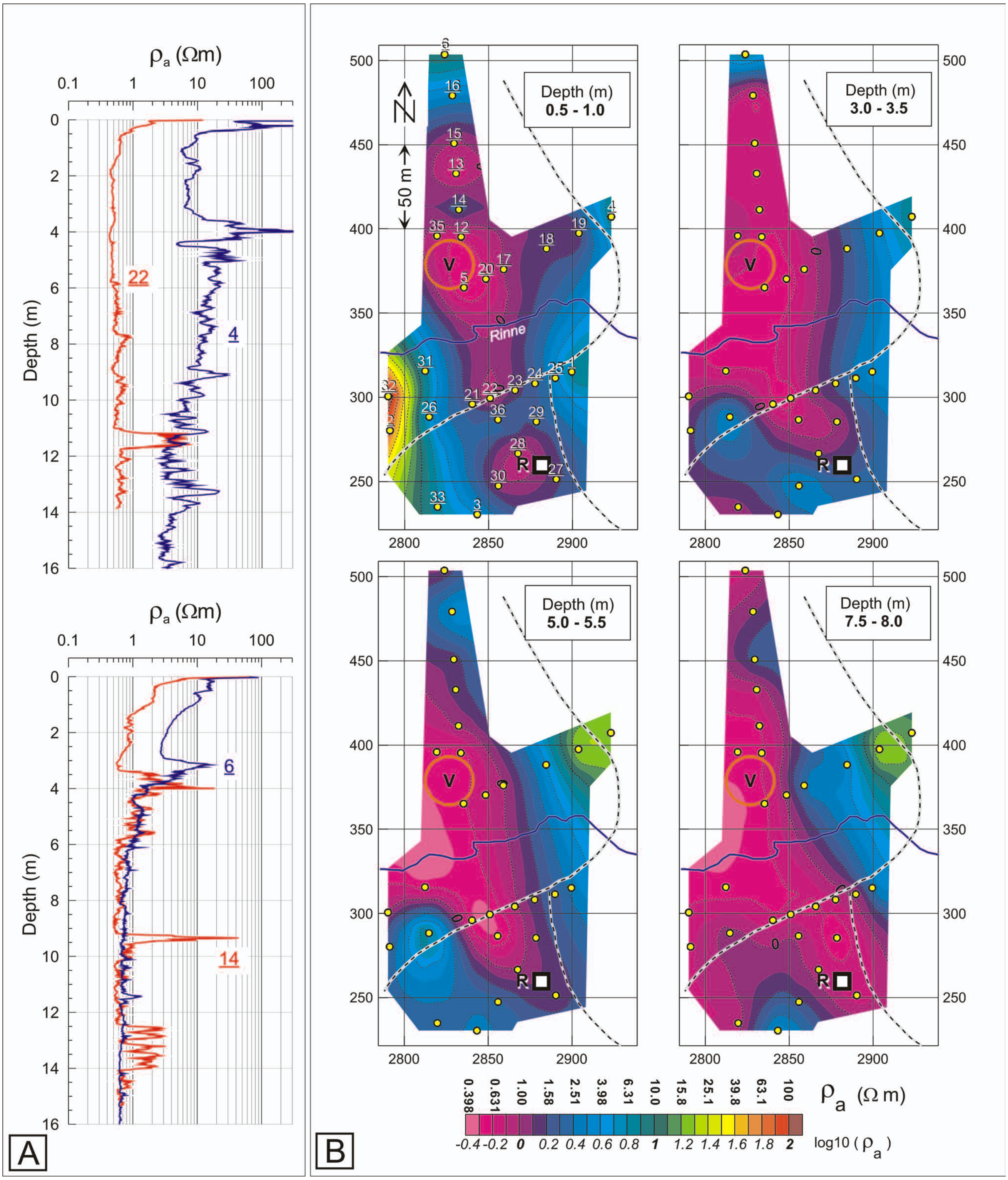

Fig. 6. **(A)** Distribution of measured resistivity with penetration depth (resistivity logs) for selected four sites, and **(B)** contours of mean resistivity calculated for 0.5 “window” at selected depths from penetrometer-based resistivity profiling

WRI2 and WRI3, the eastern boundary of the LRP is well reflected by contact of low and high-resistivity zones. This boundary seems to be sharp and rather steep (especially for the WRI2 section). The western boundary of the LRP is not so well marked. North oriented lines WRI4 and WRI5 indicate the complex distribution of low-resistivity sediments forming the LRP. It is well visible, especially on the WRI5 section which crosses the main “mud volcano”.

Detailed recognition of the resistivity of the very shallow sediments was done with electromagnetic induction profiling. Very dense mesh of the measurement lines enabled precise determination of the surface extent of LRP, although low resistivity values in the central part are probably not correctly expressed due to the measuring range of equipment, limited to 1000 mS/m. Presented contours of apparent resistivity (apparent conductivity values measured with EM31 Geonics equipment were converted to resistivity) are set together with a morphology map of the area in Fig. 5. On the morphology map, man-made alterations of the terrain surface (mine dumps limiting access for geophysical survey) and modern changes of the Velyky Lukavets River bed are visible.

At the final stage of the geoelectric survey, the penetrometer-based resistivity profiling was used for high-resolution study of the vertical variations of resistivity. As both the Wenner probe and measuring step was very small the measured apparent resistivity can be treated as good approximation of the true resistivity. Some of the resistivity logs are presented in Fig. 6A. There are no much distinct resistivity variations in individual curves, but if we compare curves for sites 22 and 4 there is a visible difference in the mean level of resistivity. Site 4 was located out of the eastern "boundary" of the LRP. What's more, that resistivity profile is a "saw" type for the whole depth of the penetrated sediments. This may be a sign of relatively lower humidity/water content in that place. There is an opposite situation for site 22, located within the LRP anomaly. This curve is very smooth and resistivity is very low in the 2–11 m depth range. Probably, sediments are very loose here and salt water penetrates that place. Peaks of higher resistivity at depths below 10 m, visible on 22 and 14 logs, may indicate the presence of more compact clayey strata. All resistivity logs were analysed together to construct resistivity maps for different depths. For that task each resistivity log was averaged in 0.5 m wide windows for a few chosen depths. Selected results are presented in Fig. 6B. Continuous lowering of the sediment resistivity with depth for most penetrated sites is visible. This confirms earlier conclusions drawn from the surface geoelectric survey, but penetrometer-based resistivity profiling gave more detailed and precise information on vertical resistivity distribution.

CONCLUSIONS

A combined geoelectric survey, performed in the 2004–2008 period, enabled the following characterization of the near-surface sediments in the area of discoveries of woolly rhinoceroses and mammoth at Starunia.

Resistivity of sediments is generally very low in the area. It generally decreases with depth up to at least 40 m, falling at some sites far bellow 1 Ωm. This may be a combined effect of salt/water content distribution within the Quaternary sediments and the upper part of the Miocene strata. Locally, values of resistivity are extremely low indicating probable underground outflow of salty water in the place.

In the central part of the study area there is a distinct low-resistivity anomalous zone. The extent of this zone is well reflected on geoelectric maps. The zone is elongated in a NW–SE direction and is probably connected with inflow of brines from the Miocene salt-bearing Vorotyshcha beds into the Quaternary sediments.

The north-eastern boundary of the zone may have a form of a steep contact separating very low-resistivity sediments (<1 Ωm) from higher-resistivity sediments (>20 Ωm), appearing in the direction towards the Velyky Lukavets River.

There are no distinct variations of resistivity in individual depth profiles, although there is variability in mean resistivity "background" from site to site. Spatial distribution of the resistivity is complex and may reflect variation of clayey and sandy sediments containing water of different salinity. Some additional anthropogenic effects (due to the mining activity in the past) on resistivity distribution are visible, too.

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