Combining ground penetrating radar and electrical resistivity tomography for the study of history of relief development in Dnieper River valley

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***Abstract* — Application of geophysical methods in geomorphological studies is aimed at the reconnaissance of drill core locations and interpolation between cores: tracing of lithological and stratigraphic boundaries, as well as the determination of bedding type within individual strata (horizontal, crossing, etc.) which is important for interpretation of their genesis. Our study was conducted in the upper Dnieper River basin, north-west of the Russian Plain, where no particular research has been conducted in the last 40 years to clarify the maximum glaciation boundary. We carried out ground penetrating radar and electrical resistivity tomography investigations to assess the geological composition of the active and abandoned Dnieper valleys downstream from Smolensk, which is crucial for understanding the river flow rerouting during the last glacial epoch.**

Keywords — GPR, ERT, upper Dnieper valley, fluvial geomorphology

I. Introduction

One of the most significant issues of modern paleogeography is the adjustments of flow systems to the influence of the last glaciation. The information about the maximum extent of the last glaciation is necessary for the reconstruction of the drainage net transformation and freshwater balance of inland seas, for the exploration of migration routes of ancient humans and for the mineral deposits prospection. Along with the examination of maps and airborne and satellite images, the important tool for approaching these issues are geophysical methods, such as ground penetrating radar (GPR) and electrical resistivity tomography (ERT) coupled with drilling and geochronological studies of the Quaternary sediments.

Our study was conducted in the Upper Dnieper valley near Smolensk, Russia, in the vicinity of the Scandinavian Ice Sheet boundary in its south-eastern sector. The most recent large-scale geological studies, including drilling, in the Upper Dnieper valley were conducted in 1950-60s [1] and subsequently led to the wide-spread concept of the late-glacial formation of the Upper Dnieper valley as well as to the discussion whether this valley was ice-dammed during the last glaciation or not. The young age of the Dnieper valley at Smolensk was questioned by Panin et al. [2, 3]. It was supposed that at the Last Glacial Maximum (LGM, ca. 20 ka BP), the Dnieper valley was dammed by the ice sheet and diverted to the south-east, from the Baltic to the Black Sea basin. The main aim of the current research is to check this hypothesis by investigating both the abandoned and active valleys of Dnieper.

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II. Study area

The research area is a part of the Russian Plain (Fig. 1), where the Dnieper River is one of the major river streams, which valley was most probably formed after deglaciation of the Moscovian ice sheet (Saale, Marine Isotope Stage 6) in the late-Middle Pleistocene. The Dnieper River was the only route linking the Black Sea to the decaying Scandinavian ice sheet in the LGM. The present-day Upper Dnieper catchment is a combination of hilly uplands with a maximum elevation of 260-280 m a.s.l. and flat swampy lowlands lying at 170-200 m a.s.l. The geomorphological setting of the area is described in detail in [2]. Bedrock is everywhere covered by Quaternary sediments deposited mainly during the Middle and Late Pleistocene glaciations – loamy glacial till (moraine), sands with fine to medium gravel, and peats.

Three key points were chosen in the valley for geophysical investigation, names are given in accordance with nearby villages: “Volkovo” – the young valley that was hypothesized to have been formed after the LGM, “Katyn’” – the abandoned pre-LGM valley, and “Chekulino”. Near Volkovo there is the abandoned channel and residual hill formed in course of valley re-routing, moreover there are several sand quarries, which allowed us to assume a lot of sand sediments here, although the sand in the outcrops contained a lot of clay. In the Katyn’ site, the marginal fluvioglacial formations that overlook the lower terrace of Dnieper are found. The Dnieper valley, consisting only of

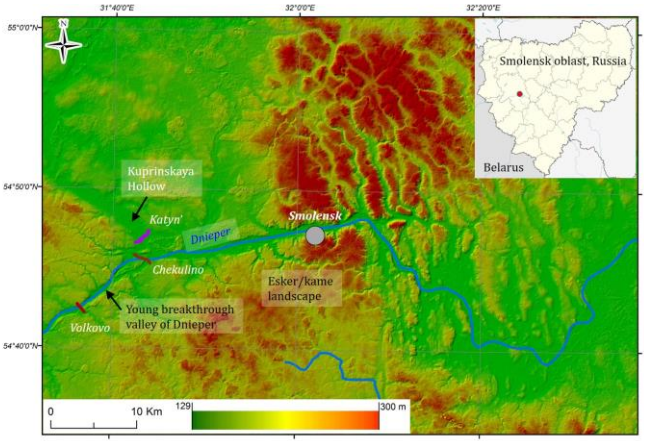

Fig. 1. Objects for the geophysical field survey at the upper Dnieper.

the channel and floodplain, strongly narrows and turns south-west downstream the Katyn' village. The single-thread palaeochannel and 30 m residual hill were discovered near the Chekulino village and detailed drilling and numerical age determination was performed [2]. In this article we will discuss in detail one of profiles – "Chekulino".

III. Materials and Methods

The main purposes of geophysical methods in this study were the reconnaissance of drill core locations and interpolation between cores: tracing of lithological and stratigraphic boundaries, as well as the determination of bedding type within individual strata (horizontal, crossing, etc.) which is important for interpretation of sedimentation mechanisms. The GPR can be applied for relatively small depths (not more than 10-15 m), but it provides high-resolution data. It is effectively used to study Quaternary river and lake sediments as a single method if there is sufficient a priori information about the section and drilling data [4]. The ERT is a geophysical technique that has been widely used to study the river valleys and palaeochannels [5]. The ERT provides a cost effective tool for characterization the geology in engineering investigations. The depth of research can reach 200 m, but increasing depth of research comes at the expense of the resolution.

A. GPR survey

We conducted GPR data using two radar systems – Python-3 (Radar Systems, Inc., Latvia) with unshielded antenna units 100, 50, 38 and 25 MHz; and OKO-2 (LOGIS-GEOTECH, Russia) with 250 MHz shielded antenna unit. Such wide range of antennas was used for different penetration depth and optimum resolution. The dominant wavelength for these antennas is 1-4 m for sand-clay deposits; the resolution is 0.5-2 m. Penetration depth is about 10-15 m in dry sand. Based on the results of the comparison of GPR profiles obtained with these antennas, units of 100 and 250 MHz were chosen for the vast majority of sections. These antenna units provided sufficient depth and resolution in the absence of heavy external noises. The upper 5 meters were examined in detail with 250 MHz of OKO-2 GPR system, depth until 10-12 meters – with 100 MHz of Python system.

We acquired our GPR data with 250 MHz/100 MHz in common offset mode with a trace spacing of 0.1 m/0.7 m, a time window of 400 ns/500 ns and a sampling interval of $\Delta t \approx 0.78$ ns/0.48 ns consequently. Positioning was controlled with an odometer wheel and tachymeter. The profile lines were previously freed from excess vegetation, branches and logs. The data were subsequently processed using RadExplorer (Radar Systems, Inc., Latvia) software. Our general processing comprised t_0-correction and background removal, gain, amplitude correction and bandpass filtering. Data were topographically corrected. We used Leica TPS-1200 total station for positioning of GPR profiles and to create the digital relief model along the geophysical profiles.

B. ERT survey

We used an Omega-48 multi-channel electric resistivity tomography (ERT) system (LOGIS-GEOTECH, Russia). The measurements used a 48-electrode line with a step between electrodes of 5 meters. The total length of one line is 235 meters. Observations were made with a combined three-electrode array Amn + mnB. The difference in the supply line varies from 7.5 to 192.5 m in increments of 5 and 10 m. The lengths of the receiving line (MN) are 5, 15 and 45 m. The transition from one receiving line to another was performed with overlapping at one point. The step between the sounding points was 5 m, the total number of measurements on one array was 1448. The measurements were performed with an output voltage of the generator of 100-200 V. The current in the supply line reached values from 5-10 to 20-40 mA. The source is multi-polar rectangular pulses with pauses; the duration of pulses and pauses between them is 100 ms (operating frequency 2.5 Hz). The signals in the receiving lines were recorded with a stacking of 4 and automatic gain control. The control observations were at least 20% of the total observations. The average relative error of measurements was ± 1%. The results of ERT observations were processed with the following procedures: viewing data and eliminating individual errors; the construction of apparent resistivity plots over all profiles; topography correction; the automatic inversion of apparent resistivity plots and the interpretation of geoelectrical sections along them. ERT data processing was performed by using X2IPI program. We performed data inversion in the Res2DInv, as well as in the Zond2D programs.

C. Combination of ERT and GPR

Complex of GPR and ERT have been widely used for Quaternary deposit lithological and sedimentological characterization. The combination of these techniques applied to map river terrace deposits [6], to recognize

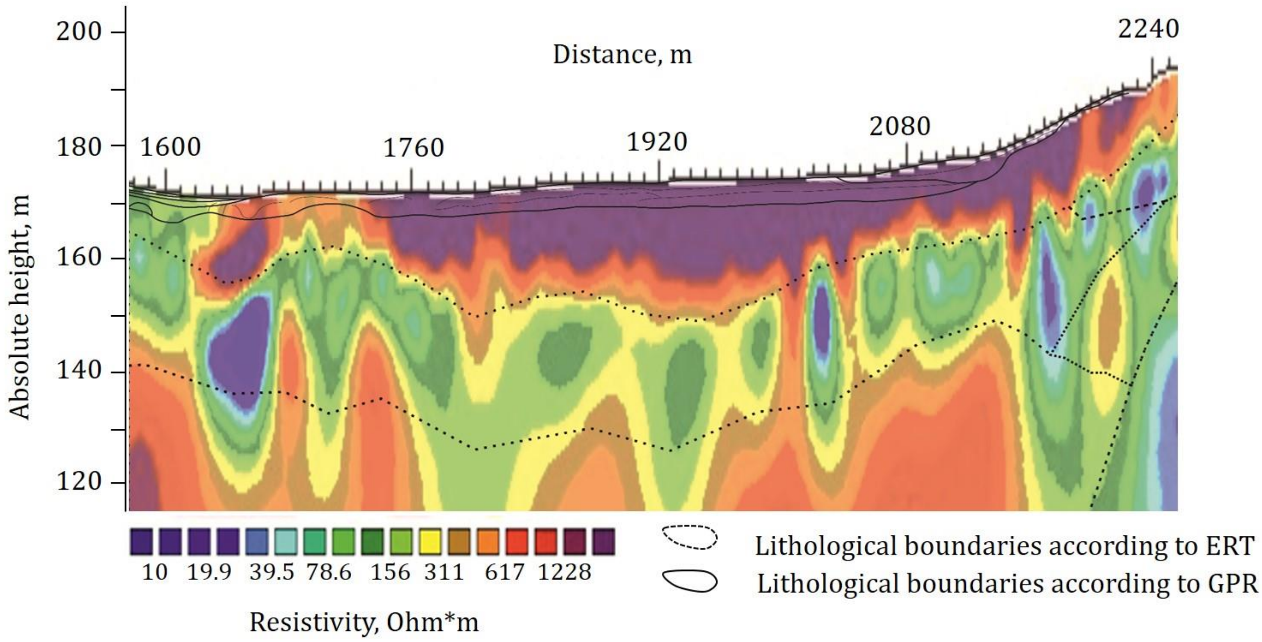

Fig. 2. Fragment of two-dimensional resistivity inversion model, obtained from the ERT profile "Chekulino".

groundwater flow through glacial sediments [7] and pathways of water and nutrients along slopes in discontinuous permafrost regions [8], to study the internal architecture of Quaternary sediments [9] and to map the underground ice [10]. The efficiency of GPR-ERT combination is due to the differences in resolution and depth of penetration.

IV. RESULTS AND INTERPRETATION

Consider the profile "Chekulino" as an example for demonstration the possibilities of combining GPR and ERT data. This profile crosses the residual hill on the left coast of Dnieper, the length of GPR profile 2250 m, length of ERT profile here is 2520 m, so that the data could be compared. ERT section along "Chekulino" profile shows strong electrical contrasts between deposits, the layers with different electrical properties are clearly recognized (Fig. 2). Fig. 3 shows the fragment of geological interpretation, based on ERT, GPR data and one borehole, presented in [2]. The upper part of the ERT profile is represented by sediments with a high electrical resistivity (700-2500 Ohm·m) corresponding with sands with gravel (layer 1 on Fig. 3), with the exception of the northwestern edge of the profile (2250-2520 m), probably represented by sands. The boundary of the upper layer is parallel to the Earth surface; the layer has permanent both thickness and resistance. A layer of loam located below 15 m; loams in the central part of the profile (layer 5) and at its edges (layer 4) differ significantly from each other, probably due to their different lithological composition. The layer of loams on the edges of the profile has lower values of electrical resistivity (10-50 Ohm·m), a permanent thickness (15-17 m) and lies almost horizontally. Loams in the central part of the profile have higher resistances (up to 100 Ohm·m); this layer has a substantially greater thickness (25-35 m) and lies cup-like. In the interval of 240-1120 m and 2170-2280 m of profile, a soil lens with relatively high resistance (200-500 Ohm·m) underlies this layer of loam – presumably sand with pebbles (layer 3). The soils that compose the base layer in the middle part of the profile most likely have a similar lithological composition, but increased resistivity (700-1200 Ohm·m) indicates an increase in particle size and the presence of gravel (layer 2). Low-resistance (50-300 Ohm·m) sands and sandy loams probably represent the base layer at the edges of the profile. Topographic data are also used to compare subsurface reflections to topography in order to aid in interpretation.

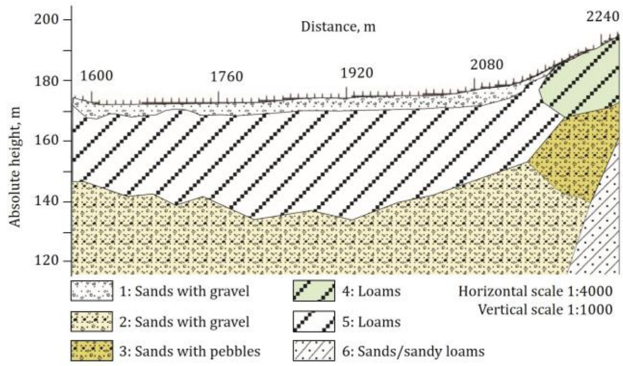

Fig.3. Geological interpretation of the half of "Chekulino" profile based on the combination of ERT, GPR and borehole data.

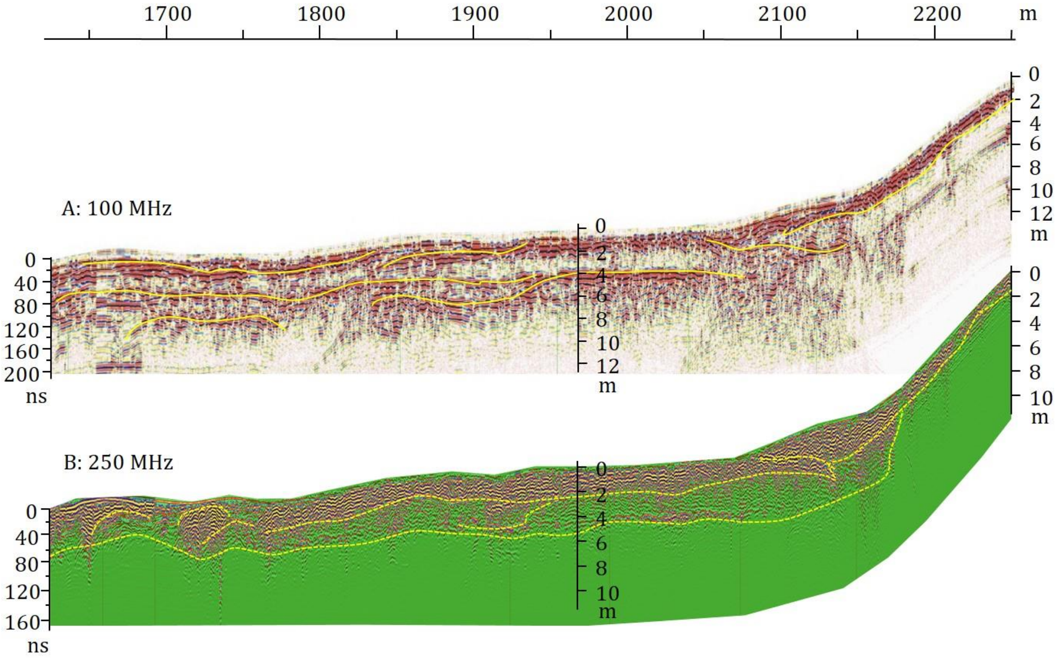

Fig. 4. Fragments of GPR profile "Chekulino", shows data, obtained with 100 MHz (a) and 250 MHz (b). Lines denote the radar facies identified in the interpretation.

Since by the ERT data it is not possible to obtain detailed information on the structure of the upper 10 m layer, GPR data were used to help the interpretation. The 100 MHz antenna reaches a maximum depth of investigation of 18-10 m along whole profile − below the semihorizontal reflection on this depth reflections does not occur due to the attenuation in loams and clays. In different part of profile (closer to the surface on the hilltop), the top of loams is located on the depth 4-5 m. The upper part (0-2 m) of "Chekulino" profile in its entirety presents chaotic reflectors agreeing with the sandy gravel − it is a wave pattern typical for coarse sand with fine to angular medium gravel. Hyperbolae reflections depicted in this layer were

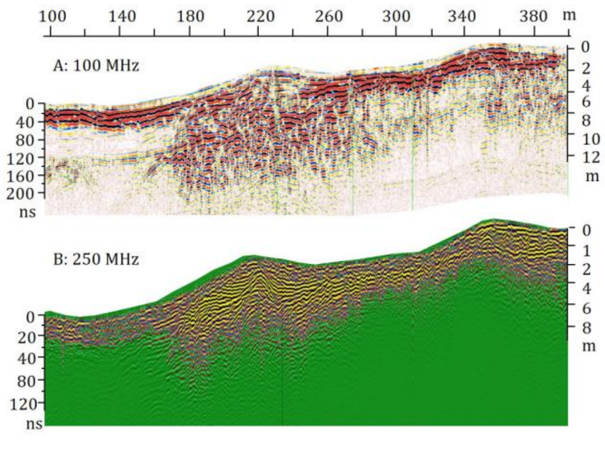

Fig. 5. Fragments of GPR profiles, acquired with 100 MHz (A) and 250 MHz (B), show a complex lithological structure within terrace of the Dnieper River.

used for velocity calibration. The thickness of sand deposits decreases to the minimum 0.8-1 m on the top of residual hill on 825 m of profile. Fig. 4 shows an interpretation of the 100 and 250 MHz data of the half of "Chekulino" profile, where strong reflections have been traced also on ERT data. After 1300 m of profile, on the descent from the hill, a layer with a thickness of 2 m appears at depths from 5 to 7 m. This layer is present in the entire depression between the residual hills. A large number of horizontal layers in this depression may represent alluvial sands of different granularity. Informative part of GPR profile here ends at a depth of 6 m. This correlates with drilling data, presented in [2], where in this place basal fluvial sediments were observed on depth 7-8 m.

The comparison of results, obtained with two different antennas, showed that 100 MHz profile more informative and, despite the lower resolution, more clearly shows the differences between lithological structures. However, a vast landslide with numerous diffraction points was observed at the end of profile (2050-2150 m), obtained with 250 MHz antenna. This important lithological feature before the rise to the next hill is hardly noticeable on lower frequency data. Boundaries, which were obtained here with GPR technique, labeled with solid lines on ERT profile on Fig. 2.

Both geophysical methods yielded stratigraphic information, and detected strong electromagnetic interfaces between sand and loam deposits. However, sand layer with thickness about 10 m was indistinguishable on ERT data due to low resolution in upper part. It was also noted that sediments with a high electrical resistivity (700-2500

Ohm·m) in the upper part of ERT profile could be the sands with gravel, because this layer has a typical wave pattern on GPR data. Furthermore, on the GPR data, we marked a number of local features not visible for ERT. In the beginning of profile, between 175 and 280 m, there is a complex lithological structure within terrace. Fig. 5 shows the comparison between two antennas above this structure. On the data obtained with the 100 MHz antenna, only common features appeared, but on 250 MHz data, all of its complex morphology, including even a layering inside, is obvious. This feature could be interpreted as a channel levee formed during lateral river migration.

V. Conclusion

Both geophysical methods showed their worth in identification lithologic units crucial for the reconstruction of palaeogeomorphic features – palaeochannels, loams and peats infilling palaeochannels, channel bars, sand cover sheets, etc. Geological mapping and the geotechnical investigations, supported by geophysics, provide meaningful information for the reconnaissance of drill core locations and interpolation between cores: tracing of lithological and stratigraphic boundaries, as well as the determination of bedding type within individual strata (horizontal, crossing, etc.) which is important for interpretation of their genesis. The radar facies obtained from GPR data correlate with the lithological structures defined from the ERT and drilling data. Combination of the two geophysical datasets together allows a comprehensive sedimentological and lithological characterization of the subsurface. In addition, using GPR profiles as an a priory information for the inversion procedure in ERT may significantly improve its quality.

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