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APPLYING GROUND PENETRATING RADAR TO TRACKING OF ANCIENT ARCHITECTURAL TRANSFORMATIONS: THE CASE OF THE MONASTERY ST. PETER ON THE ISLAND OF RAB (CROATIA)

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Abstract:
The ground-penetrating radar (GPR) method has been used for many years in archaeological research. However, this method is still not widely used in studies of past architecture. The biggest problem with the implementation of the GPR method at such sites is usually connected with extensive debris layers, plant cover and standing relics of walls and other features that restrict the available measurement area. Despite of these, properly performed GPR surveys, even on a small area, can yield significant information concerning underground architectural relicts. Moreover, the results of GPR profiling integrated with historical and archeological data allow for three-dimensional reconstruction of the examined architectural monuments and in the next step, they track architectural transformations. Relics of the Romanesque St. Peter monastery, located in the northern part of the Island of Rab, is a good example of the successful GPR survey. Results of the performed geophysical reconnaissance in conjunction with the query of archival materials made it possible to visualize a spatial (3D) appearance of three main phases of the site architectural development, despite a very limited area available for geophysical survey. According to the authors, such a comprehensive approach should be a standard in contemporary geophysical research focused on relics of the past architecture.

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Key words: ground-penetrating radar, geophysics, architecture, archaeology.

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INTRODUCION

Ground-penetrating radar (GPR) has been successfully used for many years in survey of different archaeological sites (see Goodman *et al.*, 2008; Jol and Harry, 2008; Coyners, 2013, 2016; Goodman and Piro, 2013; Witten, 2017; Welc *et al.*, 2017, 2019a, b, 2020; Deiana *et al.*, 2018, and many others). At present, this method is also more and more often used in studies of sites with remains of ancient architecture (see among others: Negri and Leucci, 2006; Nuzzo *et al.*, 2009; Papadopoulos *et al.*, 2009; Trinks *et al.*, 2009; Leucci *et al.*, 2013; Benedetto and Pajewski, 2015; Malfitana *et al.*, 2015; Monteroso-Checa *et al.*, 2019; Welc *et al.*, 2022).

The biggest problem with the use of GPR method in this type of sites is a presence of thick debris layers, which often mask useful anomalies with low and high amplitude noise. Among other significant limitations there are the still standing fragments of walls and a dense plant cover. For this reason, the implementation of GPR for architectural research requires not only advanced geophysical experience, but also a wide knowledge of architecture, archaeology and art history, which is particularly important at the stage of final interpretations. Despite these limitations, properly planned and carried out GPR profiling, even on a very limited surface, can yield very important information regarding both the layout as well as vertical and horizontal stratigraphy of the examined architectural relicts. At a later stage, after integration with historical and archaeological data (if available), these results allow for a three-dimensional reconstruction of the examined architectural feature and a presentation of its transformation phases, sometimes also within a chronological framework. An example of such approach are the results of

GPR survey conducted in the area occupied by the former benedictine monastery complex of St. Peter, located in Supetarska Draga, in the northern part of the Island of Rab in Croatia (Domjan, 2007, 228–233). The implementation of the project was also aimed at developing an integrated methodology of geophysical and architectural research of sites of architectural heritage.

The monastery in Supetraska Draga, a protected cultural heritage monument, is one of the best-preserved Romanesque monuments in coastal Croatia. Nowadays, only the basilica church, a wall of the southern wing and the eastern wing of the monastery are preserved, though with later modifications and restoration. The main goals of the implemented project were:

- Recognition of the relics of the monastery's west wing, not preserved on the ground.
- Testing the thesis, according to which the Early Medieval monastery was erected on relics of an older building (archaeological surveys carried out in recent years have shown the presence of Roman material in the monastery area).
- Integration of the results in a 3D model, taking into account architectural changes in the entire complex.

LOCATION AND HISTORICAL BACKGROUND OF THE MONASTERY IN SUPETARSKA DRAGA

On the farthest western fringe of the large valley of Mundanijsko and Supetarsko polje in the NW part of the Island of Rab, and on the slightly elevated foothills of the northern island's ridge, remains of the former Abbey of St. Peter are located (Figs 1–2). To the south of the site, there is the stream Veli Potok and in east, the complex is flanked by the mostly dry torrential watercourse, while a network of channels lead water from the valley and its slopes towards the nearby Supetarska Draga Bay, where the abbey's saltpans were located.

As mentioned, the St. Peter complex is among the best preserved Romanesque monuments of coastal Croatia. Its basilica-type church with three naves, each ending with an apse and a five-column colonnade (Jakšić, 1983, 207; Jurković, 1990, 197–200, fig. 3; Domjan, 2007, 228–233; Marasović, 2009, 119–123), underwent a restoration dating to the 1960–70s and is now preserved with its $11^{th}/12^{th}$ c. layout and appearance, with few later remodelling, and is still in function today. Few walls of the monastery are today preserved in their original appearance (e.g. the wall of the southern wing, Domjan, 2007, 233; Horvat-Levaj, 2019, 203), when they formed wings surrounding on three sides a cloister enclosed from the north by the church (Marasović, 2009, 123). Over the centuries, various buildings, e.g. the 12^{th} c. bell tower and the 19^{th} c. school building (later demolished), were added to the complex while segments of it were demolished (Domjan, 2007, 231–235).

Thanks to a substantial quantity of historic documents, a development of the St. Peter Abbey can be followed through the centuries; its foundation is dated to 1059 or 1060 when the Bishop and the whole community of the Rab town donated lands belonging to the churches of St. Peter and St. Cyprian to Fulcon, so that he might establish a benedictine abbey there (Mlacović, 2005; Marasović, 2009, 123). Along with this document that undoubtedly testifies the existence of a previous church of the same titular, few fragments of pre-Romanesque and early Christian stone furniture indicate a possible foundation of the Medieval church on a former, probably early Christian building, and testify to at least one subsequent early Medieval refurbishing (Domjan, 2007, 231; Marasović, 2009, 123; Jarak, 2017, 51–52; Jurković 2019, 120–121). Already furnished with a mill, later documents allow to reconstruct the development of the abbey's economic features with the acquisition of further lands in the valley, the building of saltpans and later, the creation of a small village in its vicinity (Mlacović, 2005; 2012, 168).

The whole area of Supetarsko and Mundanijsko fields, stretching from the hinterland of the Rab town (Banjol area) towards west, is dotted by remains or indicators of Roman occupation, including both settlements and necropolises (Konestra *et al.*, 2021). Archaeological survey carried out in the area around the monastic complex in Supetarska Draga allowed to identify a location of several Roman sites, mostly identified by pottery scatters, cairns and drystone walls made with roughly dressed limestone blocks, often exhibiting traces of mortar and mixed with fragments of roof tiles and pottery. Immediately to the east of the complex, surface morphology might point to the existence of a buried architecture, while to the SW small fragments of walls laid in N-S direction have also been noted (Lipovac Vrkljan and Konestra, 2015, 123–130, fig. 3) (Fig. 2: 2: A). Walls and finds of mosaic tesserae in the environs of St. Peter church, at a not precisely defined location, are mentioned by Nedved (1990, 27). In 2016 a rescue archaeological excavation was carried out in front of the entrance to St. Peter's church, yielding a segment of the benedictine's cemetery with residual finds and possibly a drystone wall, indicating late antique occupation (Starac, 2017; Jurković, 2019, 120–121).

According to Mlacović (2012, 169), the island's community did not feel a grave loss in income after the land donation to Fulcon, thus it is possible that in the early Middle Ages, apart from the churches of St. Peter and St. Cyprian, earlier settlements were already abandoned and the surrounding area might have been in need of upkeep and reclamation, activities often associated with the benedictines in other adjacent areas (e.g. Patitucci and Uggeri, 2007, 325). The abbey was abandoned in the late 15^{th} c. and was later shortly managed by the church of St. Mark in Venice (Mlacović, 2012, 167–168), while sparse settlement developed in relation to the field's agricultural plots, on its fringe and on low hills enclosing it from north and south (Budak, 1987, 195; Mlacović, 2012, 168), leading to the formation of today's settlements of Gornja and Donja Supetarska Draga, and smaller hamlets.

Based on this data, geophysical prospection was carried

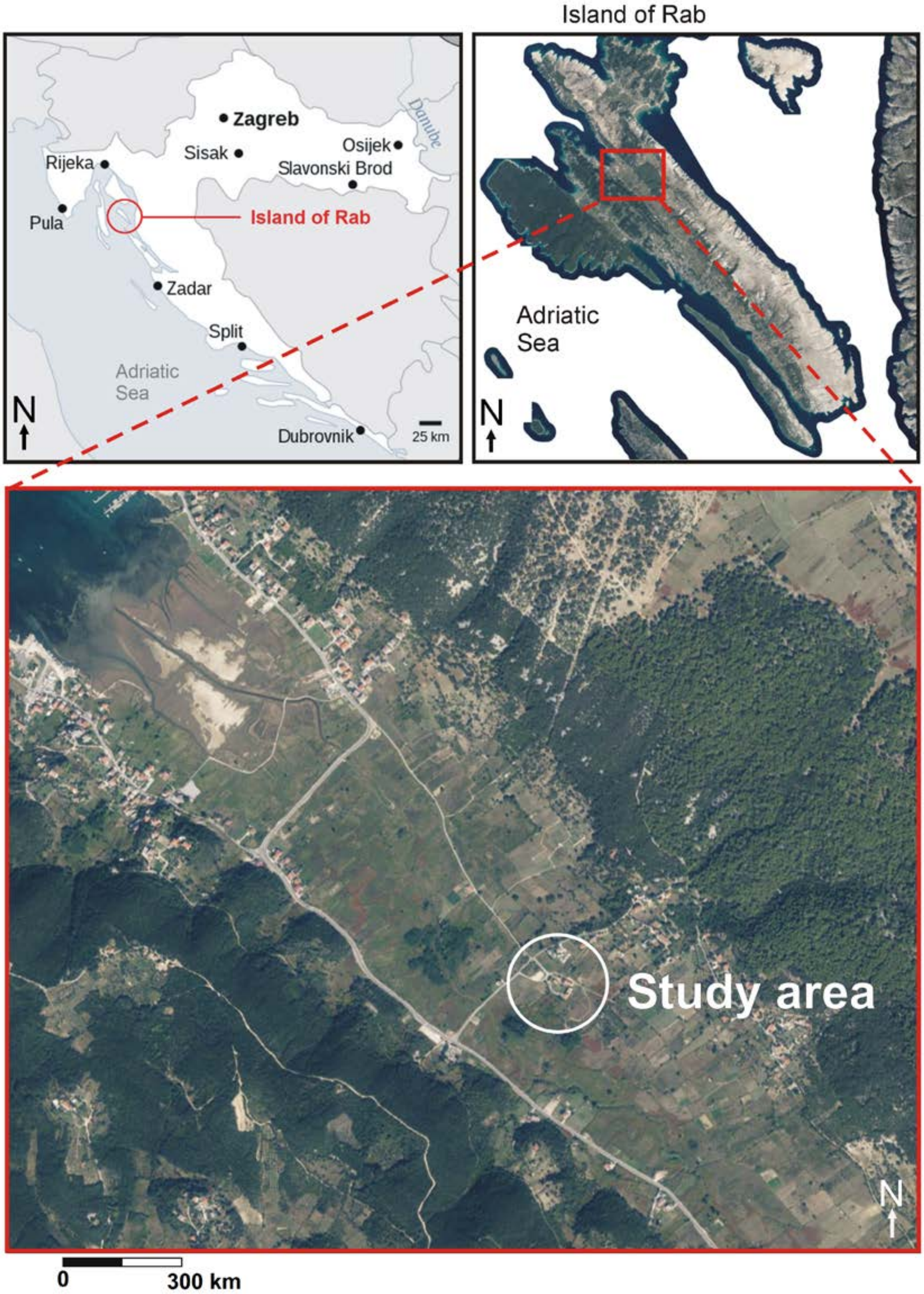

Fig. 1. Location of the Island of Rab and the monastery in Supetarska Draga; marked is the study area (drawing by F. Welc, aerial photos after Croatian Geoportal, website: https://geoportal.dgu.hr).

out in two areas located to the east and south of St. Peter's church. As already mentioned, the main goal of the project was to test the thesis that the monastery was built on relics of Roman or late antique architecture. For this purpose, an analysis of the morphology of the area was carried out, combined with previously known field survey data. Based on these results, the areas for GPR profiling were selected.

METHODOLOGY

In order to achieve the assumed goals during the project implementation, an integrated, multi-stage research methodology was implemented, which consisted of:

– Aerial photogrammetry and creation of a DSM (*Digital Surface Model)* of the area surrounding the monastery.

Fig. 2. 1 – aerial photo of the monastery in Supetarska Draga on the Island of Rab (photo: P. Waligóra), 2 – aerial photo of the monastery with measurement polygons marked as A and B (photo: P. Waligóra), 3 – the measurement polygon A, view from the east (photo: F. Welc), 4 – the measurement polygon B, view from the south-west (photo: F. Welc).

– Analysis of the DSM model in order to precisely pinpoint a suitable location for geophysical prospecting.
– GPR survey.
– Integration of geophysical results with the 3D model of the monastery complex in Supetarska Draga.

Digital Surface Model (DEM)

The first step for DSM creation was capturing areal pictures with the use of UAV (DJI Phantom). Ground Control Points of known X, Y and Z coordinates of surveyed area were taken using a GPS/RTK Topcon device. Generally, DSM is a surface model that includes all captured points during aerial survey, including not only earth surface but also different kinds of natural and anthropogenic features (buildings, trees and other terrain objects). In the second stage a photogrammetric map was processed using Agisoft Photoscan Professional software. The result of this step was a creation of dense cloud point ensemble. The point cloud was generated starting from a sparse cloud, adding high detail to the three-dimensional model for mesh generation in the next step, using Planlauf Tarrain software. A vector mesh of the monastery area was obtained, interpolating the ground points. The last step was DSM generation degrading the mesh and interpolating the TIN (Triangulated Irregular Network). The size of the DSM cells was proportional to the number of points generated in the dense cloud. Export of generated data can be seen in a form of graphics where DSM elevations are represented by a colour scale (Fig. 3).

GPR prospection

GPR is based on the emission of electromagnetic waves (EM) with frequencies ranging from short to ultra-short radio waves by the transmitting antenna and the registration of pulses reflected from layers characterized by different electrical properties. During the research project in Supetarska Draga, Ground Explorer (GX) system produced by Mala Geoscience (https://www.guidelinegeo.com/product/mala-groundexplorer/) was used. The prospection was carried out with the shielded transmitting, bimodal antenna with a frequency of 450 MHz. The individual measurement profiles were spaced apart by a constant interval of 0.4 m.

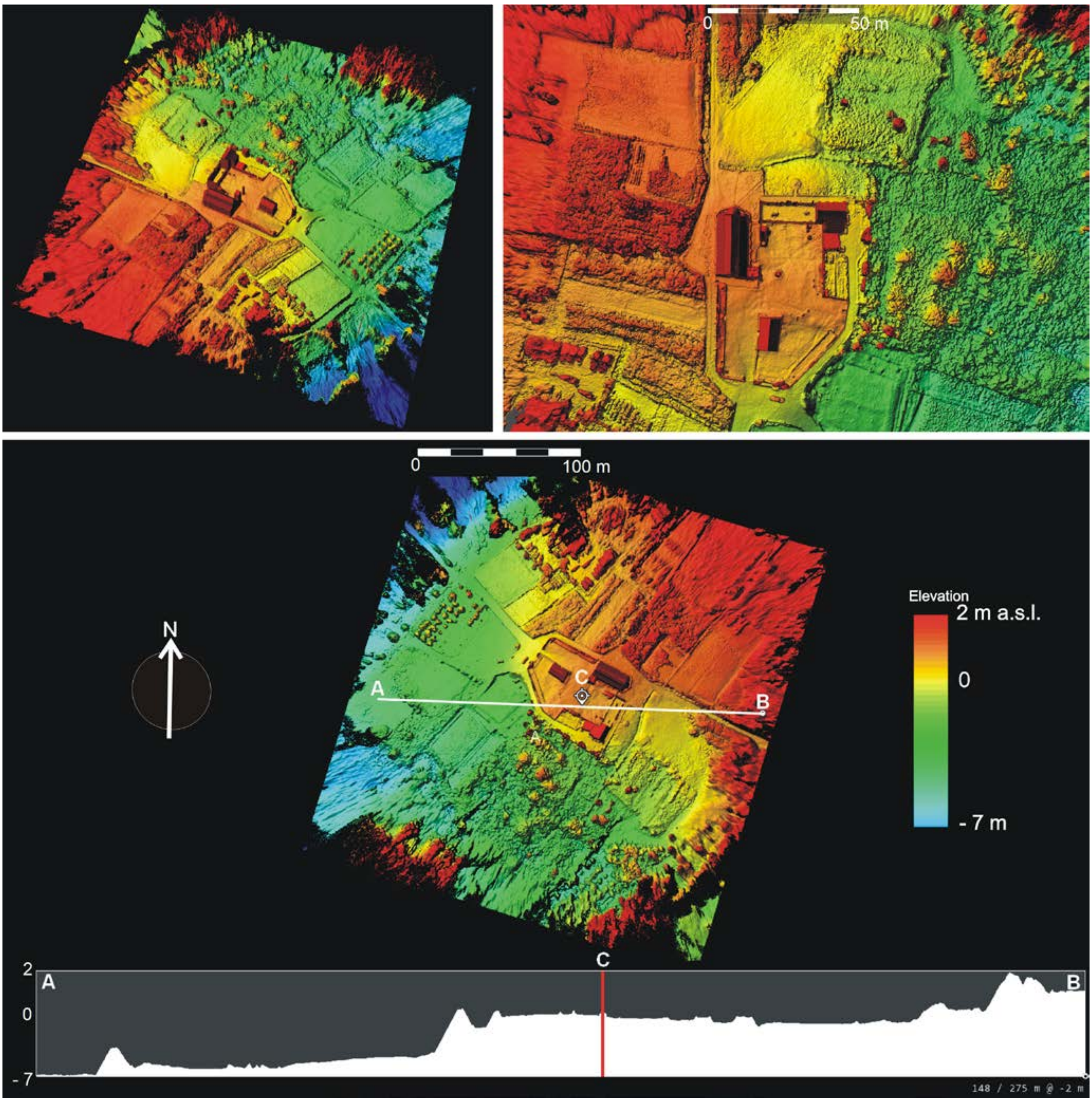

Fig. 3. DSM and cross-section of the Supetarska Draga area with the monastery complex visible in the middle (drawing and processing by F. Welc).

The physical foundations of the GPR method were discussed in detail in many publications, including Jol (2008), Coyners (2013) and most recently – Utsi (2021). Generally speaking, main purpose of radar data processing is to improve the N/S ratio (noise – useful signal) through a multistage procedure of GPR data obtained during field measurements. For this purpose, the *GPR slices* and *ReflexW* software were used with implementation of following procedures:

– *Move start time* (correlation of the first ascent of EM wave).
– *Gain* (amplification of GPR signal. The AGC (Automatic Gain Control).
– *Bandpass frequency.*
– *Background removal* (random noise and direct wave removal).
– *Migration* (procedure for folding diffraction hyperbolas into a point).
– *Static correction.*

For optimal operation of the migration algorithm, it is necessary to know the EM wave velocity in the geological medium. In our case, the procedure of geometric matching of the arms of the diffraction hyperbolas visible on echograms to synthetic hyperbolas with fixed parameters was used to determine it (function in the GPR slices program). The average velocity of wave propagation in the local geo-

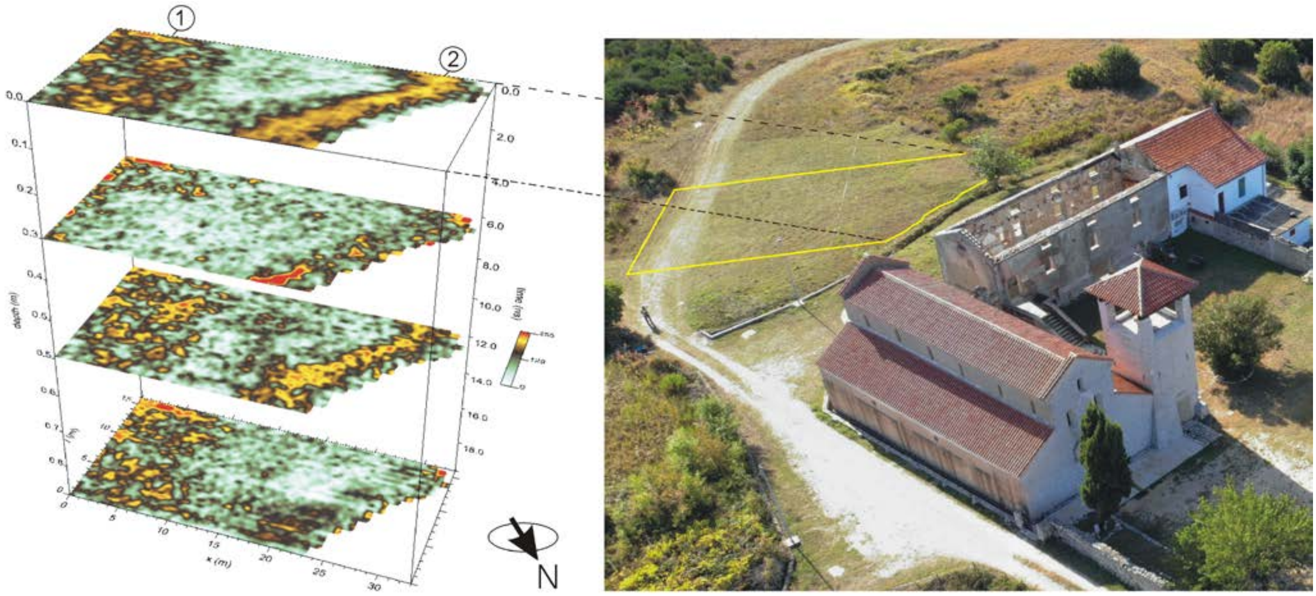

Fig. 4. Measurement area (right), selected GPR plans for individual depth levels. 1 – signal amplification zone corresponding to leveling embankments for the local road, 2 – analogous GPR signal amplification zone echoing the embankment resulting from the excavation of a modern drainage channel (drawing, processing and interpretation by F. Welc).

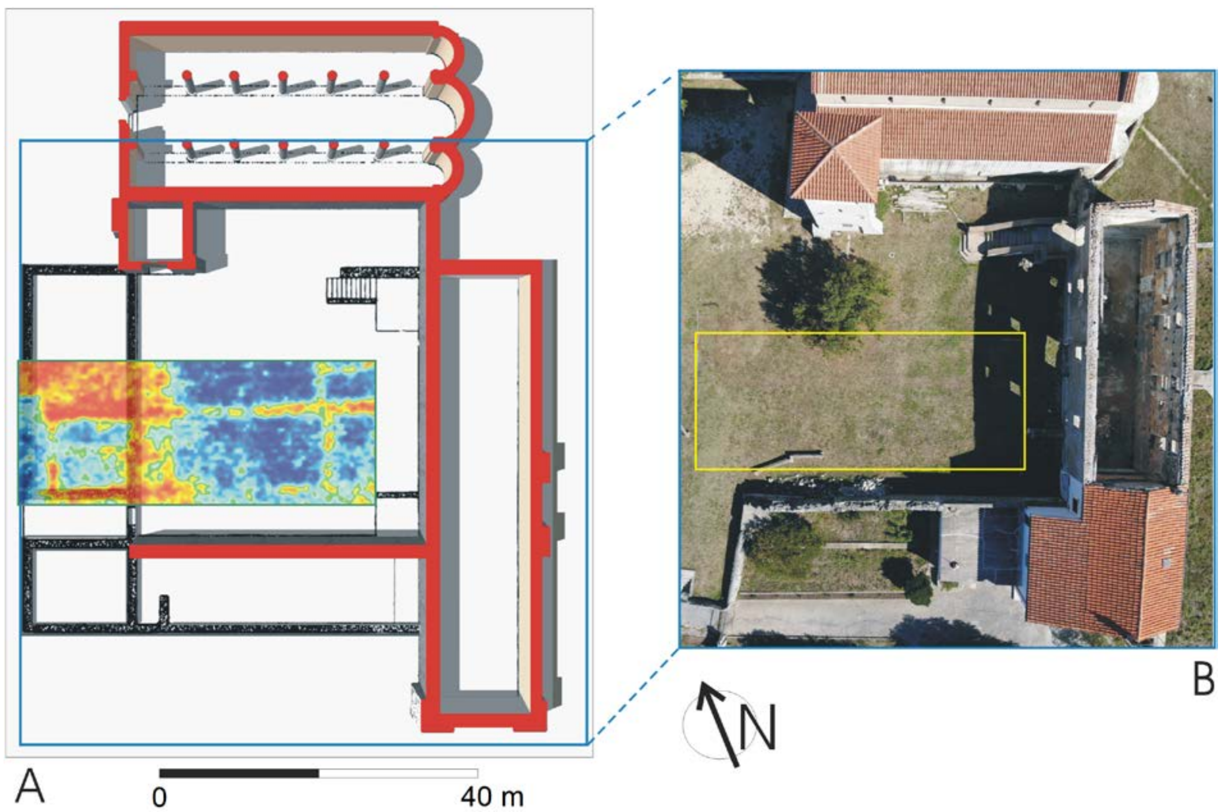

Fig. 5. Plan of the monastery complex in Supetarska Draga according to Domijan (2007), compared with results of GPR profiling (time slice for 1.4 m). The red colour marks the preserved elements of the complex, i.e. the basilica church with a bell tower, the eastern wing of the monastery and a southern wing's wall (drawing by F. Welc after Domijan, 2007). On the right, the aerial photo of the preserved buildings of the monastery complex and the location of the GPR measurement area B (photo: P. Waligóra).

logical medium in Supetarska Draga was determined as 0.06 m/ns. Such velocity has waves passing through, among others, clay sediments. This is in line with the geological map, which in the area in question shows the dominance of the Quaternary formations and diverse characteristics, mainly of runoff-deluvial sediments (Mamuzić *et al.*, 1969).

The effect of data processing are time slices (GPR amplitude planes) and reflection profiles (radargrams) (Welc,

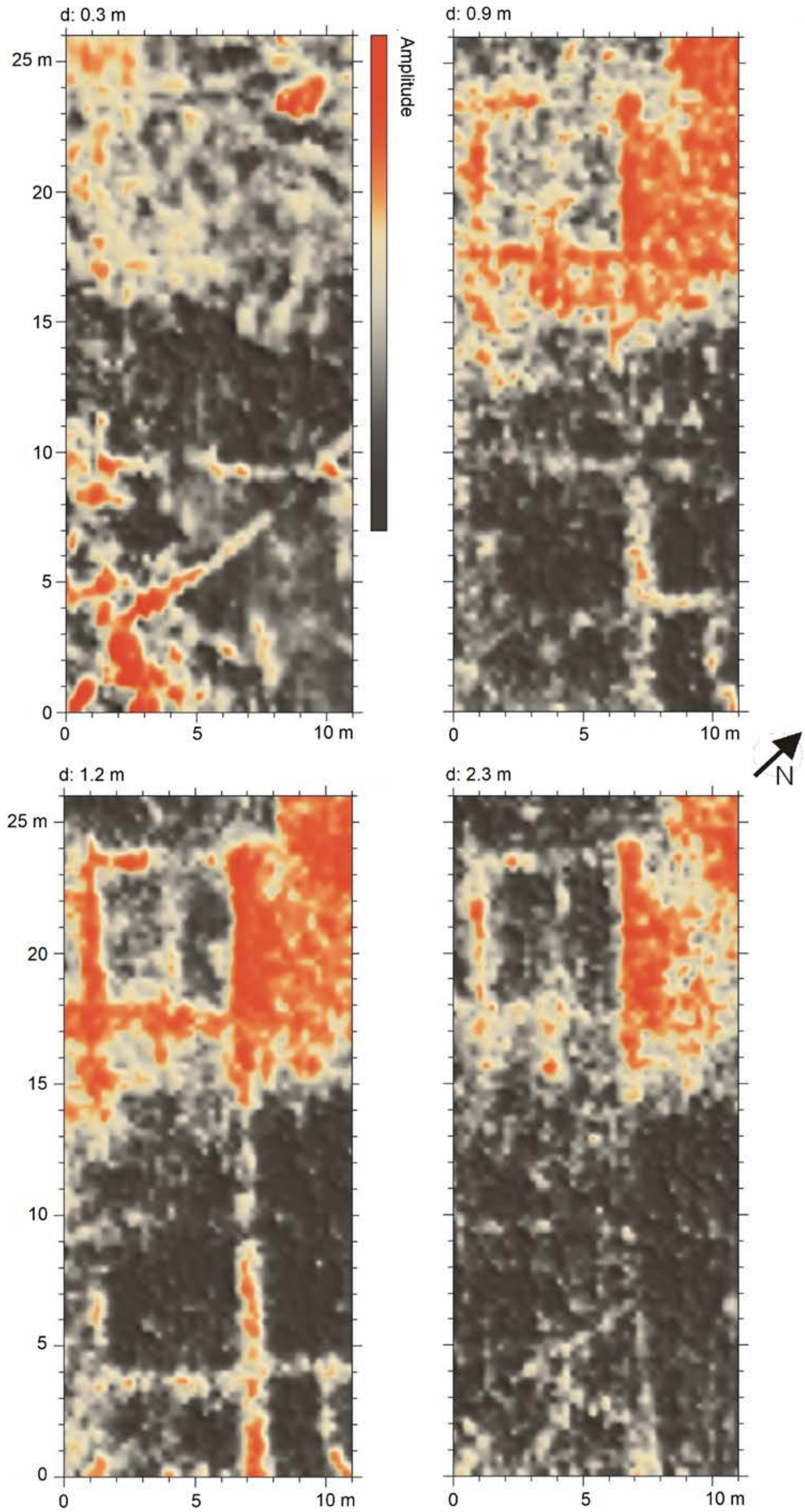

Fig. 6. Selected time slices (GPR plans) for 0.3–2.3 m depth (processing and interpretation by F. Welc).

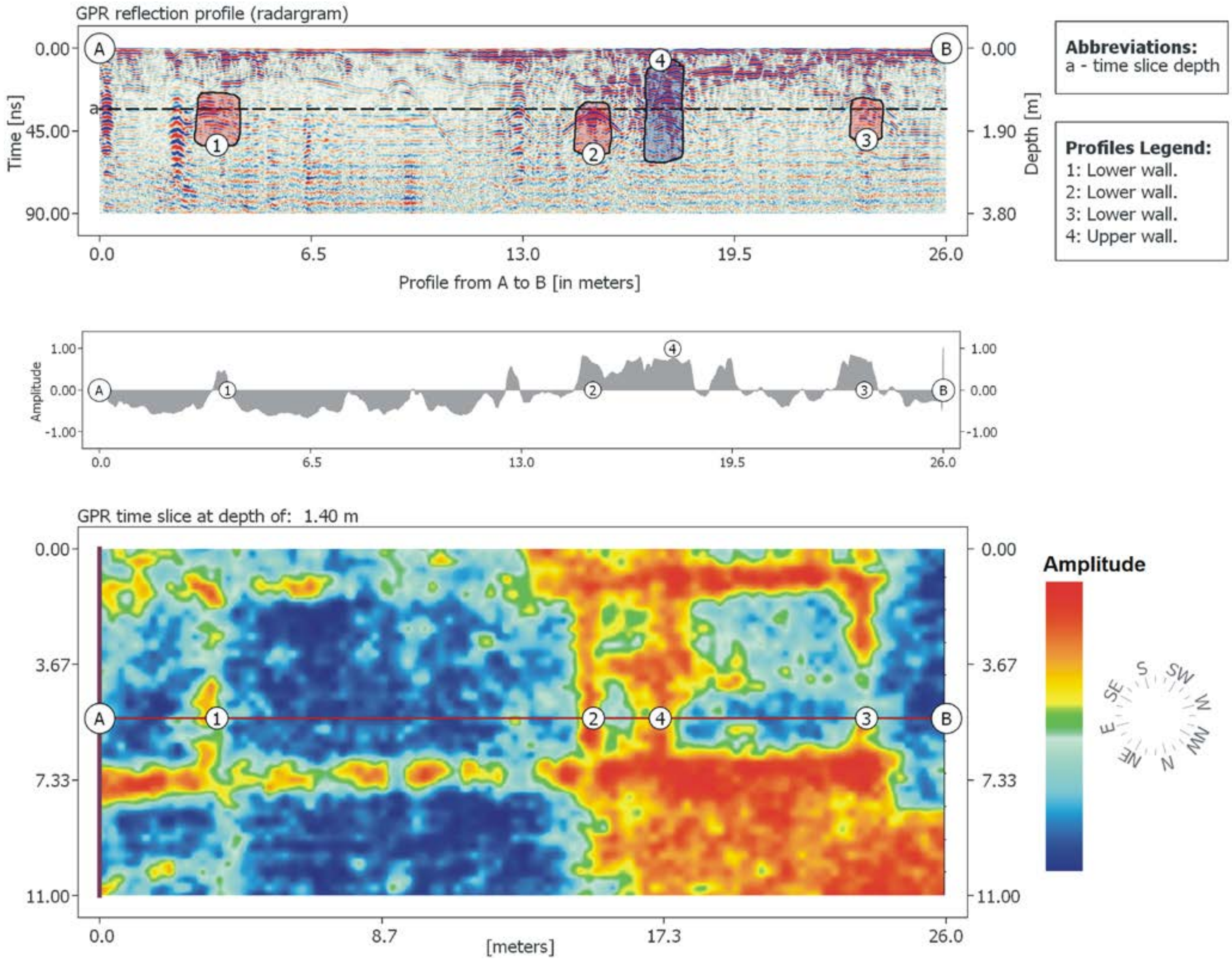

Fig. 7. Time slice prepared for a depth of about 1.4 m, juxtaposed with reflection profile no. 22, with records of the relative amplitude value and interpretation (drawing and interpretation by F. Welc).

2017). In other words, they are linear (vertical) sections of the variability of the soil electrical parameters. These profiles are a graphic image representing a record of the GPR signal amplitude through a colour scale. The last advanced procedure of processing selected groups of radargrams was their compilation into quasi 3D block diagrams, using the modules available in the GPR slices software.

RESULTS

DSM analysis

The analysis of the DSM model showed that the monastery complex in Supetarska Draga is located on a plateau with regular outline, an area of approximately 0.31 hectares and about 0–1 m above sea level (Fig. 3). From the west, the monastery borders with slopes descending towards the west and from the north with a slope of a local hill. The entire area surrounding the site is currently very strongly human-transformed through a development of small arable plots, separated by drystone bordering walls. In this way, the area was given a terrace structure, which significantly hinders the search for relics of past architecture. Directly to the east of the monastery complex there is a flat spot (on the same level as the monastery, approximately at sea level), relief of which contrasts with the surroundings. For this reason, it was selected for geophysical prospecting with the use of GPR and designated as the area A. To test the supposition that the medieval monastery was built directly on the relics of ancient buildings, another measurement polygon was defined within its courtyard, marked as the area B, in order to perform analogous non-invasive prospecting.

GPR

Area A

As already mentioned, the polygon marked as A is located east of the preserved wing of the monastery (Fig. 4). It had dimensions of 16 × 34 m. Time slices produced for the

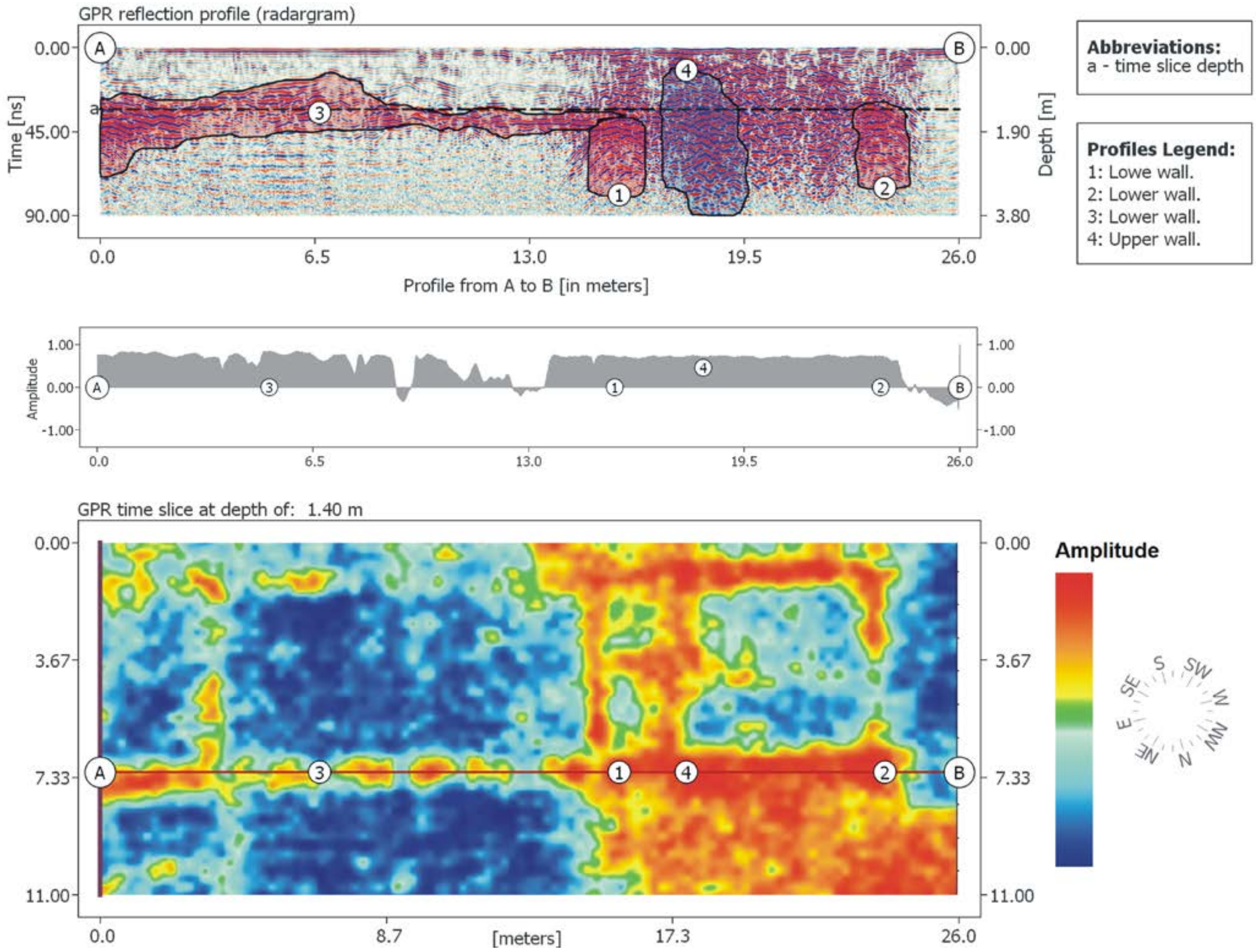

Fig. 8. GPR plan (time slice) prepared for a depth of approx. 1.4 m compiled with reflection profile no. 29, records of the relative amplitude value and interpretation (drawing and interpretation by F. Welc).

depth range from 0.20 to approx. 1 m revealed two distinct sets of anomalies. In the eastern part of the area, an EM signal amplification zone is visible, which most probably should be connected with leveling embankments needed to harden the local road (Fig. 4: 1). The linear anomaly revealed in the western part of the discussed area is probably an echo of the leveled embankment created as a result of digging for the drainage canal (Fig. 4: 1). Therefore, the conducted measurements did not reveal any architectural relics directly east of the monastery complex.

Area B

The test site B was located in a southern part of the courtyard of the monastery complex. It had dimensions of 11 × 26 m. Time slices produced for the depth range from 0.2 to approx. 2 m revealed complexes of linear anomalies that should be interpreted as architectural relics of the west wing of the medieval monastery. These are probably foundations of the walls and accumulation of stone debris (Figs 5–6). For a detailed analysis of the vertical stratigraphy, the GPR (time slice) plan prepared for a depth of approx. 1.4 m was compared with selected reflection profiles (radargram) (Figs. 7, 8). Additionally, the reports also include the relative value of the GPR signal amplitude (Fig. 6).

Both the time slice and the reflection profile reveal at 1.4 m two levels of reflexes (diffraction hyperbolas) reflected from the foundation walls, which are here referred to as the lower walls (Fig. 7: 1–3) and the upper wall (Fig. 7: 4). The difference in the height of their preserved crowns is approx. 1 m. It is important to note that the so-called upper walls coincide with the eastern wall of the west wing of the medieval monastery (Fig. 7: 4, and Fig. 6). So-called lower walls seem to be unrelated to the monastery complex, which is also confirmed by a slightly different orientation. Such a spatial arrangement and stratigraphy may suggest that they are chronologically older and constitute a relic of a destroyed, most likely previous (Roman?) building. The same stratigraphy is revealed by the analyzes of other selected reflection profiles. Again, we see two sets of anomalies characterized by increased GPR amplitude signal (Fig. 8). On the lower one, in addition to the echo of two walls along the S-N axis (Fig. 8: 1–2), we can trace reflection from the wall located at

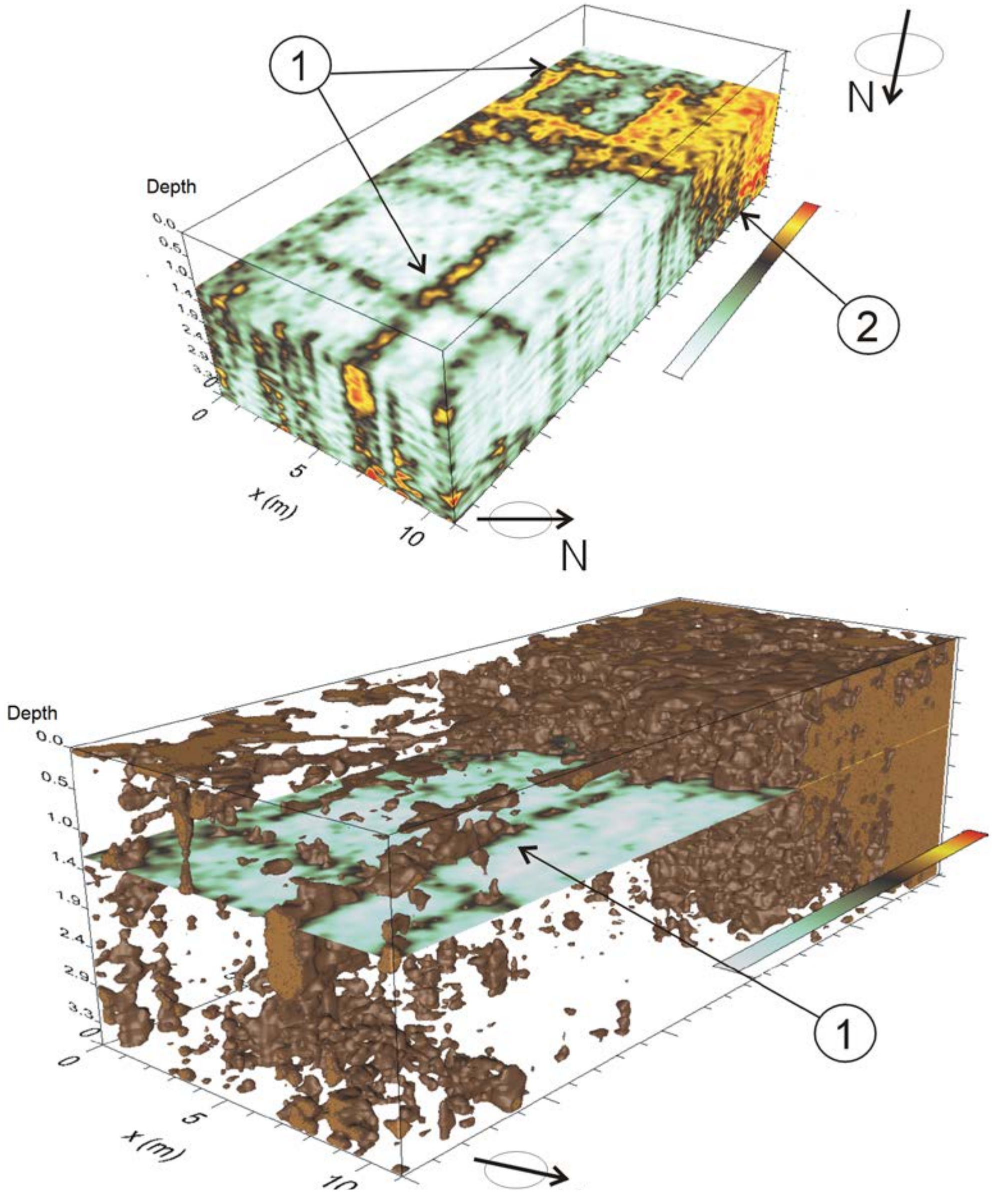

Fig. 9. The spatial (quasi 3D) model of anomalies revealed within the area B with the interpretation: 1 – relics of the so-called lower walls, 2 – relics of the ruined basement of the monastery wing from the Middle Ages or modern times (processing and drawing by F. Welc).

the same level, but oriented along the E-W axis (Fig. 8: 3). Between the walls visible in the western part of the analyzed reflection profile, i.e. between 15 and 26 m of the x-axis, there is a GPR signal amplification zone in the form of chaotically decomposing reflection surfaces, which should be interpreted as a space occupied by stone debris (Fig. 8). It corresponds to the width of the non-existent west wing of the medieval monastery, hence the conclusion that this wing was partially based on the relics of an earlier building.

The above assumptions are also confirmed by the analysis of the 3D model of anomalies revealed within the area B (Fig. 9). In the eastern part of the area in question, linear zones of GPR signal amplification are visible, which are an echo of the stone walls referred to here as the so-called lower walls (antique) (Fig. 9: 1). In the northern corner, the highlight is a zone of high amplitude values that extends from the earth surface to about 3 m depth (Fig. 9: 2). It should be associated with the later, medieval phase of the monastery expansion and possible modern additions. It is most likely a backfill of a basement room. It is worth paying attention to the differences in levels (approx. 1 m) between the crown of the walls, the so-called bottom and top of the backfill (Fig. 9).

In the next stage, results of the GPR survey were integrated with the 3D model of the monastery complex in Supetarska Draga, thus significantly supplementing our knowledge about spatial planning and the phases of the development of this valuable monument. The following architectural phases were identified:

1. The ancient phase (Fig. 10: 1): a hypothetical reconstruction of the oldest phase (blue) is proposed here, based on the results of geophysical profiling. These are

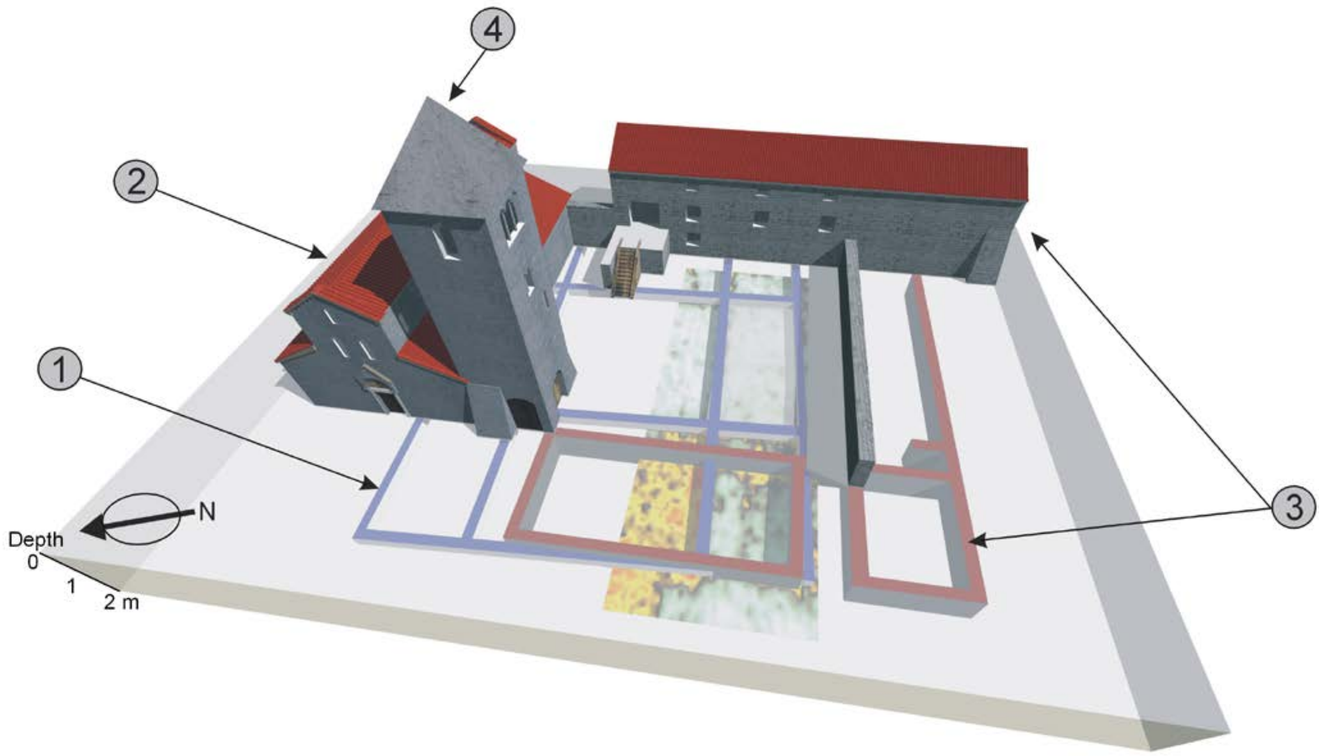

Fig. 10. Integration of results of GPR profiling carried out in the courtyard of the monastery within the 3D model. 1 – reconstruction of the oldest phase (blue) based on geophysical survey: most probably Roman villa with a courtyard, 2 – late Antique/Medieval phase including the basilica church, 3 – Medieval phase (brown). The walls of the southern and western wings of the monastery were reconstructed based on Domijan (2007). 4 – Medieval phase reconstructed with the bell tower based on archival materials by F. Welc, 5 – GPR profiling results for ~1.5 m depth.

most probably foundations of a Roman villa with an internal courtyard (atrium), the dimensions of which can be estimated at approx. 50 × 50 m.

2. In late antiquity a possible remodeling of the complex occurred, with the building of a church to which early Christian stone furniture might be related (Fig. 10: 2)

3. The medieval phase (Fig. 10: 3): partly on the foundations of the western and eastern wings of a Roman villa (the northern wing was possibly still occupied by the church), a three-wing monastic complex was created.

4. The medieval or late medieval phase (Fig. 10: 4) when a bell tower was added to the church from the south, reconstructed on based on historical images (Domjan, 2007, 235) by F. Welc.

5. Later additions to the complex (some today partly demolished), might be evidenced here by the thick backfill layer.

CONCLUDING REMARKS

The complex of the St. Peter monastery at Supetarska Draga on the Island of Rab is an outstanding monument of medieval architecture, development of which can be followed thanks to historical sources, from its foundation in the 11th c. into early Modern times. Nevertheless, as hinted by survey and recent rescue excavations (Lipovac Vrkljan and Konestra, 2015, 123–130, fig. 3; Starac, 2017; Jurković, 2019, 120–121), its history should go further back at least to the Roman times, when this area was part of a vibrant rural landscape dotted by residential-productive complexes (villas, farms) thriving within the island's fields (Welc *et al.*, 2019a).

Multidisciplinary research carried out in the area of the St. Peter monastic complex allowed to confirm a presence of the earlier, presumably Roman/late antique architecture at this site and suggest its possible layout. This would place St. Peter in Supetarska Draga within a group of the eastern Adriatic sites where benedictine monastic complexes were erected on remains of earlier architecture, usually comprising an early Christian church as well. In fact, erection of churches within Roman rural properties, on actual remains or in any case within earlier settlements has been ascertained both on the Island of Rab and elsewhere (see Konestra *et al.*, 2021, 405 and bibliography therein), while the formation of monasteries in the environs of the former is also attested by several examples (e.g. Begović and Schrunk, 2002, 118; Bully and Čaušević-Bully, 2011, 2–4). Therefore, though limited to only two areas in the environs of the monastic remains, this research has brought forth important evidence for the continuity of frequentation of the site, consequently providing data for a better understanding of the developments and transformations of rural areas of the island from (late) antiquity into the Middle Ages.

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