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ELECTRIC RESISTIVITY AND COMPACTNESS OF SEDIMENTS IN THE VICINITY OF BOREHOLES DRILLED IN THE YEARS 2007–2008 IN THE AREA OF STARUNIA PALAEONTOLOGICAL SITE (CARPATHIAN REGION, UKRAINE)

Włodzimierz J. MOŚCICKI & Tadeusz SOKOŁOWSKI

Faculty of Geology, Geophysics and Environmental Protection, AGH University of Science and Technology,
Al. Mickiewicza 30, 30-059 Kraków, Poland,e-mail: moscicki@geol.agh.edu.pl

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Abstract: Geoelectric research aiming to assess heterogeneity of geological environment was carried out in the Starunia area, where the unique specimens of woolly rhinoceros were discovered at the beginning of the 20th century. The DC azimuthal pole-dipole resistivity soundings and penetrometer-based resistivity profiling with simultaneous penetration-velocity measurements were used to study variability of environment in the vicinity of geological boreholes. No evident correlation was found between lithology of drilled sediments and geophysical data. Nevertheless, remarkable horizontal and vertical variability of geophysical parameters were observed. The largest horizontal changes may reflect an existence of some sharp boundaries in study area. The measured physical properties of geological strata: electric resistivity and compactness (estimated from penetration velocity) change also with the depth but correlation with geological structure can be found in limited cases only. Registered variability may have originated from several reasons: complex geological arrangement of shallow layers, salty underground water and bitumen presence in voids and pores, influence of neotectonic activity, and/or from transformations of near surface environment caused by past mining activity.

Key words: geological boreholes, geoelectric survey, DC azimuthal pole-dipole resistivity soundings, penetrometer-based resistivity profiling, penetration velocity measurements, Starunia, Ukraine.

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INTRODUCTION

Starunia village is located near Ivano-Frankivsk, western Ukraine (Fig. 1), and is famous of the discovery of woolly rhinoceros and mammoth fossils at the beginning of the 20th century (Alexandrowicz, 2004). These paleontological finds gave rise to an interest among Earth scientists in more detailed studies of the area. As a result, there were several research projects run in Starunia including a joint research carried out at the beginning of the 21st century. Results of this project and history of Starunia site are described in detail in a special monograph (Kotarba, *ed.*, 2005). Nevertheless, the most advanced studies were completed in the years 2006–2009 in the frame of an interdisciplinary research project including geological, geophysical, geochemical, biological and archaeological studies of the Starunia area (Kotarba, 2009).

Among the main targets of this project was a recognition of near-surface geological structure and sediment properties. This task was achieved by studies of drill cores supplemented by surface geological observations (Sokołowski *et al.*, 2009). Both drillings and later interpretation of geological data faced problems caused by variable drilling conditions and variability of the deposits properties *in situ*. Near-surface sediments in the study area are geologically complicated and additionally affected by remnants of shallow mining activity, focused on exploitation of ozokerite and oil in the 19th and 20th centuries. This historical exploitation is documented by many dumps and old shafts. Some of these shafts are still visible at the surface, but most of them were closed and filled with wastes; hence, their precise localization is unknown. The presence of salty underground water (brines) and occurrences of oil outflows was noticed in the area, too. The study area is also affected by recent neotectonic processes, the most spectacular evidence of which is a “mud volcano”.

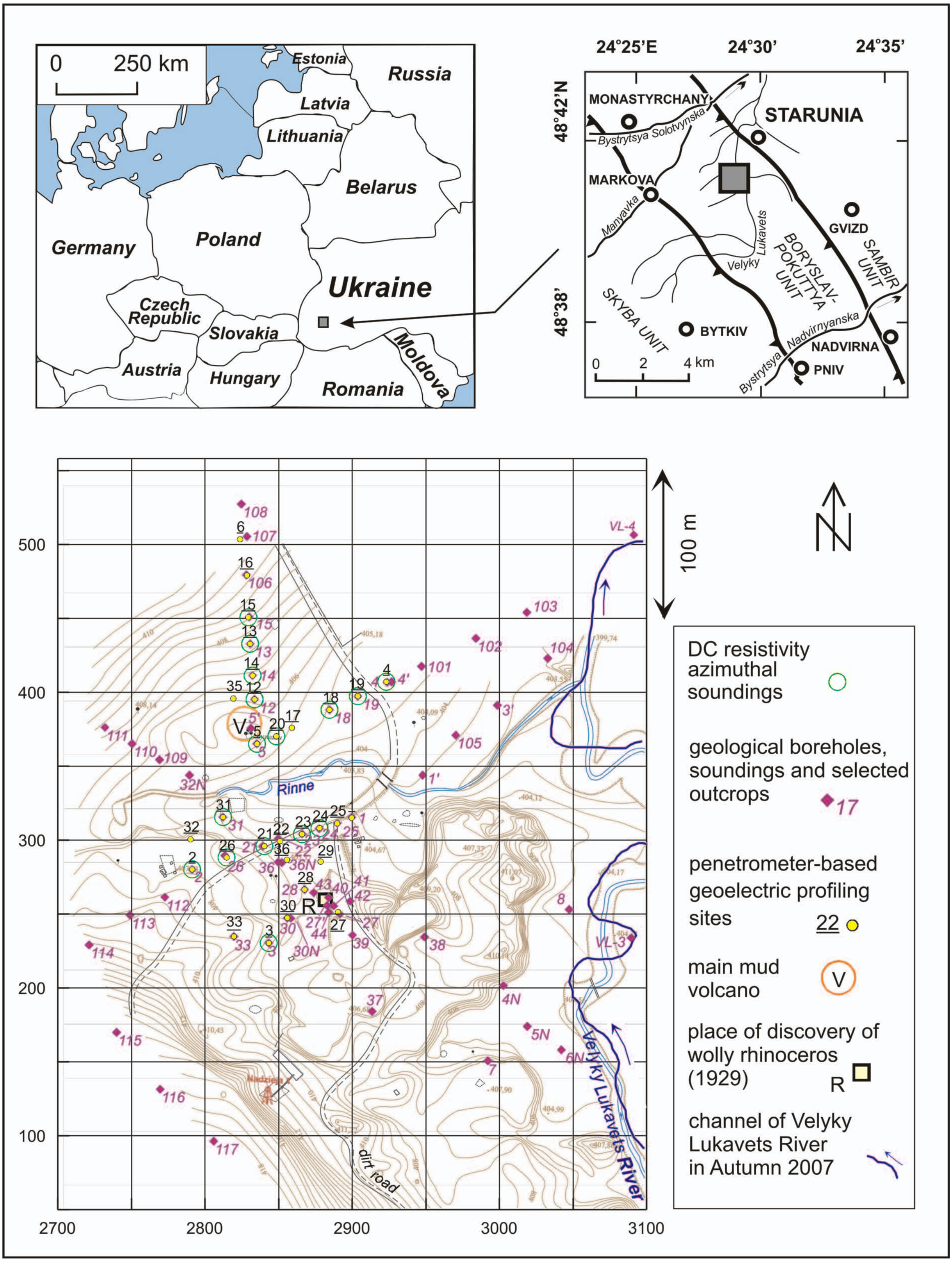

Fig. 1. Location of geological boreholes and geoelectric survey. Nadzieja-1 – old oil well

Questions arise how “uniform” are sediments in the vicinity of boreholes drilled in the years 2007–2008 and if there is a noticeable relation between lithology and physical properties of sediments (electric resistivity and compactness)? Some results of surface geoelectric surveys run in the area provided general, rough estimation of the problem. These surveys covered a much wider area than drillings and documented significant variability of electric properties of sediments (Mościcki, 2005, 2009). For much more detailed study of the problem special surface geoelectric measurements were carried out by DC azimuthal resistivity soundings. Combining these data with the results of earlier, penetrometer-based resistivity profiling and with geological information, enabled the authors to disclose complex character of sediments in the vicinity of drillings.

METHODS

The following geoelectric methods were applied: azimuthal DC resistivity soundings and penetrometer-based resistivity profiling. Detailed location of geological boreholes and geoelectric measurements is given in Fig. 1.

Azimuthal sounding (AVES) can be treated as a variant of the standard DC resistivity sounding, which is known also as Vertical Electrical Sounding – VES (Keller & Frischknecht, 1966; Koefoed, 1979). In our survey, a pole-dipole array with 8 spacings: AB/2 = AO = 1.47, 2.15, ... , 14.7 and 21.5 m (six points per logarithmic decade) and MN/2 = 0.4 and 2.0 m was used. Measurement procedure differs somewhat from the typical VES, which is usually limited to expanding array in only one direction. In the case of the AVES, after collecting measurements in one direction (azimuth) the sounding is repeated in another direction with the position of registration point (midpoint between potential electrodes MN) remaining unchanged. During the first sounding the current electrode (A) was directed towards the north. After completing this sounding, the whole array was rotated by 60 degrees and sounding was repeated. In that manner the six pole-dipole soundings were performed at the same site. Sounding point was located as close to the borehole as possible. For most sites the difference was less than 1 m. Favourable local surface conditions (for VES a flat surface is highly desired) enabled us to perform AVES in the vicinity of sixteen boreholes.

Details of **penetrometer-based resistivity profiling** are described by Mościcki (2009). Although the main parameter measured with the method is electrical resistivity, the velocity of probe movement can be also estimated. In GEOPROBE system this velocity is measured with a draw-wire displacement transducer (string pot). Measured velocity depends on sediment compactness but it should be treated as an estimate only because the side friction of the rods supporting the electrical probe rises with the depth and is not well controlled. As a result of the side friction measured velocity is lowered. In total, 30 sites were measured in 2007 (Fig. 1). The penetration depths depended on local conditions and ranged from 8 to16 m. Geological boreholes were drilled later (in the years 2007–2008). Most of them were located at the geoelectric sites if technical and terrain conditions allowed.

Remarks on electric resistivity of rocks. For a proper assessment of geophysical data some information about researched physical properties of sediments is advisable. Any type of rock can be characterized by measurable specific electric resistivity. Unfortunately, even for the same lithology the measured resistivity may vary in more or less. Moreover, different rock types may reveal very similar resistivity values (McNeil, 1980; Kobranova, 1989) depending on local conditions. For loose sediments (typical for the Quaternary formations) the problem is especially complicated because porosity, water/gas content in pores and voids, pore-fluid chemistry, temperature and content of clay minerals are the most important factors determining effective resistivity of any sediment. As will be shown, in the Ropyshche area, the shallow strata are often saturated with salty water (which is very good current conductor) and/or with oil and gas (which, when fresh, are bad current conductors, but their properties may change with time due to biological and/or chemical transformations). Thus, the resistivity of the same rock may vary for similar lithology depending on the “looseness” (compactness) of the sediments and pore and void fills. Nevertheless, even if there is no clear and unique resistivity-lithology relation, variations in resistivity reflect variability of sediments properties, state, structure, etc.

GEOLOGICAL DATA AND THE RESULTS OF GEOELECTRIC MEASUREMENTS

The study covers the area of the former ozokerite mine (which bears the local name “Ropyshche”) located in the Velyky Lukavets River valley (Fig. 1). From the geological point of view this area belongs to the Boryslav-Pokuttya Unit of the Carpathian Foredeep Basin. The Boryslav-Pokuttya Unit includes a flysch sequence uncomformably covered by the Miocene molasse. The upper part of the molasse is represented by the Lower Miocene Vorotyshcha salt-bearing beds, probably of Egerian (Korin, 2005) or Ottnangian (Andreeva-Grigorovich *et al.*, 1997) age.

The rocks are mostly sandstone-shale-marly breccia with clayey-salt cement cut by gypsum veinlets and occassional, single crystals of Na-K salts. Breccias are intercalated by medium- and coarse-grained sandstones of poor clayey-carbonate cement, by marls and host lenses, and layers of ozokerite. Zuber (1885) reported on the appearance of quartzite, limestone and schist fragments in the breccias. These rocks are underlain by shales. Laterally, breccias are replaced by the Sloboda Conglomerates and the Dobrotiv Sandstones.

Earlier information about lithology of Quaternary sediments is completed by Alexandrowicz (2004) and Alexandrowicz *et al.* (2005). Recent studies (Sokołowski & Stachowicz-Rybka, 2009; Sokołowski *et al.*, 2009) revealed that both the Pleistocene and Holocene sediments represent several environments typical of river valleys and their slopes: channel deposits, floodplain deposits and slope deposits.

Diversity of structural and textural features of sediments in each sub-environment enabled authors to distinguish several lithofacies, to which letter codes were attributed (for details see Table 1; Sokołowski *et al.*, 2009). Here, only a simplified version of this classification is presented, *i.e.* only those lithofacies, which may cause differences in the discussed physical properties of rocks were commented on. Coarse-grained channel deposits (mostly gravels) usually occur in the lowermost parts of boreholes and are rarely more than 2 metres thick. Almost all of them are clearly saturated with bitumen, which causes their high cohesiveness.

Floodplain deposits are dominated with fine-grained lithofacies of massive mud, up to 6 metres thick. The main fraction is poorly sorted from coarse grain to fine dust sediments, of mean grain diameter between 61 μm and 7 μm. In most of the studied sequences, variability of grain size is insignificant (Sokołowski *et al.*, 2009). In the floodplain subenvironment are also biogenic deposits, which appear at various sites as randomly distributed, lensoidal bodies. Peat reveals various degrees of decomposition of plant remains. Locally, admixture of dispersed mud (peat mud lithofacies) appears or peat grades into mud with high content of plant debris (biogenic mud lithofacies). Slope deposits appear above the valley bottom and include muds or sandy muds of thickness below 1.5 metre.

Apart from natural deposits, anthropogenic grounds occur in the study area, as well. These are mainly mine dumps composed of wastes left after former ozokerite mining in the area. The mine wastes form a continuous layer in the southeastern part of Ropyshche or a discontinuous one in the northern and northwestern parts of the area, and cover the above described natural deposits. Mine dumps, which have been intensively accumulated since the 19th century, contain breccias, sandstones, marls, gypsum and ozokerite together with bricks, concrete, ceramics, slag, wood and metals fragments embedded in silty cement.

The simultaneous presence of natural and anthropogenic sediments complicates a proper interpretation of geophysical data. Moreover, high salinity of sediments and groundwaters was noticed (Mościcki *et al.*, 2009), which may obliterate natural diversity of electric properties of rocks. In some places sediments saturated with bitumen were identified, as well. This saturation can be partial if the oil migrated through burrows and/or roots casts, but locally full saturation of rocks was observed. The presence of both oil and gas in Quaternary sediments also modifies physical parameters of rocks.

The discussed, complex geological environment is illustrated in Fig. 2, where detailed geological descriptions of cores from two sites located in different parts of the area (for location see Fig. 1) are set together with geophysical data. Penetrometer-based data are shown as graphs of apparent resistivity and penetration velocity versus depth. Results are different for the two sites. For the site No. 4 variations in lithology cause visible variations in resistivity. A layer of gravel at depths of 3.6–5.0 m with mud intercalation is well reflected on resistivity graph. That situation changes for borehole No. 22. In that case the resistivity curve is very flat and gravel layer at 6.0–6.5 m depth generates a very weak anomaly, only. The main reason of such differences is the presence of salty underground water filling pores and voids in borehole No. 22, while in the case of borehole No. 4 the bitumen filling dominates. There is a visible difference in mean resistivity level, too: 20–30 Ωm for site No. 4 and 5–6 Ωm for site No. 22. This difference probably reflects humidity/salinity of the sediments. At both sites, sediments are relatively loose (high penetration velocity) to the depth of 3.5–4 m.

For further analyses and comparisons with geophysical data the detailed geological description of cores were simplified. Such simplified lithostratigraphic columns supplement penetrometer data for the same measurement sites displayed in Figs 3–6. Additionally, for 16 boreholes azimuthal soundings were carried out and their results are presented, too. Apparent resistivity measured by azimuthal resistivity soundings is shown in the form of polar diagrams. For simplicity, the whole set of field data was limited to array spacings AO ≤ 14.7 m and MN = 0.8 m. Data for each measuring array spacing, AO, are represented by individual curves (it is worth to remind that for larger spacings the investigation depth is bigger). Interpretation of these diagrams needs some basic explanation. Let us consider a few simplified situations. In the case of homogenous rock formation the resistivity is constant for any spacing and all curves show the same sizes and shapes. In the case when layered sediments are parallel to the surface, the polar curves have the same shape but different size, which reflects vertical changes in resistivity of the layers. Inclination of the strata appears as similar deformation of all curves. If there is a local obstacle between current electrode (for some spacing – AO) and potential dipole (MN) the appropriate polar curve may be individually deformed.

Detailed analyses of graphs presented in Figs 3–6 do not reveal a clear correlation between lithology and geophysical data: resistivity and penetration velocity. Nevertheless, some interesting observations can be gained from these results. Locally, for relatively small study areas, resistivity graphs correlate between adjacent sites. The examples are sites Nos 33, 3 and 30 (PPO-33, PPO-3 and PPO-30) (Fig. 6). Here, the decrease of measured resistivity at 7–8 metres depth is visible, but resistivity drop correlates with the top of the Miocene strata for borehole No. 30 only. Other examples are sites Nos 6, 16, 15, 13, 14 and 12, arranged in a profile given in Fig. 5. In three (four) initial sites, resistivity drops gradually and then rises, which is followed by radical decrease of penetration velocity. Lowered velocity can be explained by the rising content of sand fraction (site No. 15) or gravel fraction (site No. 16) in deeper strata. An important role may be played by intercalations of sandstones in the salt-bearing Vorotyshcha beds, too. If water content in penetrated strata is low, the velocity slow-down may be much more evident. Distinct changes in velocity were observed at site No. 12, where resistivity values are very small and rather stable. Here, the Miocene strata were geologically identified at very shallow depth, but this fact was not evidenced by penetrometer data (the very small rise in resistivity was noticed, only). In sites Nos 12 and 14 (partly also in No. 13) the subsurface layers characterized by high penetration-velocity extend to distinctly deeper sediments in comparison with initial three sites Nos 6, 16, 15. Geologically, it may be interpreted as lowering of sandy component within the Miocene sediments. Interesting geologic conditions exist in the vicinity of sites Nos 21 to 25 (Fig. 3), where at some depth intervals negative correlation between resistivity and penetration velocity for sediments underlying sub- surface zone of high penetration velocity was

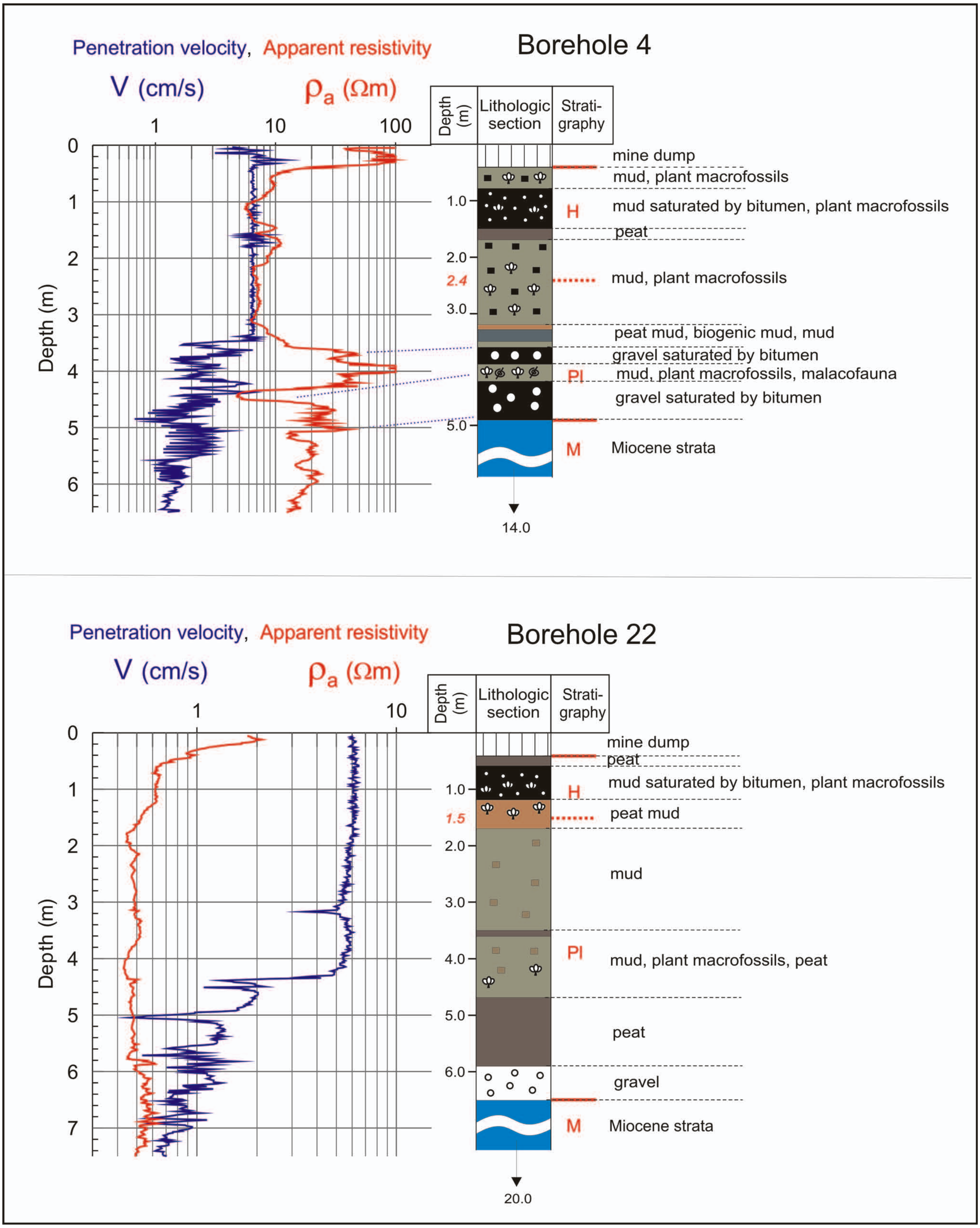

Fig. 2. Geological description of cores of two chosen boreholes Nos 4 and 22 and penetrometer-based data. Stratigraphy: H – Holocene, Pl – Pleistocene, M – Miocene

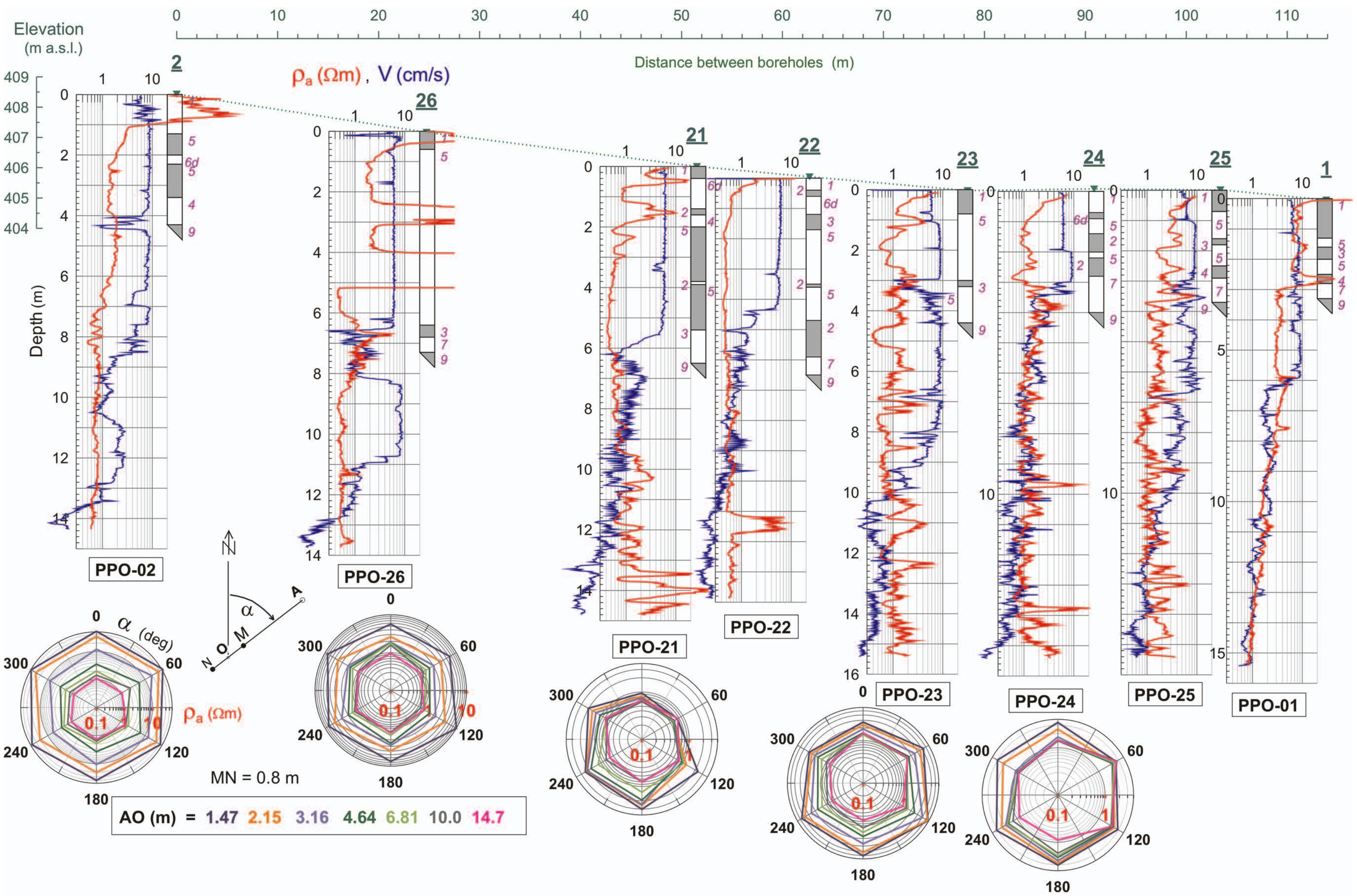

Fig. 3. Results of penetrometer-based measurements of sites Nos 2, 26, 21, 22, 23, 24, 25 and 1, DC azimuthal pole-dipole soundings, and lithostratigraphic columns interpreted from drill cores. 26 – penetration sites, usually the sites of geological boreholes; PPO-2 – penetration graphs (ρ_a – electric resistivity and V – penetration velocity). Symbols used for types of sediments: 1 – mine dump, 2 – peat, 3 – peat mud, 4 – biogenic mud, 5 – clayey mud, 6d – mud saturated with bitumen, 6g – coarse clastics saturated with bitumen, 7 – gravel, 8 – sand, 9 – salt-bearing Lower Miocene Vorotyshcha beds

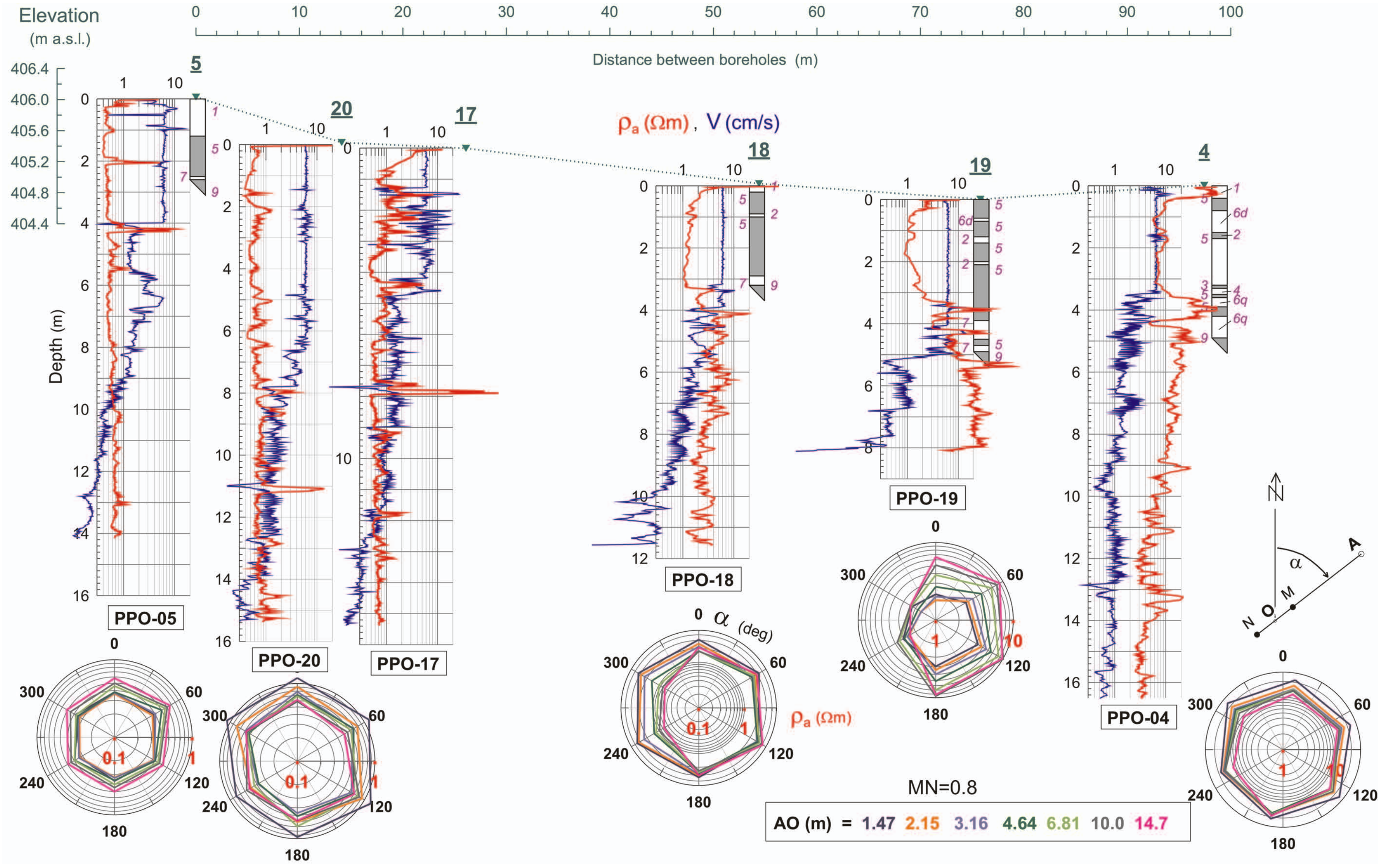

Fig. 4. Results of penetrometer-based measurements of sites Nos 5, 20, 17, 18, 19 and 4, DC azimuthal pole-dipole soundings, and lithostratigraphic columns interpreted from drill cores. Explanation of symbols as in Fig. 3

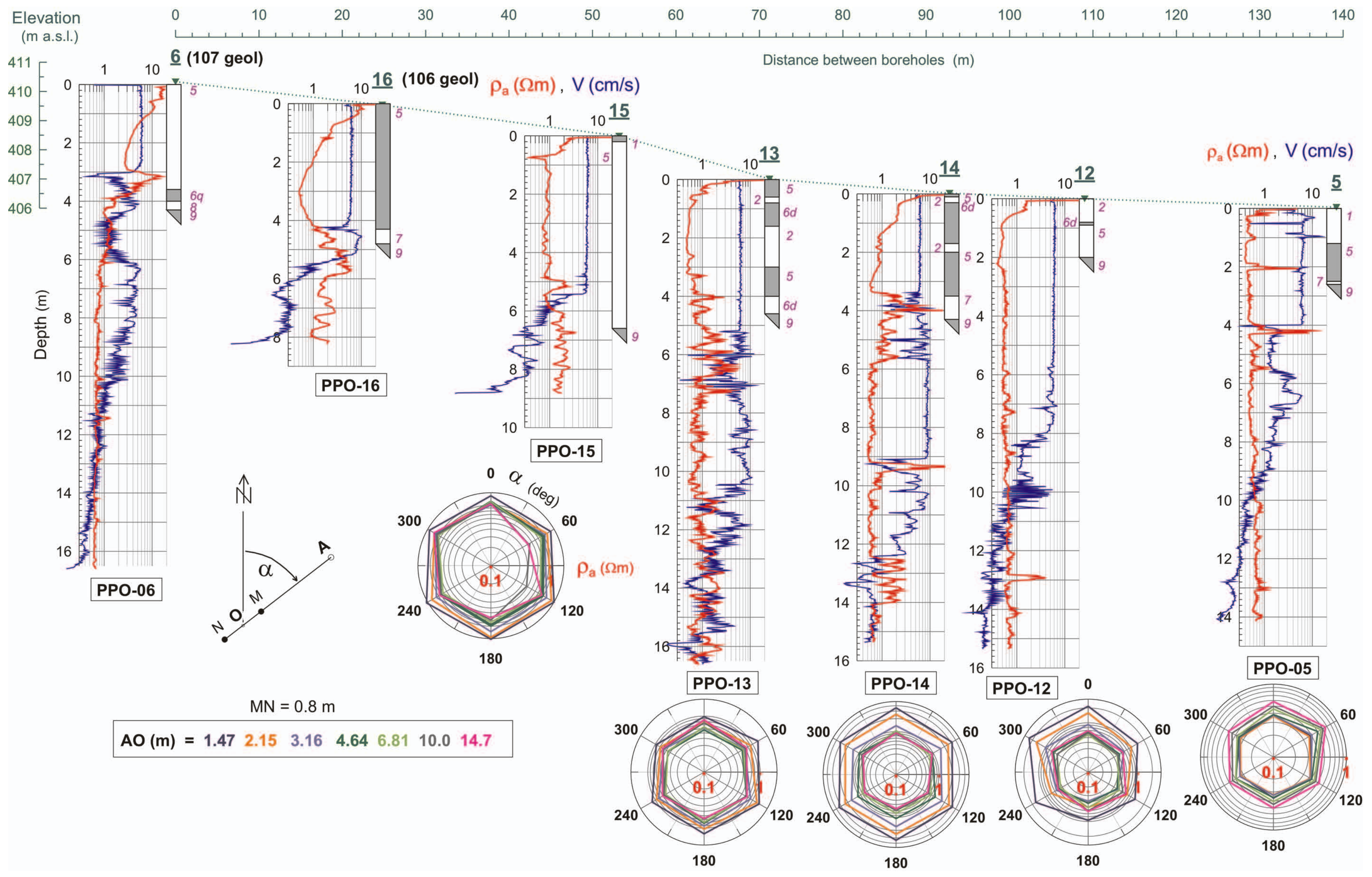

Fig. 5. Results of penetrometer-based measurements of sites Nos 6, 16, 15, 13, 14, 12 and 5, DC azimuthal pole-dipole soundings, and lithostratigraphic columns interpreted from drill cores. Explanation of symbols as in Fig. 3

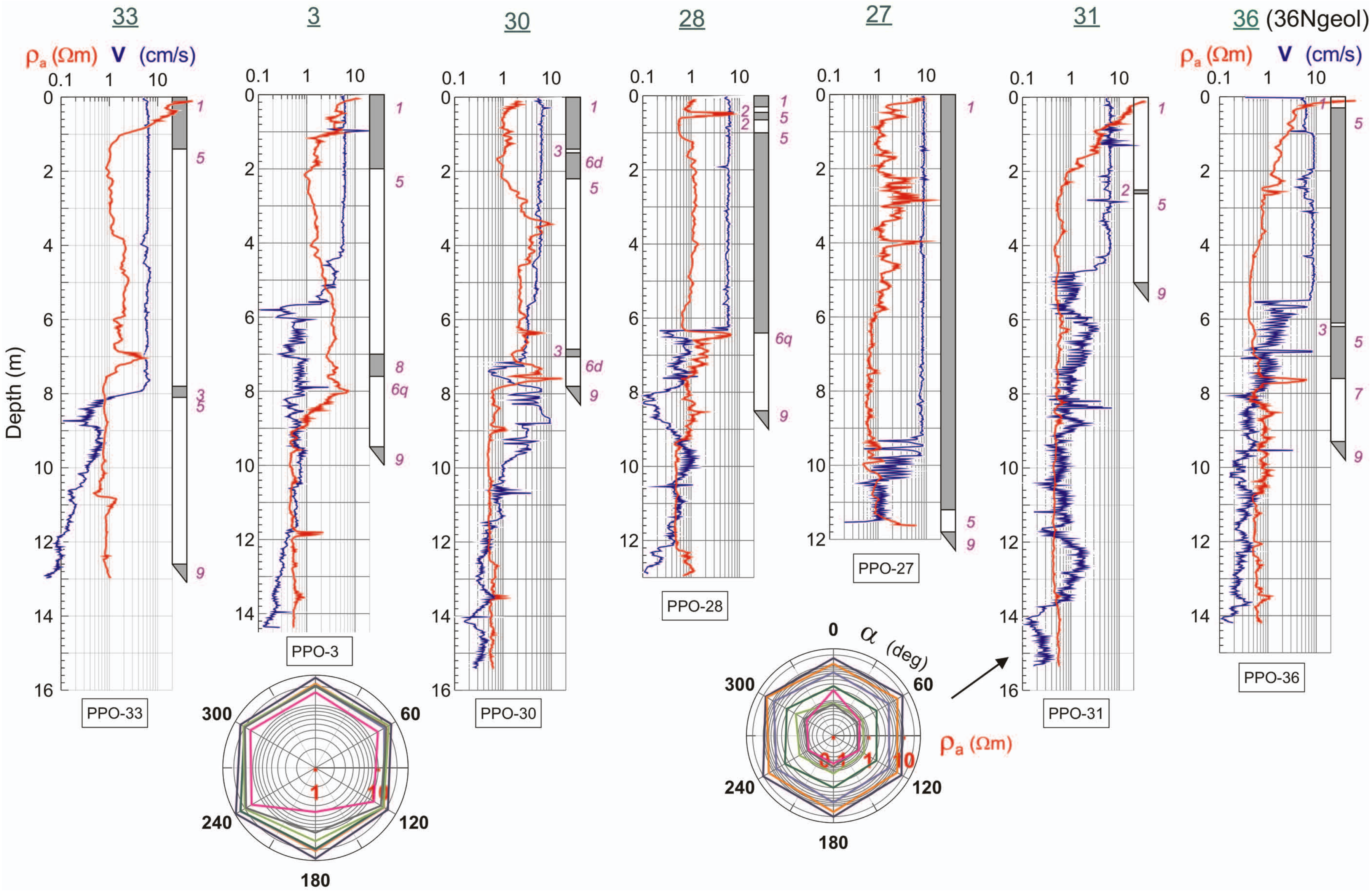

Fig. 6. Results of penetrometer-based measurements of sites Nos 33, 3, 30, 28, 27, 31 and 36, DC azimuthal pole-dipole soundings, and lithostratigraphic columns interpreted from drill cores. Explanation of symbols as in Fig. 3

found. Unfortunately, geological boreholes were too shallow here and identification of lithology within the mentioned interval was impossible. The highest penetration velocity was noticed in the area of thick anthropogenic sediments (site No. 27).

Environment in the vicinity of geological boreholes is commonly very heterogeneous (or disturbed), as reflected by deformations of relevant AVES polar graphs. The most remarkable deformation pattern was recorded for site No. 19 (Fig. 4). The east-oriented part of the graph differs completely from the west-oriented one, especially for larger spacings AO. Polar graph for adjacent, No. 18 site is also far from uniform. It may be interpreted as a result of steep geological boundary. It is consistent with other geoelectric data – apparent resistivity contours based both on the standard VES and on electromagnetic profiling with the EM31 Geonics (Mościcki, 2009). A lot of heterogenities exist also in the vicinity of boreholes Nos 21 to 24. As lithology of the Quaternary sediments is very similar at these sites, the probable reasons of polar diagram deformations are local variations of porosity or salinity, or anthropogenic obstacles in the vicinity of sites. The remaining resistivity polar graphs show more or less symmetrical patterns indicating rather uniform distribution of sediments (in relation to direction of the AVES).

For a better illustration of spatial complexity of sediments, the whole set of penetrometer-based data were used to generate maps for different depth levels. For that purpose raw data were averaged within 0.5 m wide depths window and obtained mean values of a desired parameter were used as map contours. Selected results concerning resistivity data are displayed in Fig. 7. Generally, the central fragment of the study area is filled with low-resistivity sediments, which tend to “expand” with depth. In this part of the area, the top of Miocene strata lays at a relatively shallow depth (Fig. 8D), so resistivity decrease in deeper sediments may be a sign of rising salinity in that strata. In the eastern part of study area, higher resistivity boundary remains generally unchanged for all depth levels shown (see also Mościcki, 2009). However, resistivity contours do not follow fossil morphology of the underlying Quaternary sediments, modern morphology of the terrain (Fig. 1) or elements of morphology of the top of Miocene strata (Fig. 8D). The main reason for such a specific distribution of the resistivity in the area (higher in the eastern part and lower in western one) is probably of hydrogeological nature, *i.e.* salinity and direction of flow of underground water what determines resistivity of sediments. On the other hand, ways of underground water flow (preferring less compact loose, permeable material) may be influenced by anthropogenic, post-mine transformations of the sediments (loosing). One can also take into account some effects of neotectonic activity noticed for the area (Stelmakh, 2005), which might influence shallow sediments properties, too.

One more particular pattern needs explanation. On the map representing the 4.0–4.5 m depth range, there is a distinct, high-resistivity anomaly around site No. 26 (compare with PPO-26 resistivity graph in Fig. 3). One reason of such anomaly may be an anthropogenic effect of post-mining cavities filled with oil or ozokerite clod (as penetration-velocity was high at this site). On the other hand, a momentary problem with electric contact of the probe might generate such anomaly, too.

The next set of maps (Fig. 8A–D) gives a better insight into the compactness of geological material. At a planning stage of penetrometer survey, penetration depths were assumed down to 15–16 metres. However, at some sites high mechanical resistance of penetrated sediments precluded such depths. Therefore, variations in the final depth achieved give some insight into local basement compactness. These data are presented in Fig. 8A. The next interesting parameter is penetration velocity. Velocity usually decreases with increasing depth. For one selected depth level the estimated contours are given in Fig. 8B. Another considered parameter is the thickness of relatively loose sediments. As it may be seen in penetration velocity graphs (Figs 3–6), the velocity is usually very high in near-surface sediments, which are mainly Quaternary strata and, sometimes, also mine dumps. The thickness of this high-velocity zone (layer) changes from site to site. Sometimes, there is more than one high-velocity layer in a vertical profile of the same site. The appropriate map of high penetration-velocity zone was constructed (Fig. 8C) for the topmost zone only. All presented maps are supplemented with the depth to the top of Miocene strata map interpreted from boreholes (Fig. 8D). On the last map rapid increase of the depth to the top of Miocene formation in the southern part of the area is visible. It may be connected with collapse of the former underground post-mining open spaces. This pattern partly correlates with the near-surface high-velocity layer thickness, which also rises is the southern part of the region. Such lowered compactness of the near-surface sediments was noticed in the NW-SE oriented belt crossing the area, too (Fig. 8C). This direction has probably some deeper importance for that area as it appears on distribution of geoelectric, gravimetric (Porzucek & Madej, 2009) and geochemical anomalies (Kotarba *et al.*, 2005).

CONCLUSIONS

All studies performed in the Starunia area were focused on the recognition of the site of paleontological discoveries, although the exact location of these finds was unknown. The area and volume of detailed geological and geophysical works were determined on the basis of historical documents and results of earlier reconnaissance surveys (Kotarba, 2005). As remnants were found in “… grey muds with *Betula nana*…” (Nowak *et al.*, 1930), the studies of geological boreholes were focused on sediments like Pleistocene fine-grained (mud, clayey mud) and biogenic (peat, peat mud, biogenic mud) deposits. Geophysical methods: DC azimuthal pole-dipole resistivity soundings and penetrometer-based resistivity profiling supplemented by penetration velocity measurements were applied to assess variability of sediments in the vicinity of geological boreholes. No evident relation was observed between lithology of drilled sediments and their geoelectric characteristics. The main reason of this was the presence of underground salty water, which radically lowers and covers natural differences in

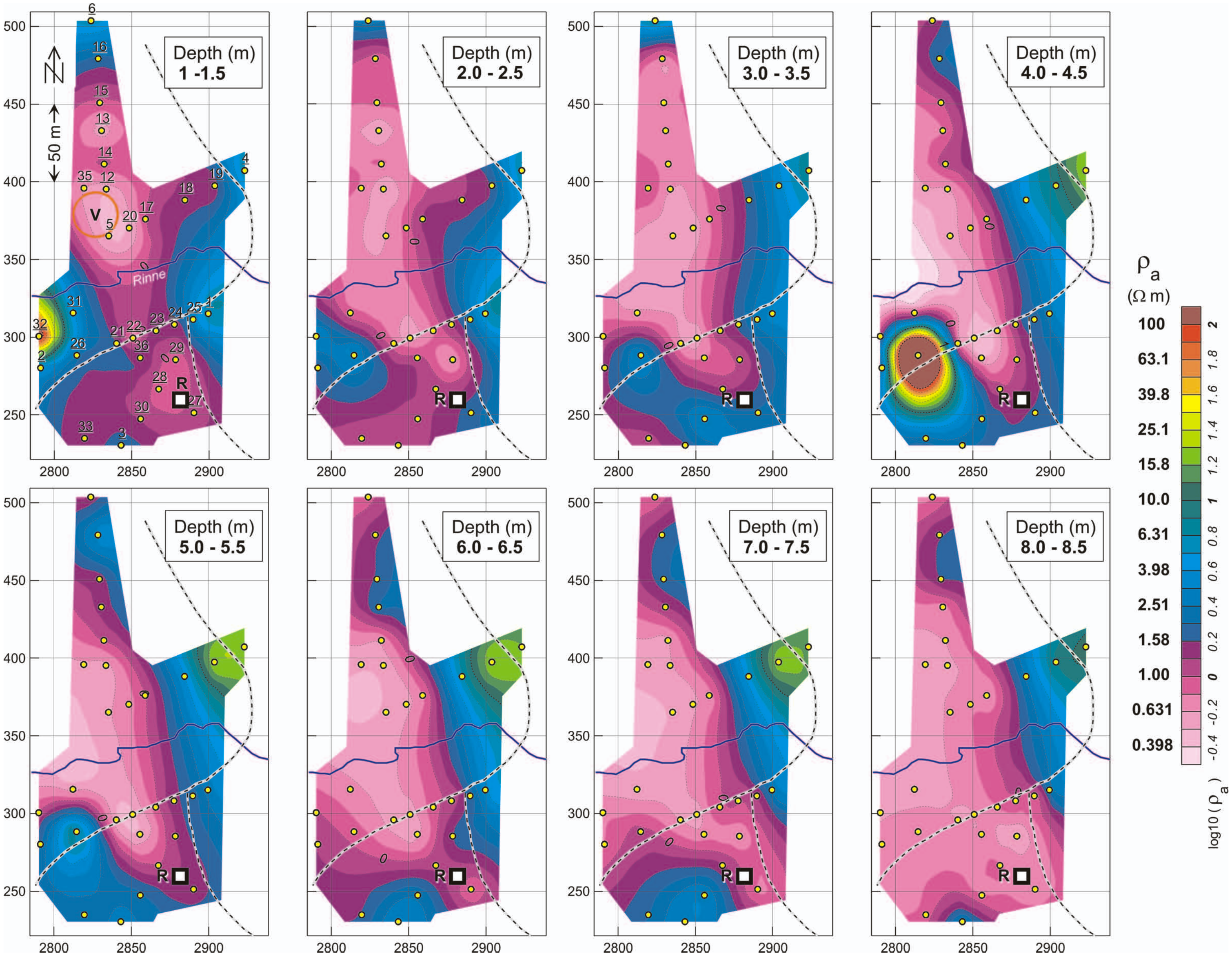

Fig. 7. Resistivity contours of sediments based on averaged penetrometer resistivity data. Each map was drawn for different depth window. Contours expressed as logarithms of resistivity given in Ωm

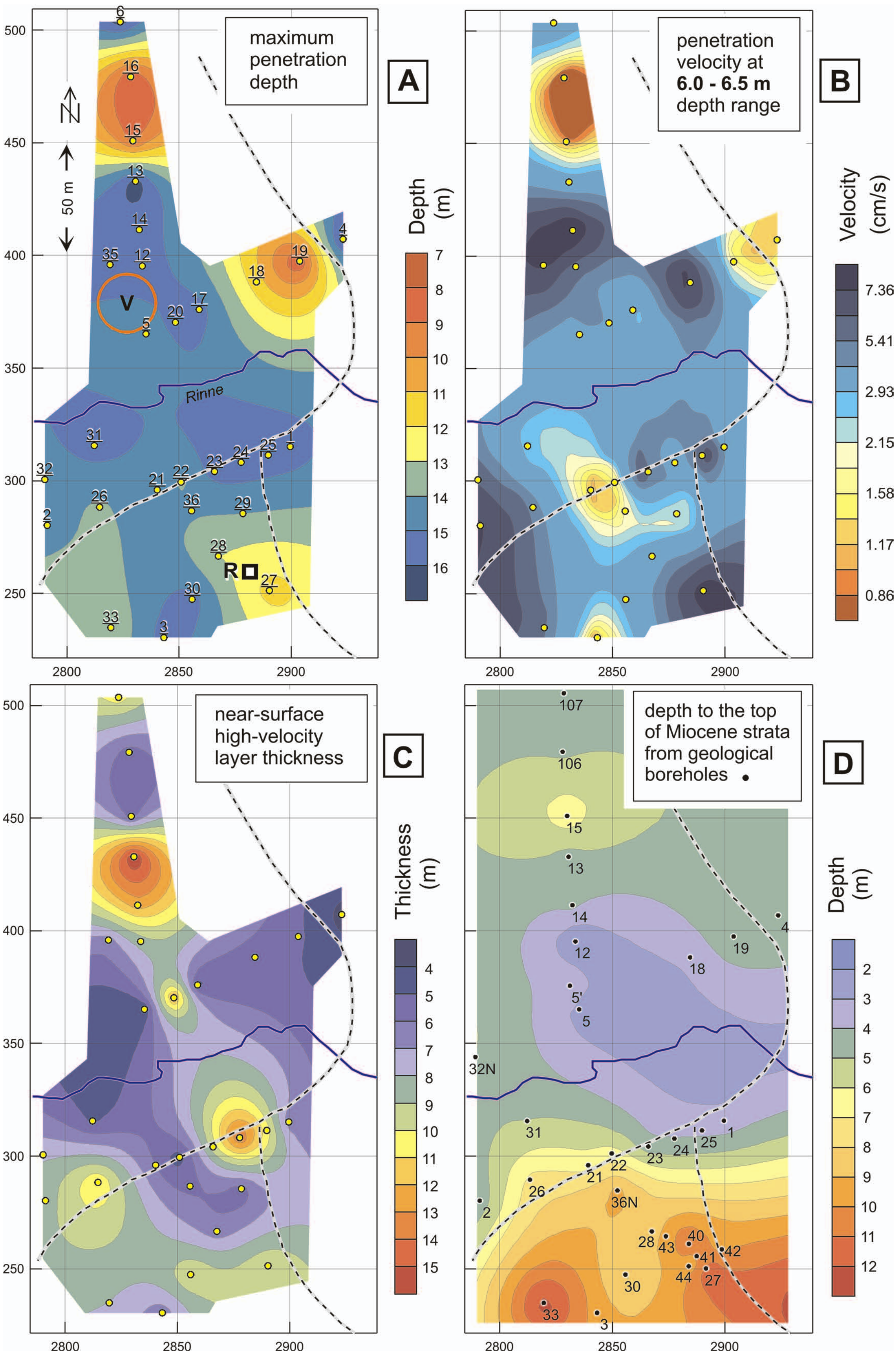

Fig. 8. Maps of mechanical properties of sediments (compactness) estimated from penetration data and depth to strata identified as Miocene beds: (**A**) maximum penetration depth, (**B**) penetration velocity at 6.0–6.5 m depth range, (**C**) near-surface high-velocity layer thickness, and (**D**) depth to the top of Miocene strata from geological boreholes

sediments resistivity. Nevertheless, at some measurement sites, a significant variability of measured geophysical parameters was observed. This variability interpreted as heterogeneity of sediments and their physical properties/state was observed both horizontally and vertically. The strongest horizontal changes were noticed in the vicinity of sites Nos 12 and 14, located on the north-south line of boreholes and near boreholes Nos 19 and 4 situated in the eastern part of the study area. These zones generally coincide with changes of the depth to the top of Miocene strata. The presence of loose and compact zones, assessed from penetration velocity, may result from neotectonic movements or from antropogenic transformations of sediments (*e.g.*, collapse of post-mining cavities). Physical properties of geological strata: electric resistivity and compactness (inferred indirectly from penetration velocity) change also with depth, but only in limited number of cases correlation with lithology can be found.

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