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ORIGINAL PAPER

GPR (Ground Penetration Radar) research in forest areas to identify archaeological sites (Mount Ślęża, Poland)

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ABSTRACT

The register of archaeological remains in forests is one of the important elements hindering the optimal planning of forest management, especially in key areas from the point of view of cultural heritage. In areas managed by the State Forests National Forest Holding, archaeological sites may need to be precisely described in the registers. This may make it difficult for forest services to plan appropriate forest management. Numerous finds and archaeological sites have been inventoried on Mount Ślęża. However, detailed research is needed to identify the archaeological sites accurately. The GPR method is one of the most effective tools enabling a quick and non-invasive inventory of archaeological objects. The paper presents the research results on two objects in the State Forests on Mount Ślęża: a hill and a forest road. GPR equipment was used in the MALÅ Ground Explorer (GX) HDR. Based on field prospection and GPR measurements of the hillock in the forest and the forest area adjacent to it, various permittivities of the mediums were observed. The results indicate that the tested object is anthropogenic. The applied GPR methodology has also proven itself in studying a forest road with a rock cobblestone surface in some places. GPR echograms, however, showed that most of the pavement surface is covered with a layer of soil. Based on the obtained 2D images, it was found that the georadar can be successfully used to recognize archaeological objects in forests. It is also advisable to conduct research in the 3D system.

KEY WORDS

archaeology, forests, GPR

Introduction

In forest area management, knowledge of the specifics and conditions, both natural and those related to historical heritage, is necessary for forest management. In managed forest areas, recognizing the location and nature of archaeological objects allows, among others, appropriately plan and adjust economic activities, such as felling and maintenance of forests, preparation of soil for

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planting tree stands, *etc.* (Paschalis-Jakubowicz, 2015). By the national requirements of the Act on Forests (Ustawa, 1991), the forest management plan includes the principles of protecting nature and cultural monuments. Archaeological sites should be covered by a protection program and marked on the appropriate thematic maps of each Forest District. The Act on Forests stipulates that forest management in areas entered in the register of monuments and in forests with archaeological monuments should be carried out in consultation with the Provincial Conservator of Monuments and should comply with the regulations on the protection of monuments. In connection with the regulations above, foresters must have precise knowledge of the location of archaeological sites.

In the case of some forest districts with a significant number of cultural heritage resources, their records, and detailed descriptions are prepared. The available remote sensing data, especially laser scanning (LIDAR), allow for a detailed location of archaeological objects and their appropriate protection in forest management planning. Identification of archaeological remains in forest areas requires quick and non-invasive research. The GPR method meets these criteria.

Based on the entry in the register of monuments – all identified objects, such as barrows, conical strongholds, and ring strongholds, are legally protected as monuments. Therefore, in forest areas, the inventory of such objects is a very important factor, necessary to gain knowledge about them and implement their adequate protection.

In 2022, documentation of the Cultural Heritage of the Ślęży Massif of the Miękinia Forest Inspectorate was created (Zasób, 2022). The documentation contains a detailed record of archaeological monuments and their description. However, two places that foresters are interested in, a hill and a fragment of a forest road, were not included in the document above. These objects are located on the northern slope of Mount Ślęża (Fig. 1). In the documents and maps of the AZP (Polish Archaeological Record) of the Provincial Office for the Protection of Monuments in Wrocław, the places where the hill and a fragment of the forest road are located are marked as site 73 (area AZP 84-25), the exploitation area.

Literature shows that the barrow is a small earth mound built as part of the funeral rites in the Stone Age. Its shape resembles a truncated cone. The size varies from 1 m to about 6 m. The barrow consists of several internal embankments with different layers of soil, stones, and wooden structures. Moreover, it is a burial ground with skeletons, often with everyday objects (vessels, ornaments, weapons) covered with layers of earth. On the other hand, the remains of a stronghold

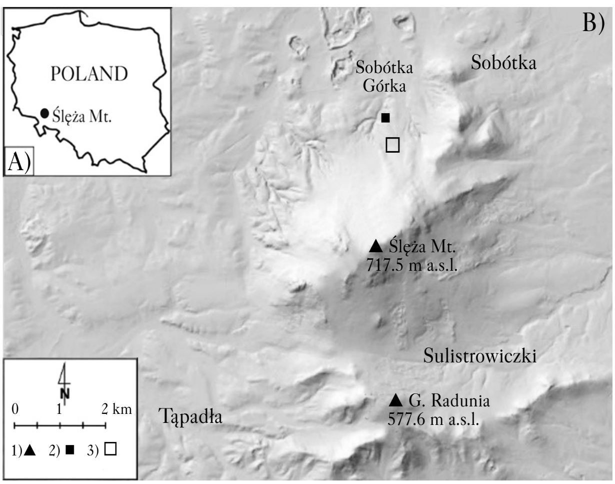

Fig. 1.
Mount Ślęża
A) – location on the map of Poland, B) – research area (LIDAR map according to geoportal 2); 1) the highest peaks, 2) the castle in Sobótka Górka, 3) the GPR research area

or a defensive settlement can be hidden under a small hill (which can be circular or polygonal), usually with preserved traces of wooden and earth embankments and a moat around.

Fortified settlements could have the following functions: defensive, cult, residential, and craftsmanship. In the case of a ring-type hillfort, its diameter could even exceed 200 m. In the case of a conical hillfort, its diameter could be 10-20 m. Such fortifications were built in the Bronze Age, the times of the Lusatian culture, and the times of the Pomeranian culture. Castles were built in the early Middle Ages.

Communication roads were a constant landscape of emerging kingdoms and states. Their condition and maintenance were closely related to the development of internal and external trade and the organization of state administration. In the mountains and forests roads were often paved with crushed rock fragments to improve the transport and communication system. There was also a custom of marking trails, *e.g.*, with stones with the cross sign. Placing place stone pillars along the roads at important points was also customary.

The research area

Mount Ślęża (717.5 m above sea level), located in South-Western Poland (Lower Silesia), is a very characteristic element of the landscape and relief of the Sudeten Foreland (Fig. 1). There are rocks here: granite, gabbro, serpentinite, amphibolite, and in them minerals of quartz and gold. In the past, the presence of these rocks encouraged locals to mine them. Traces of human mining activity from prehistoric times to the present are being studied (Lisowska *et al.*, 2014; Chudzik and Kuźbik, 2021).

From the early Middle Ages to the beginning of the 12th century, Mount Ślęża was an important place of pagan worship (Szafrański, 1979; Pawleta, 2017). On the top of the mountain are stone structures in the form of low embankments of boulders. It is believed that these were the fences of sacred places where pre-Christian rites took place. Researchers (Hołubowicz and Hołubowicz, 1950) associate them with the Hallstatt period (700-400 BC) and the sun cult of the Lusatian culture. It is also believed that the beautiful stone sculptures (named, *e.g.*, fish, bear, mushroom, monk) on Mount Ślęża and its vicinity come from this period. There are traces of signs in the form of an oblique cross on the stones, which may suggest a solar cult associated with Celtic influences (Słupecki, 1992) or may be related to their function as boundary markers. On the top of the mountain are traces of fortifications in the form of stone ramparts. At the beginning of the 15th century, there was also a castle there, which was the center of dissident resistance during the Hussite Wars, and in 1428 it was destroyed by the townspeople of Wrocław (Labuda and Stieber, 1975). On Mount Ślęża, ceramic elements from the Hallstatt, Lusatian, and early Middle Ages cultures were found. In addition, capitals of Romanesque columns were discovered here. Research on Mount Ślęża has been conducted for over three centuries and has significantly intensified since the 1980s. Research related to preparing maps of archaeological sites in Poland allowed the discovery of new archaeological sites and the inventory of those previously known (Domański, 1965, 2002). Contemporary research in the Ślęża Massif has been carried out in many directions, the most important of which are geological and petroarchaeological research on using granites in the early Middle Ages (Lisowska *et al.*, 2014).

GPR method

Ground Penetration Radar (GPR) is an equipment for geophysical research. The georadar method (GPR) is a non-invasive / non-destructive method that allows the analysis of the propagation capacity of high-frequency electromagnetic waves (EM) through media with different dielectric constants (Daniels, 2000, 2007). This method uses a transmitting antenna that emits an electromagnetic signal into the ground, which is partly reflected at the junction of two different media and partly transmitted to deeper layers. The receiving antenna records the echoes of the EM waves. The main advantages of GPR are the high speed and continuity of obtaining data on soil structures and the lack of destructive interference in the examined soil/rocks, which is of great importance in archaeological research (Conyers, 2004) or road research (Solla *et al.*, 2021). GPR is one of the most commonly used electromagnetic methods in geophysics, which has found application in archeology due to its high resolution and speed of data acquisition (Oliveira *et al.*, 2022) and is very useful in archaeological work (Sternberg and McGill, 1995; Carcione, 1996; Basile *et al.*, 2000; Conyers, 2004).

The GPR method is also used in research in forest areas. The most important research directions in forest areas include, for example: testing the surface of shallow rock/soil in forests, determining the course and arrangement of layers in the substrate, and determining the depth of the first aquifer. In forest areas, research is carried out using the GPR method, aimed, for example, at determining tree species based on the variability of their EM wave reflection coefficients, analyzing the spatial distribution of tree roots, and assessing the thickness of structural layers of forest roads (Lorenzo *et al.*, 2010; Potępa *et al.*, 2018; Kasztelan, 2021; Kurowska *et al.*, 2021).

The test area

On Mount Ślęża, the State Forests Board indicated two objects for the GPR research: object 1 – a small hill (a mound or barrow) and object 2 – a fragment of a forest road (Fig. 2, 3). These sites are located in the area of AZP 84-25 within the site 73 – exploitation area (Provincial Office for the Protection of Monuments in Wrocław).

Object 1: hill, N: 50.8828, E: 16.7078 (area of the State Forests: 13-17-2-13-136-d)

The hill is about 500 m south of the castle in Sobótka Górka (Fig. 2, 3, 4). The object has not been subjected to detailed archaeological research before. The question was posed: is this hill a barrow or a former small fortified settlement?

The hill is located on the northern slope of Mount Ślęża (about 270 m above sea level) and has dimensions: 30×20 m and a height of about 2-5 m. The hill at the base is fan-shaped. The ridge

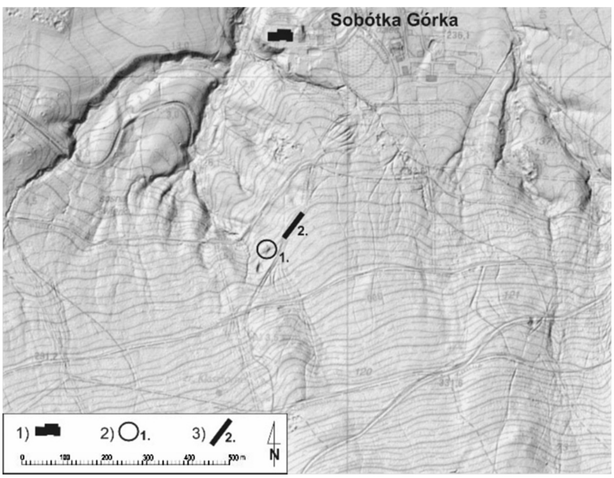

Fig. 2.

Mount Ślęża, northern slope

GPR research areas: 1) the castle in Sobótka Górka (the control point), 2) object 1 – a hill, 3) object 2 – a fragment of a forest road

Fig. 3.
Mount Ślęża, northern slope
GPR research areas: 1) GPR section lines: 86, 87 (object 1 – hill), 2) checkpoints (on forest road), 3) GPR section lines: 82, 84 (object 2 – forest road), fragments of the GPR section discussed in the text are marked with a thick line, 4) former granite quarry

Fig. 4.
Mount Ślęża, northern slope
GPR research area: object 1 – hill

of the hill is leveled and overgrown with trees. The southern slope of the hill slopes gently. On the other hand, the northern, north-western, and north-eastern slopes are inclined at a large angle (approx. 20-30°). A hill located about 30 m to the north of a former, small granite quarry (mining slope excavation). The former granite quarry is 25 m long and 15 m wide and is visible in the LIDAR image (Fig. 2, 3). The height of the southern exploitation slope of the quarry is about 5-8 m (275-270 m above sea level). This quarry is open to the north, and there is a southern entrance to the hill's surface in its extension. Archaeological observations show that granite blocks were mined in the quarry to produce mill quern wheels. One such abandoned boulder (unfinished in processing) is located at the bottom of the excavation. There is a hole in the boulder in the shape of a square, about 5×5 cm. Mill quern wheels with square holes are characteristic of the Roman period in this area. It is possible that this quarry functioned in the Roman period.

To the west of the former granite quarry, there is a bed of a periodic mountain stream cut into the slope of Mount Ślęża to a depth of about 1-2 m. To the east of the quarry and the hill, a forest road runs along the slope of Mount Ślęża (Fig. 3). On this road, there is a blue tourist trail from Sobótka Górka to the top of Mount Ślęża.

Near the quarry, a forest mountain road cuts about 1-1.5 m into the slopes and runs in a shallow gorge. Parallel to it, at a distance of about 3 m (in a similar gorge), there is also an old road, currently disused, which is also cut into the slope formations to a depth of 1-1.5 m. In this place of Mount Ślęża, the slope formations are clayey and silty, with a small amount of rock crumbs, and reach a thickness of up to 2.5 m. Moving along the road down the slope, it can be seen that more sand and gravel fractions and more small rock crumbs appear in the weathered covers. In places, the road surface contains larger rock fragments, which were brought here in order to harden this forest road. In places, the road surface has rock fragments in the form of cobblestones (Fig. 5). The research covered a fragment of a mountain forest road on the northern slope of Mount Ślęża (running along the contour line about 270 m above sea level), located about 400 m south of the castle in Sobótka Górka (Fig. 1, 2, 3).

Object 2: road, N:50.8836, E:16.7089 (area of the State Forests: 13-17-2-13-136-a)

GPR surveys were carried out on a section of the road about 60 m long, about 50-100 m to the northeast of object 1 – hill. The road here is 2.5 m wide. In the initial section, the road runs along clay-dust slope formations. There are deep ruts here. In one place (over a distance of about 6 m), a fragment of the artificially paved road surface has been preserved: the road is paved with rock fragments (Fig. 5). Further down, the road runs along a sandy slope covered with a large number of rock fragments of various sizes (fragments of gabbros predominate). A question was asked about the structure of the road.

Research methodology

GPR research on Mount Ślęża was carried out with the MALÅ Ground Explorer (GX) equipment based on High Dynamic Range (HDR) technology, with a shielded antenna with a central frequency of 750 MHz. GPR surveys were carried out using the linear profiling method in the 2D system. Parallel cross-sectional lines were made every 0.5 m. The length of the cross-sectional lines on the dorsal surface of the hillock (S-W) was 8.5 m. At about 50 m NE from the hill, two checkpoints were marked on the forest road: ×1 – at the first intersection with the forest road leading NW and ×2 – at the third intersection, with several forest road forks. Along the axis of the forest road, from control point x1 to control point ×2, georadar SW-NE sections were made, 66 m long (Fig. 3).

The following measurement parameters were used during the field tests:

SF=9600 MHz, S=1, Time Window=63 ns (hill) and 42 ns (road), EM pulses were sent to the ground every: i=0.049 m.

Fig. 5.
Mount Ślęża, northern slope
GPR research area: object 2 – a forest road with a rock pavement Surface

The GPR data collected in the field was processed in MALÅ Object Mapper and GroundVision using different sets of filters.

The following filters were used during GPR data processing: DC correction, automatic gain control, band-pass filtering, amplitude analysis, spectral analysis, proper amplitude recovery, and diffraction hyperbola velocity analysis. Each echogram is marked with a 'zero point' based on the timeline (Benedetto *et al.*, 2017). Echograms are represented by grayscale (black to white) colors. The possibility of enhancing or weakening the contrast was used. Layer thickness parameters were determined using vectorization and calibration (Karczewski *et al.*, 2011; Conyers, 2013, 2016). Data prepared in post-processing were visualized graphically on echograms of EM waves in the 2D system (GPR sections, linear data). Interpretation of echograms and their descriptions were made in CorelDraw. Only selected georadar cross-sections have been presented in this paper.

Results

The Hill. An example GPR cross-section through a hill is shown in Fig. 6. Fig. 6A – shows raw data, where various noises and reflections make data analysis and interpretation difficult. After

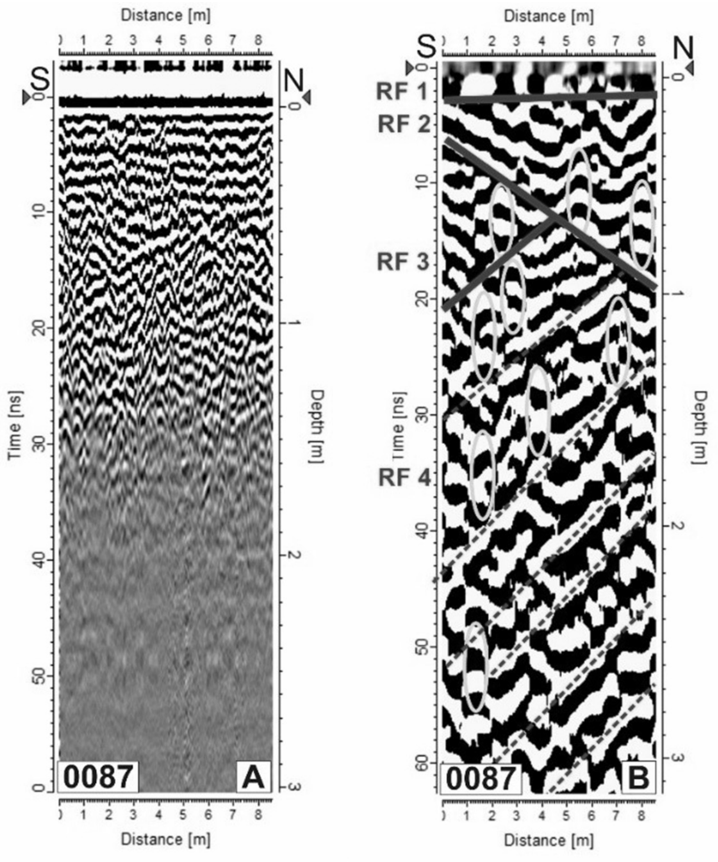

Fig. 6.
Mount Ślęża, northern slope
GPR research area: object 1 – hill; GPR section: 0087; A, B – results from two different sets of filters, RF – radar facies; continuous and dashed lines – sets of rock layers; grey oval – a larger piece of rock (<0.5 m)

applying several filters (Fig. 6B), several different EM fields can be distinguished in the hill structure, which we call radar facies (RF). RF 1 – this is probably the humic level of modern soil. Radar facies: RF 2, 3, and 4 are different layers within the hillock. The layers in the RF 2 radar facies are inclined towards the north. Presumably also, in the radar facies RF 3 – the layers are inclined towards the north. In contrast, in the radar facies RF 4 – the layers are inclined towards the south. During the filtering and analysis of the GPR data, characteristic EM wave refractions were detected as parabolas marked with ovals. They are probably larger rock fragments but <0.5 m in diameter. The analysis of GPR data using various filters shows no structures in the hill.

The road. Fig. 7 shows an exemplary georadar cross-section (GPR) along a forest road in a mountain area. Fig. 7A – shows raw data (only basic filters were used: STMF, DC, TG), noise and reflections make data analysis and interpretation difficult. After applying several additional filters: STMF, DC, TG, and BP (Fig. 8B), several different surfaces can be distinguished in the construction of the road (different EM fields). The most interesting places are marked as anomalies: 1, 2, 3. In Fig. 8, it can be seen that in the cross-section on a section of 12-30 m, there is a depression in the roadbed.

The soil structure in the subsoil of the examined mountain forest road is very variable. In the initial section of the cross-section (anomaly 1 in Fig. 7, 8), the road surface consists of clay-dust formations (about 0.5 m thick) occurring on the slope covers of Mount Ślęża. In the GPR section: 20-25 m, the road surface is preserved, paved with rock fragments (anomaly 2 in Fig. 7, 8, 9). The cross-section of the GPR shows that in section: 12-30 m, there is a depression in the road base. Due to the increased thickness of the weathered cover, it was probably necessary to harden the forest road in this place. The next section of the road: 30-40 m (anomaly 3 in Fig. 7, 8), is a sandy surface with a small clay and dust fractions content. There are more small rock fragments here. Such a road surface does not cause deep ruts that hinder transport.

Conclusions

Reconnaissance GPR surveys were carried out in the area of the State Forests of the northern slope of Mount Ślęża (within site 73, AZP 84-25, Voivodship Office for the Protection of Monuments in Wrocław). The research covered: object 1 – a hill, and object 2 – a fragment of a mountain forest road.

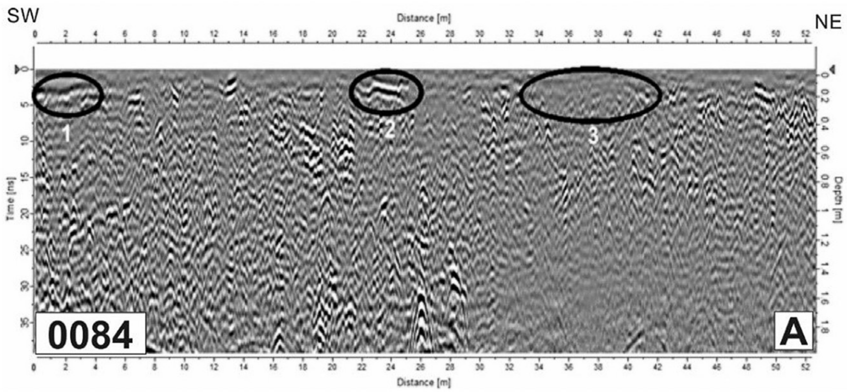

Fig. 7.

Mount Ślęża, northern slope

GPR research area: object 2 – forest road; GPR cross-section: 0084; A – set of filters: STMF, DC, TG; 1, 2, 3 – GPR anomalies, different types of road surfaces

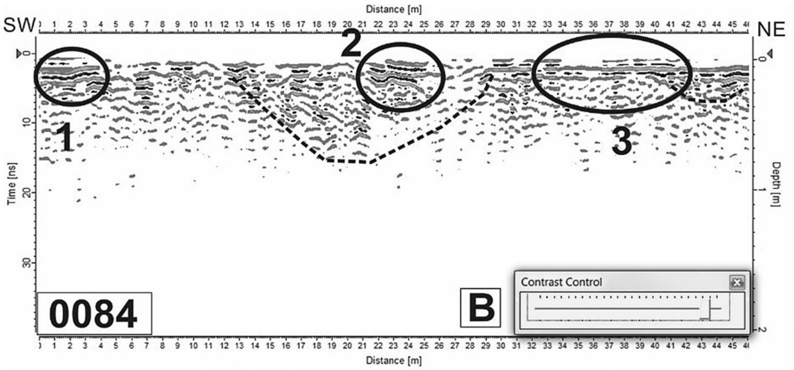

Fig. 8.
Mount Ślęża, northern slope
GPR research area: object 2 – forest road; GPR cross-section: 0084; B – set of filters: STMF, DC, TG, BP (FIR); 1, 2, 3 – GPR anomalies, different types of road surfaces

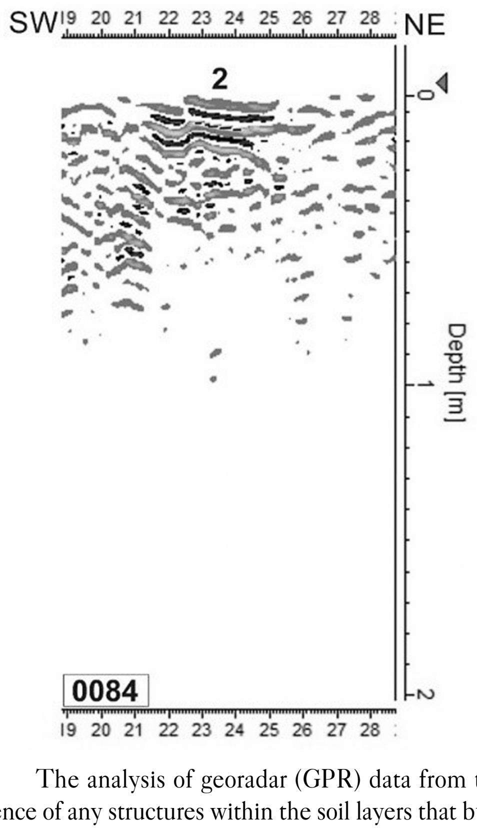

Fig. 9.
Mount Ślęża, northern slope
GPR research area: object 2 – forest road; GPR cross-section: 0084; B – set of filters: STMF, DC, TG, BP (FIR); 2 – group of GPR anomalies, road surface paved with rock fragments

The analysis of georadar (GPR) data from the area of the hill does not indicate the existence of any structures within the soil layers that build the hill. It is a former mining heap from the period of granite extraction in a nearby quarry. However, archaeological methods are recommended to be used to verify these data.

The structures in the subsoil of the examined mountain forest road are very variable. The road runs along the weathered slopes in many places with a high clay and dusty fractions content. There are places where there is no paving or organic cover, proving its old construction and lack of maintenance (Treskon, 2006; Petrović and Filipović, 2007).

GPR road surface surveys focus mainly on technical issues and are related to examining modern infrastructure, controlling structural layer thickness, and assessing their damage. Unfortunately, there are few studies devoted to the remains of old roads. Data on medieval roads is quite scattered and can only be found in more extensive studies (concerning larger objects, *e.g.*, entire cities), so there is little comparative material available (*e.g.*, Verdonck, 2011; Cozzolino and Gentile, 2019).

The amount of data on the remains of historical roads, especially in forest areas, needs to be increased. Adequate protection of this type of object requires their inventory and detailed research. The conducted GPR research not only broadens the knowledge about the examined objects but also indicates the possibility of practical application of the georadar method (GPR) to research roads in forest areas.

The research should be continued due to the high historical value of the existing archaeological remains in forest areas and the need to inventory them for the needs of the Forest Inspectorate's Nature Protection Program, resulting from the Act on Forests. (GPR), which is a quick and non-invasive (non-destructive) method.

Author's contributions

A.K.G. – performed the field work (equal), wrote most of the manuscript (lead), approvals the final version of article (equal); A.C. – conceived the idea and designed the methodology (lead), performed the field work (equal), approvals the final version of article (equal); J.B. – performed the field work (equal); approvals the final version of article (equal); A.K. – performed the field work (equal), processed collected data by software (lead); approvals the final version of article (equal); M.P.-P. – performed the field work (equal), approvals the final version of article (equal).

Conflicts of interest

We have no conflicts of interest to disclose.

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STRESZCZENIE

Zastosowanie metody georadarowej (GPR) do badań obiektów archeologicznych na terenach leśnych (góra Ślęża, Polska)

Wiedza na temat charakteru oraz rozmieszczenia zabytków archeologicznych stanowi jeden z elementów niezbędnych dla planowania działań związanych z prowadzeniem gospodarki leśnej. Zgodnie z wymogami ustawy o lasach (Dz. U. 1991 Nr 101, poz. 444) informacje na temat tego typu obiektów powinny być wskazane w Programie Ochrony Przyrody dla nadleśnictw oraz zaznaczone na odpowiednich mapach tematycznych. Ustawa ta stanowi ponadto, że na obszarach wpisanych do rejestru zabytków oraz w lasach, na terenie których znajdują się zabytki archeologiczne wpisane do rejestru zabytków, gospodarka leśna prowadzona jest w porozumieniu z wojewódzkim konserwatorem zabytków i musi uwzględniać przepisy o ochronie zabytków i opiece nad zabytkami. Jedną z metod powszechnie stosowanych w badaniach archeologicznych jest technika georadarowa (GPR). Jest to sposób nieinwazyjny i nieniszczący, wykorzystujący zjawisko przenikania fal elektromagnetycznych o wysokiej częstotliwości przez ośrodki o różnych stałych dielektrycznych. Metodę GPR charakteryzuje duża szybkość prowadzenia badań, ciągłość pozyskiwania danych, a także brak ingerencji w badany grunt, dzięki czemu jest ona szczególnie przydatna w badaniach zabytków archeologicznych. Pomimo tych zalet stosunkowo niewiele jest publikacji, w których opisano badanie zabytków na terenach leśnych z użyciem georadaru. Celem niniejszej pracy było rozpoznanie możliwości użycia metody GPR pod kątem prowadzenia badań obiektów archeologicznych znajdujących się na terenach leśnych. Badania przeprowadzono na Ślęży (717,5 m n.p.m.), będącej najwyższym szczytem Masywu Ślęży i Przedgórza Sudeckiego (ryc. 1-3). Góra ta, począwszy od epoki brązu, stanowiła ważny ośrodek kultu solarnego, którego ślady zachowały się w postaci pozostałości kamiennych konstrukcji oraz rzeźb. Na szczycie góry znajdują się ponadto ślady urządzeń obronnych, materiał ceramiczny z kultury łużyckiej i wczesnego średniowiecza, a także kapitele romańskich kolumn. Przedmiot badań stanowiły 2 obiekty: wzniesienie mogące stanowić dawną hałdę górniczą z okresu wydobywania granitu w pobliskim kamieniołomie oraz pozostałości drogi (ryc. 4-5). Badania przeprowadzono za pomocą anteny o częstotliwości centralnej 750 MHz: MALÅ Ground Explorer (GX) HDR. W ramach prac terenowych wykonano profile podłużne, a analizie poddano echogramy o długości 8,5 m dla wzniesienia i 8,5 m dla terenu bezpośrednio sąsiadującego z nim oraz 53 m dla drogi. Na podstawie pomiarów i uzyskanych obrazów 2D dla wzniesienia zaobserwowano odmienną przenikalność elektryczną ośrodka niż na otaczającym je terenie. Pomiar georadarowy wykonany na wzniesieniu wykazał ponadto nierównomierny rozkład warstw gruntu oraz zmienną grubość i strukturę warstw, natomiast pomiar wykonany na sąsiadującym z nim terenie leśnym pokazał poziomy, równomierny układ warstw gruntu (ryc. 6). Wyniki te wskazują na antropogeniczny charakter badanego obiektu. Pomiar wykonany na drodze pokazał wyraźnie wielowarstwowy układ gruntu oraz pozwolił na wyróżnienie w konstrukcji drogi kilku różnych nawierzchni. Na początkowym odcinku przekroju wystąpiły utwory pyłowo-iłowe, w dalszej części nawierzchnia utwardzona fragmentami skalnymi oraz nawierzchnia piaszczysta z drobnymi fragmentami skalnymi (ryc. 7-9). Uzyskane wyniki poszerzają wiedzę na temat analizowanych obiektów, pokazują przydatność metody georadarowej w badaniach obiektów archeologicznych na terenach leśnych oraz stanowią wkład metodyczny pomocny przy prowadzeniu dalszych tego typu badań.