

Ground penetrating radar investigations of the geological structure of loose sediments at solid mineral deposits

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Abstract. For effective commercial development of deposits, an increase in the information content of operational exploration is required. In recent years, the range of methods used to obtain complete and reliable information about the structure and properties of the rock mass of a developed field include remote methods of high-frequency electrical prospecting, in particular, the ground penetrating radar (GPR) method. The paper presents a methodological experience in the interpretation of GPR data of sandy river sediments based on the identification of radar facies. In the considered area, four types of radar facies have been identified that characterize the structure of sandy deposits and the morphology of the river bed. The criteria for identifying radar facies were used to analyze wave patterns of loose sediments in a sand and gravel pit and a placer gold deposit. Experimental GPR investigations are presented by data from a sandy-gravel pit (Warsaw, Poland) and from a placer gold deposit (Yakutia, Russia). As an example, a GPR section along the Paplin quarry and its interpretation, with the identification of GPR facies, is presented. A cross-sectional GPR profile of the dredging landfill is considered for the placer gold deposit. The analysis of the wave pattern was carried out, geological boundaries were highlighted. Based on the interpretation results, the characteristics of the rocks were given. It was noted that according to the GPR data, it is possible to identify zones of uplift of bedrock, which can affect the course of the dredge. As a result of using GPR in a swampy area where drilling was impossible, a deep three-layer section was obtained. The presented results of the successful use of GPR investigations and methodological approaches in the interpretation of data, show the promise of using the GPR method in assessing mining and geological conditions, in particular, placer deposits. At the same time, the efficiency of obtaining data can further contribute to the optimization of technology and increase the efficiency of field development.

Keywords: placer gold deposits, dredging range, GPR, structure of loose sediments, sandy river sediments, radar facies, wave pattern.

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1 Introduction

A significant part of gold is mined from placer deposits in the Far East region. In this area, mining operations are associated with permafrost and difficult mining and geological conditions. The main factors that determine the feasibility and possibilities of commercial development of subsoil include mining and geological conditions for the development of deposits. Of these, at the stage of actual mining, the most significant are the form and internal structure of mineral deposits. These indicators to a large extent determine the choice of the scheme and method of stripping and preparation for stope excavation, the parameters of development systems and production processes, and safe mining.

To improve the efficiency of mining operations, an increase in the information content of mining exploration is required. In recent years, high-frequency electrical prospecting methods have been included in the set of methods used to detail the mining and geological conditions of the developed field. The most effective of them for studying the upper part of a geological structure is the GPR method [1-3]. The advantages of this method are high performance and resolution, the ability to work at different conditions. Nevertheless, even now it needs to be admitted that significant opportunities of the GPR method are not fully realized in practice. The variability of the properties and condition of the rock mass during mining requires active scientific and methodological research to adapt and improve the GPR technology for studying the mining and geological conditions of deposits being mined [4, 5].

2 Methodology

GPR is a modern method of electrical exploration, based on the property of electromagnetic waves to be reflected from the boundaries of media with different electrophysical characteristics. Technically, it is realized by periodic radiation of ultra-wideband (nanosecond) pulses of the meter and decimeter range of electromagnetic waves, followed by reception and registration of signals reflected from the boundaries. The parameters of the reflected signals depend on the electrophysical properties of the tested medium, the range, shape, size, and contrast of the dielectric properties of the reflecting objects.

Experimental studies are presented by data obtained by the Mala ProEx GPR (Mala Geoscience, Sweden) with a shielded antenna (central frequency 500 MHz), OKO-2 GPR (LogiS-Geotech group of companies, Russia) with a linear dipole antenna (central frequency 50 MHz) and VIY5 GPR (Transient Technologies LLC, Ukraine) with a shielded antenna (central frequency 300 MHz). The data were obtained using the profiling technique in contact with the research surface (Fig. 1). Shooting parameters were set in accordance with the operating instructions [6, 7, 8].

The processing of field data was carried out using the Geoscan32 software for OKO-2 GPR, Reflex-W 6.0 (Sandmeier Scientific Software) for the Mala ProEx GPR and Synchro 3 software for VIY5 GPR from Transient Technologies LCC [8, 9, 10]. Primary processing includes the choice of the processing time window, correction of the beginning and end of the radargram. Next, radargrams are processed using various procedures to isolate the in-phase axes from the reflecting boundaries.

In the subsequent interpretation of the data obtained, they often rely on a priori information about the area under study. However, sometimes it is not enough. In this case, the analysis of the wave pattern is performed on the basis of criteria such as: change in the delay time of signals forming in-phase axes of diffraction of electromagnetic waves (displayed on the radargram as alternating white and black lines); rupture of in-phase axes, different intensities of amplitudes of reflected signals [11-14].



Fig. 1. GPR surveys of loose sediments.

Geological structures reflecting radio waves in the thickness of the rock mass are also characterized by different wave patterns. These are both extended in-phase axes from layered structures and chaotically distributed signals from clastic rocks, in places forming karst zones. To confirm the interpretational sections, the wave images of various verified geological structures obtained earlier, or by computer modeling, are correlated with field data [15].

As an example of the interpretation of GPR data based on the identification of radar facies, GPR profiles are presented for the study area of sandy river sediments on the banks of the Narew River (Poland) [16]. Field data were obtained by VIY5 GPR (Transient Technologies LLC, Ukraine) with a shielded antenna (central frequency 300 MHz). GPR sections (Fig. 2, 3) are characterized by low-angle reflections, probably due to the washing out of bottom sediments by river waters during flooding of the study area. Since the study area is near the Narew River, loose sedimentary rocks are constantly being changed due to the flow of the river water. The sections show erosional surfaces with erosional channels (marked by a yellow line), indicating successive stages of erosion and sediment accumulation.

At the same time, four different types of radar facies can be noticed in the GPR sections (Fig. 2, 3). The characterization of these facies is based on the relationships between reflections, their shapes and the geometry of the bounding surfaces [1, 17], as well as on the proposed classification [18, 19]. Thus, the following four GPR facies were recognized:

1. Radar facies 1: high-angle inclined reflections. Facies 1 (RF1) is characterized by dipping parallel reflections. They are interpreted as inclined strata formed by migration of bar margins [18].
2. Radar facies 2: discontinuous undulating or trough-shaped reflections. Facies 2 (RF2) is characterized by subparallel to oblique reflections. In some places these reflections may look chaotic. The reflections are undulating to trough-shaped and discontinuous. They are interpreted as cross-strata formed by migrating dunes [19].
3. Radar facies 3: upstream-dipping, parallel reflections. Facies 3 (RF3) is characterized by continuous parallel reflections that dip upstream (Fig. 3). These facies are interpreted as upstream-accretion deposits [20].
4. Radar facies 4: low-angle reflections. Facies 4 (RF4) is characterized by subparallel reflections with an almost planar shape. They can be arranged in sets that dip downstream, upstream or laterally to the main channel. They are interpreted as strata accumulated by the migration of low-amplitude sand waves or unit bars [18].

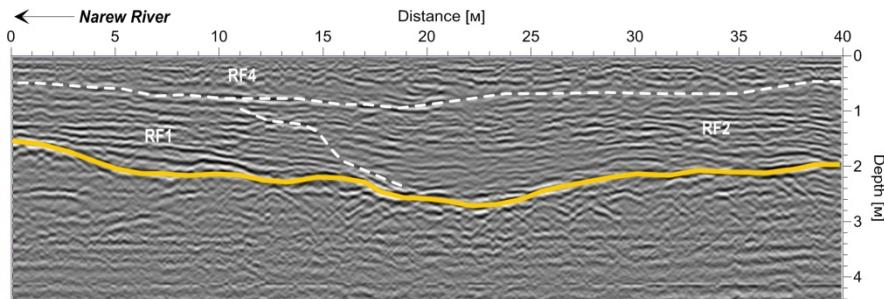


Fig. 2. GPR section of a perpendicular profile with respect to the Narew river [16].

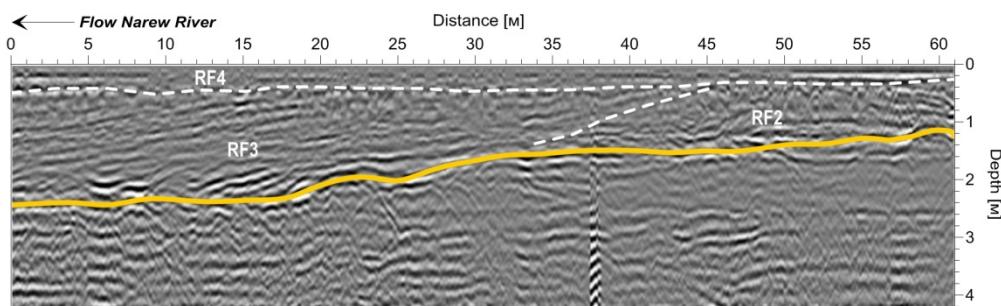


Fig. 3. GPR section of a parallel profile with respect to the Narew river [16].

3 Results and Discussion

Experimental GPR studies were carried out in the Paplin quarry, which is located about 60 km southwest of Warsaw (Poland) (Fig. 4) [21]. The quarry is located on a sandy postglacial highland. The thickness of the Quaternary deposits in this place is up to 50 m. In the sides of the quarry, glacial deposits of the Middle-Polish glaciation (Saalian) were found, represented by sands, gravel and deposits of glaciolacustrine clay. Above, fluvioglacial sands and gravels were found, characterized by a variety of granulometric composition, variable sorting, and planar or depression transverse stratification [22]. Sedimentological studies were carried out for 5 profiles for the analysis of lithofacies and mineralogical and petrographic composition of the deposits (Table 1) [21].

The exploration of the quarry was carried out by the Mala ProEx GPR (Mala Geoscience, Sweden) with a shielded antenna (central frequency 500 MHz). As a result, 10 GPR profiles were obtained. Editing and processing of GPR data was performed with Reflex-W software version 6.0 by Sandmeier Scientific Software [10]. The data show four GPR facies: discontinuous and oblique reflections that sometimes look chaotic (GPR facies 1), oblique reflections at a high angle (GPR facies 2), parallel and continuous reflections under facies 4 (GPR facies 3) and subparallel and continuous reflections (GPR facies 4). Fig. 5 shows an example of a GPR profile of the Paplin quarry and its interpretation.



Fig. 4. Sand and gravel quarry Paplin [21].

Closer to the day surface, the sections contain GPR facies 4, which may be associated with the presence of soils and massive sands (Sm lithofacies) in the studied sedimentary outcrops. They are also associated with the last stage of the evolution of the studied area. The interpreted sections are dominated by radar facies 3 and 1 – in these places, there are different types of lithofacies, from horizontally layered sands to massive sandy-gravel depoists. GPR facies 1 can be interpreted as the initial stages of development of the studied areas with sedimentation. GPR facies 2 are found locally, in former canals, where lithofacies Sp, St, and SGt are present. As a result of the integration of the sedimentological studies and the GPR method, it was possible to conduct an accurate spatial analysis of the forms of glacial deposits and establish a more accurate description and visualization of the arrangement of sedimentary rocks.

Table 1. The main types of lithofacies in the Paplin quarry corresponding to the GPR facies [21].

Lithofacies characteristics	Corresponding GPR facies
Lithofacies Sm poorly to moderately sorted, fine- to coarse-grained quartz sand; mostly massive structure; forms layers up to 15 cm thick.	GPR facies 4
Lithofacies Sh very poorly to moderately sorted, very fine- to coarse-grained sand; in mineralogical-petrographic composition limestone fragments and quartz grains dominates.	GPR facies 1 and 3
Lithofacies St very poorly to moderately sorted, medium to coarse-grained sand; forms trough cross-strata sets up to 1.5 m thick; transport direction towards south-west; overlies erosional facies SGt.	Medium (sandy) lithofacies
Lithofacies Sp / Sp _{ls} poorly to moderately well sorted, medium to coarse-grained sand; planar cross-bedding; forms layers up to 2 m thick; transport direction towards south, south-west; overlies erosional facies SGt.	GPR facies 2
Lithofacies SGt poorly sorted, medium to coarse-grained sand with gravel; trough cross-stratified sets up to 2 m thick; transport direction towards south-west.	Coarse (gravelly) lithofacies

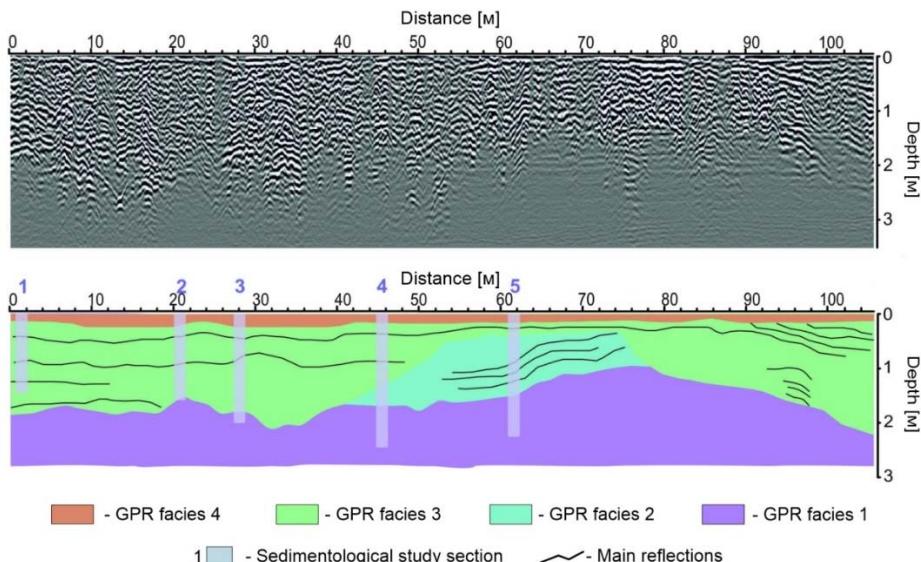


Fig. 5. GPR section with interpretation [21].

Experimental GPR studies of loose sediments at a gold field were carried out in the North-East of Yakutia. According to preliminary information, the thickness of loose sediments in the field is small (up to 10-15 m) and is available for geophysical surveying using GPR. The presence of boulders suggests the possibility of registering hyperbolas in the wave pattern, which can allow more accurate setting of the depth scale on the radargrams.

For research, a site prepared for dredging was selected. The profiles planned for it were cleared of snow with a bulldozer. The measurements were carried out using an OKO-2 GPR with a central frequency of 50 MHz, in the spring, during the period of maximum freezing of rocks. Later, a well was drilled the site for geological referencing of ground penetrating radar data.

As an illustration of the GPR data from the research site, Fig. 6 shows the wave pattern along the transverse profile of the dredging area. The GPR data were processed layer-by-layer in Geoscan32 software, with the correction of the amplitude intensity and dielectric constant values for each layer.

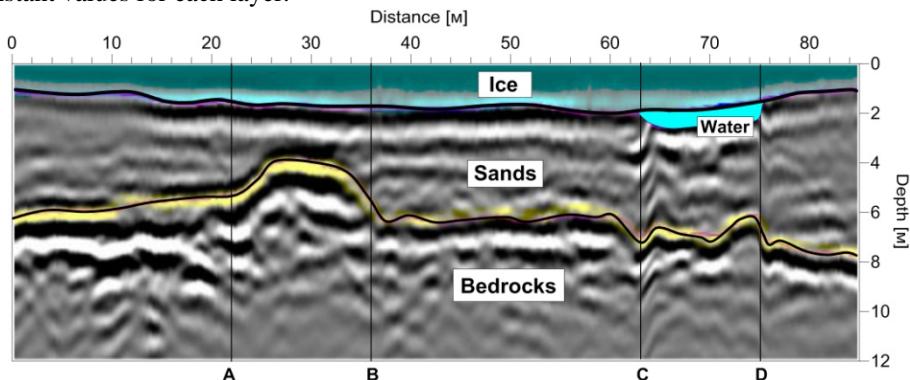


Fig. 6. GPR section along the transverse profile of the dredge landfill.

The boundaries of the layers: ice, sands, bedrock, unfrozen water (section CD) are clearly traced along the in-phase axes throughout the entire section. Loose deposits, represented by sands, correspond to radar facies 2 (RF2), and have undulating, trough

reflections, with areas of sub-parallel reflections. On the CD section of the radargram, these reflections look chaotic, which is associated with distortions of the wave pattern that arise during the processing of a section of unfrozen water. The in-phase axis formed by reflections from the bedrock surface is practically continuous. Below it, chaotic signals associated with the disturbed structure of rocks are observed. When analyzing the surface of bedrocks in the AB radargram section, a zone of uplift to a depth of 3 – 3.5 m was revealed, which can lead to a change in the course of the dredge movement.

Fig. 7 shows a section constructed according to ground penetrating radar profiling and drilling data in the area of a placer gold field in South Yakutia. The boundaries of the layers, confined to the loose sediments and bedrocks, are also traced along the in-phase axes of reflected waves. The contrast of the dielectric properties of the rocks makes it possible to show the geological structure of the placer with the identification of thickness of sand, roof morphology and the disturbance of the bedrock.

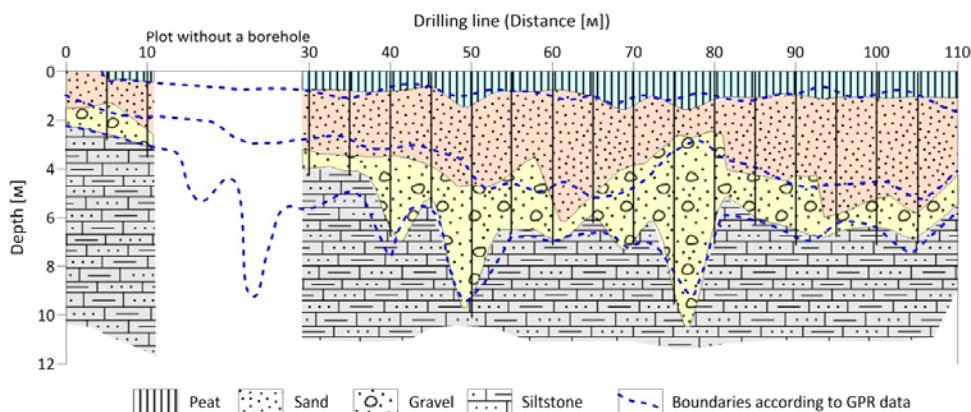


Fig. 7. Classification of the geological structure of the placer according to GPR data.

As a result, a deep three-layer section was obtained – the upper boundary was identified within 0.5 – 2 m (peat), below two other boundaries are located within the depths of 2 – 6 m (border of loose sediments) and 4 – 10 m (boundary of bedrock). Drilling was not carried out in the section of well 10-30 due to the inability of drilling equipment to move (wetland). According to GPR data, thalweg (the bottom of the valley) was identified exactly in this interval. The result of the above studies is confirmed by mining the placer along the indicated contours.

4 Conclusions

Experiments on the use of ground penetrating radar in the conditions of the developed massif showed the method promising for studying the structure of loose deposits. The parameters obtained from the GPR data can help identify the route for the dredging complex. It becomes possible to trace the boundaries of layers of loose deposits, differing in some properties. The results of the work showed that the GPR method can be widely used in solving problems related to the study of morphostructural features of sediments. At the same time, the efficiency of data acquisition may additionally contribute to the optimization of technology and increase the efficiency of field development.

References

1. M. J. Harry, *Ground penetrating radar: theory and applications* (Amsterdam: Elsevier, 2009)
2. A.V. Omelyanenko, L.L. Fedorova, *Georadiolocation studies of permafrost rocks: monograph.* (Yakutsk: Publishing house of Yakut Scientific Center of the SB RAS, 2006)
3. KI. Dimitriadis, V. Perez-Gracia, *Civil Engineering Applications of Ground Penetrating Radar (Proceedings First Action's General Meeting Rome)*, COST ACTION TU1208, Rome, 183-190 (2013)
4. L.L. Fedorova, G.A. Kulyandin, S.V. Panishev, A.P. Vinokurov, *Modern technologies for the development of mineral resources: proceedings of the 6th International Scientific and technical conference*, 181-188, (Krasnoyarsk: Siberian Federal University, 2008)
5. L.L. Fedorova, K.O. Sokolov, D.V. Savvin, Advances in current natural sciences, **9**, 190-195 (2016)
6. Technical description and operating manual for Georadar OKO-2. URL: <http://www.geotech.ru/files/georadar/gprtov26beta303.pdf> (last retrieved on: 24.07.2020)
7. MALA ProEx Manual. URL: <https://www.guidelinegeo.com/wp-content/uploads/2016/07/MALA-ProEx-Control-Unit-Manual-v.2.0.pdf> (last retrieved on: 24.07.2020)
8. VIY 3 GPR – Synchro 3 user manual. URL: https://viy.ua/download/Synchro UM_en.pdf
9. GeoScan32: software for control of Georadar OKO-2 and visualization of the received data: illustrated user manual. URL: <http://logsys.ru/download/new/geoscan32manual.pdf> (last retrieved on: 24.07.2020)
10. K. J. Sandmeier, *REFLEXW Version 9.5 Windows™ XP/7/8/10-program for the processing of seismic, acoustic or electromagnetic reflection, refraction and transmission data.* URL: https://www.sandmeier-geo.de/Download/reflexw_manual_a4.pdf (last retrieved on: 24.07.2020)
11. M.L. Vladov, A.V. Starovoitov *Introduction to georadiolocation* (Moscow: Publishing house of Moscow State University, 2004)
12. *Issues of subsurface radar: collective monograph*, ed. A.Yu. Grinev (Moscow: Radiotekhnika, 2005)
13. S.V. Izyumov, S.V. Druchinin, A.S. Voznesenskiy *Theory and methods of georadiolocation: textbook* (Moscow: Publishing house Gornaya kniga, Moscow State University, 2008)
14. G.A. Kulyandin, L.L. Fedorova, Yekaterinburg: Publishing house of the Ural State Mining University, Izvestiya Vuzov. Mining Journal, **4**, 108-113 (2015)
15. L.L. Fedorova, Ye.E. Soloviev, K.O. Sokolov, G.A. Kulyandin, Mining Journal, **2**, 38-42 (2019) DOI: 10.17580/gzh.2019.02.07
16. A. Lejzerowicz, *17th International Conference on Ground Penetrating Radar (GPR)*, Rapperswil, 1-4 (2018) DOI: 10.1109/ICGPR.2018.8441570
17. A. Neal, Earth-Science Review, **66**, 261-330 (2004)
18. G. H. Sambrook Smith, P. J. Ashworth, J. L. Best, J. Woodward, C. J. Simpson, Sedimentology, **53**, 413-434 (2006)
19. P. J. Ashworth, G. H. Sambrook Smith, J. L. Best, J. S. Bridge, S. N. Lane, I. A. Lunt, A. J. H. Reesink, C. J. Simpson, R. E. Thomas, Sedimentology, **58**, 1860-1883 (2011)
20. C. L. Wooldridge, E. J. Hickin, Journal of Sedimentary Research, **75(5)**, 844-860 (2005)
21. A. Lejzerowicz, A. Wysocka, S. Kowalczyk, Studia Quaternaria, **35(2)**, 103-119 (2018) DOI: 10.2478/squa-2018-0008
22. M. Markowiak, *Documentary cart No. 1617 of 'Paplin gravel pit' geosite*. Ministry of the Environment; PIG-CAG, (in Polish) (2010)