Studia Quaternaria, vol. 43 (2026): 55–73
DOI: 10.24425/sq.2026.158731

RESULTS OF AN INTEGRATED GEOARCHAEOLOGICAL SURVEY (GPR AND BOREHOLE CORING) OF THE BURIED REMAINS OF THE MEDIEVAL CHURCH OF THE SAN SAVINO ABBEY IN JESI (CENTRAL ITALY)

Fabian Welc[1]*, Matteo Tadolti[2], Michelle Mariani[2], Bartosz Nowacki[1], Emanuela Grassetti[2]

[1] *Institute of Archaeology, Cardinal Stefan Wyszyński University in Warsaw, Wóycickiego 1/3, 01-938 Warsaw, Poland; e-mail: f.welc@uksw.edu.pl*

[2] *ABACO soc. coop., Via G. Leti, 82, 63900 Fermo (FM), Italy*

* *corresponding author*

Abstract:
An integrated geoarchaeological investigation was carried out at the site of the former San Savino Abbey in Jesi (central Italy, Marche region), combining ground-penetrating radar (GPR) survey with eight full-core geoarchaeological boreholes. The primary objectives were to document the spatial layout of the buried church, reconstruct the stratigraphic sequence of the site, and establish its chronological framework. GPR time slices and three-dimensional amplitude models identified at least two main phases of architectural development: the uppermost phase corresponds to a three-nave Romanesque-Gothic basilica (ca. 40×19 m) with a rectangular apse, confirmed both by surface observations and geophysical data; a deeper phase is indicated by a rounded apse form and possible transverse walls within the nave, tentatively attributed to an earlier medieval building. Geoarchaeological coring revealed three main stratigraphic horizons: an upper destruction-sepulchral horizon associated with the Romanesque-Gothic church and later use as a burial ground (radiocarbon-dated to 1474–1638 AD); a middle, chronologically complex horizon containing redeposited Roman-period ceramics and charcoal dated to 153 BC–79 AD (94.6% probability); and a lower horizon of natural fluvial substrate. The geomorphological analysis indicates that the site was established on a slightly elevated colluvial-alluvial surface within the Esino River floodplain, a position offering relative protection from flooding. The results demonstrate the high potential of combining non-invasive geophysical methods with minimally invasive coring for the investigation of buried architectural heritage.

Key words: GPR survey; geoarchaeological coring; medieval abbey; Marche (Italy); site formation processes.

Manuscript received 20 May 2026, accepted 3 July 2026

INTRODUCTION

At present, buried architectural remains can be effectively documented and analysed using geophysical techniques, complemented by aerial survey methods such as photogrammetry and LiDAR. Among these, ground-penetrating radar (GPR) is of particular importance in the investigation of architectural structures, as it enables the identification of both the horizontal layout of subsurface walls and their vertical stratigraphic relationships. Under favourable conditions, it also allows for inferences regarding the material properties of the detected features. Even at sites characterised by heavily transformed surfaces, limited accessibility, or the presence of modern infrastructure, carefully designed GPR surveys can provide reliable three-dimensional representations of subsurface structures (see, among others: Ranalli *et al.*, 2004; Conyers, 2006, 2011; Urbini *et al.*, 2007; Gaffney, 2008; Bini *et al.*, 2010; Capizzi *et al.*, 2012; Martinho and Dionísio, 2014; Leucci *et al.*, 2015; Welc *et al.*, 2017, 2022; Cozzolino *et al.*, 2018; Deiana *et al.*, 2018; El-Qady and Metwaly, 2018; Barone *et al.*, 2019; Capozzoli *et al.*, 2019; Costanzo *et al.*, 2021).

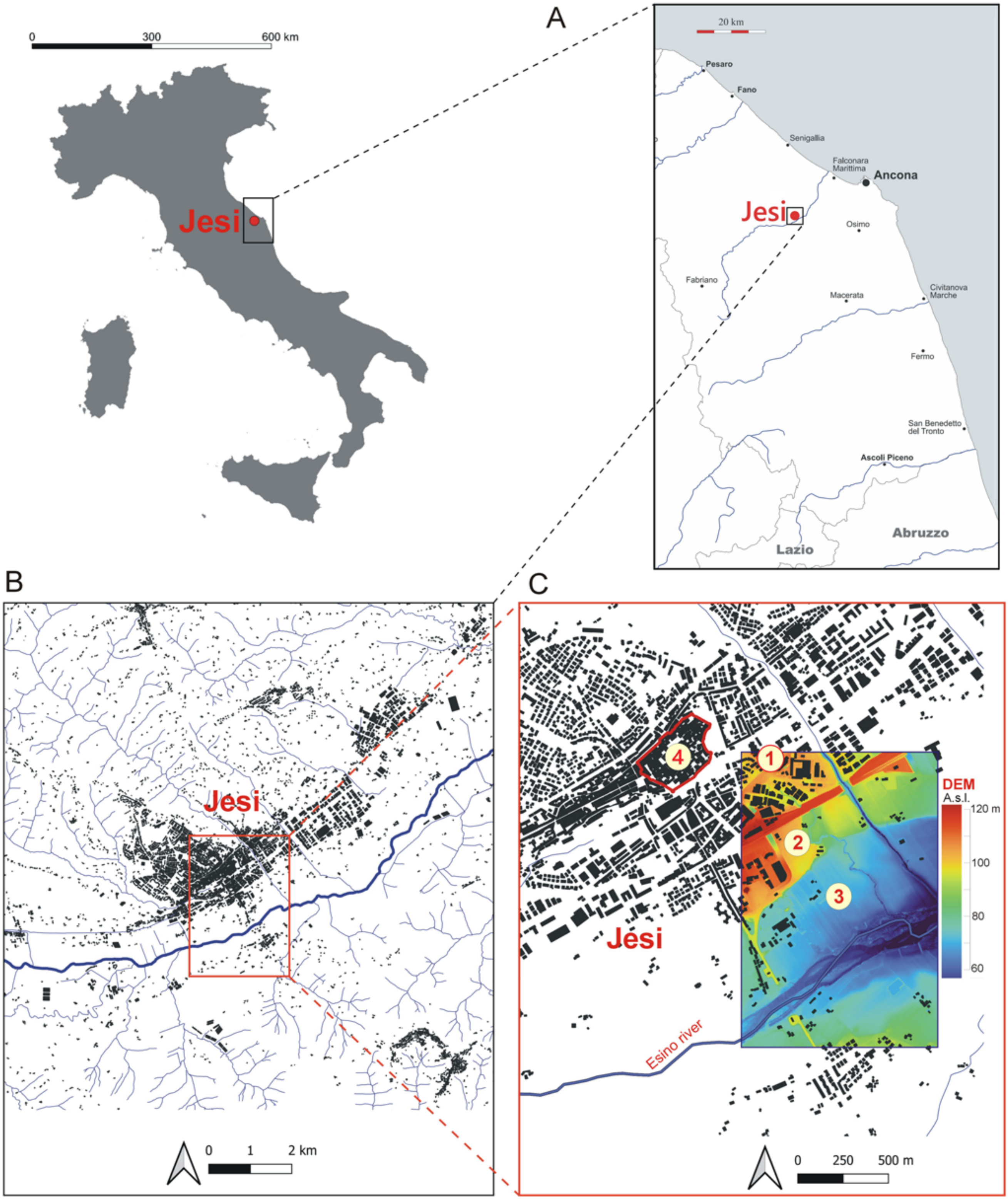

Fig. 1. A: Location of the city of Jesi against the background of the map of the Italian region of Marche. B: the central part of the city; the area enlarged in the adjacent illustration is marked with a red rectangle (drawing: F. Welc). C: 1 – the study area including the remains of the San Savino Abbey (drawing: F. Welc), 2 – the upper riverside terrace (DEM), 3 – the lower terrace (DEM), 4 – the area occupied by medieval Jesi surrounded by defensive walls (drawing: F. Welc).

In a subsequent stage, the results of non-invasive investigations can be successfully verified through geoarchaeological full-core drilling. As a minimally invasive method, coring allows for a near-complete characterisation of vertical stratigraphy and, consequently, for the identification of developmental phases of a given architectural complex (Welc, 2024).

This methodological framework underpins the research conducted at the San Savino Abbey in Jesi (Fig. 1), carried out as part of the Jesi-San Savino Archaeological Project in collaboration with ABACO soc. coop. (Dr. Matteo Tadolti) and the Institute of Archaeology of the Cardinal Stefan Wyszyński University in Warsaw (Prof. Fabian Welc). The primary objective of the project was the non-invasive documentation of the remains of a basilica forming an integral part of the medieval monastic complex, located in the area of the former *Forum Boario* in the eastern sector of the modern city of Jesi (Figs. 1B, 2). The research also aimed to verify historical accounts suggesting that the origins of the San Savino Abbey date back to the transition between Late Antiquity and the Early Middle Ages.

The GPR survey constituted the first and fundamental stage of spatial recognition of the church layout and was subsequently complemented by drilling in order to identify its developmental phases. The aim of this paper is to present the methodology of the geophysical survey and drilling investigations, with particular emphasis on the interpretative potential of the obtained results. As will be demonstrated below, this approach provides insight into the layout, stratigraphy, and state of preservation of the buried architectural remains. Of particular significance are the data concerning the extent and thickness of backfill and rubble layers, which are essential for the effective planning of future archaeological investigations.

HISTORICAL AND ARCHITECTURAL OUTLINE

In 1578, Pietro Grizi, in *Il ristretto delle istorie di Jesi*, asserted that the abbey was founded by the Goths in the first half of the sixth century AD and subsequently restored in the 7th–8th centuries by the Lombards, with the assistance of monks from Farfa Abbey (Grizi, 1578; McClendon, 1987). The earliest extant historical record pertaining to the abbey dates to July 5, 1222, when Pope Honorius III, through Papal Bull No. 7 of 1222, addressed the Bishop of Jesi and the Abbot of San Savino (Pressutti, 1888; Kehr, 1909). At that time, the monastery of San Savino held sufficient importance to be directly addressed by the Papal Curia (Kehr, 1909).

A subsequent document indicates that in AD 1230 a concord was reached in Pierosara between Abbot Attone of San Savino and the abbot of San Vittore alle Chiuse concerning the church of San Michele di Lappurano (Paoli, 1976). Between the 12th and 14th centuries, the monastery underwent significant renovations (Costantini, 1986). Nevertheless, the monastic church exhibited considerable structural deficiencies, necessitating the reconstruction of the chapel dedicated to San Savino in 1454 (Costantini, 1986). By the mid-14th century, the monastery had fallen into marked decline, and in 1458 Pope Callistus III transferred the abbey's assets to the episcopal *mensa* in Jesi (*Bullarium Romanum*, 1739). The abbey continued to function until the mid-15th century, when it was ultimately destroyed (Costantini, 1986). In 1974, the remains of the San Savino Abbey were discovered near the *Forum Boario*.

The archaeological site, comprising the remains of the abbey church, is currently located near the intersection of Via Minzoni and Forum Boario (Fig. 2A). The remains of the church's perimeter walls, approximately 1 m thick, were exposed during the 1970s and have since been preserved *in situ*. Within their structure and on their surfaces, numerous fragments of Roman tiles (*tegulae*) and small limestone blocks were identified, most likely reused from a Republican-Imperial villa uncovered in the 1970s beneath a modern school approximately 50 m southwest of the church remains (Accademia Nazionale dei Lincei, 1998).

The preserved walls visible at the surface are constructed of bricks varying in size, composition, and firing technology (Fig. 2B–D), including characteristic flat ancient bricks, similar Romanesque bricks, and larger, darker Gothic bricks fired at lower temperatures, the latter predominating in the upper parts of the surviving masonry. A comparable variability is observed in the mortars and masonry bonding techniques (Fig. 2D), highlighting the complex history of architectural transformations within the church.

The remains preserved at the surface are primarily associated with the final Gothic phase of the church's architectural development. During this period, the structure appears to have been a substantial edifice, oriented southwest-northeast, with estimated dimensions of approximately 40×19 m. The interior was divided into three naves by two rows of five square-section pillars, each measuring approximately 2×2 m. The central nave was 5.72 m wide, while the side aisles measured approximately 3.30 m each. At the northeastern end, the church was likely terminated by a square or rectangular apse approximately 10 m wide. Within the nave and side aisles, fragments of stone slabs of varying dimensions were observed on the surface, which may derive either from the church's flooring or from disturbed burial structures.

Analysis of the digital elevation model (DEM) indicates that the preserved remains of the church are situated on a small, oval-shaped mound approximately 2 m high (69 m a.s.l.), likely formed by the accumulation of debris (Fig. 3). To the south, the mound shows evidence of truncation, probably resulting from road construction or erosional processes. At its summit, particularly in the northeastern sector, the outlines of walls, the church perimeter, and pillar bases are visible as a series of shallow depressions, which are interpreted as traces of earlier archaeological investigations.

GEOLOGICAL BACKGROUND

The area occupied by the remains of the San Savino Abbey is located northeast of the historic centre of Jesi, within the wide floodplain of the Esino River, on one of the terraces formed through the accumulation of fluvial sediments (Cilla *et al.*, 1994; Coltorti, 1997; Guerrera and Tramontana, 2004). Based on the digital elevation model (DEM) (Fig. 1C), the abbey remains are situated on a higher Pleistocene terrace composed of deposits belong-

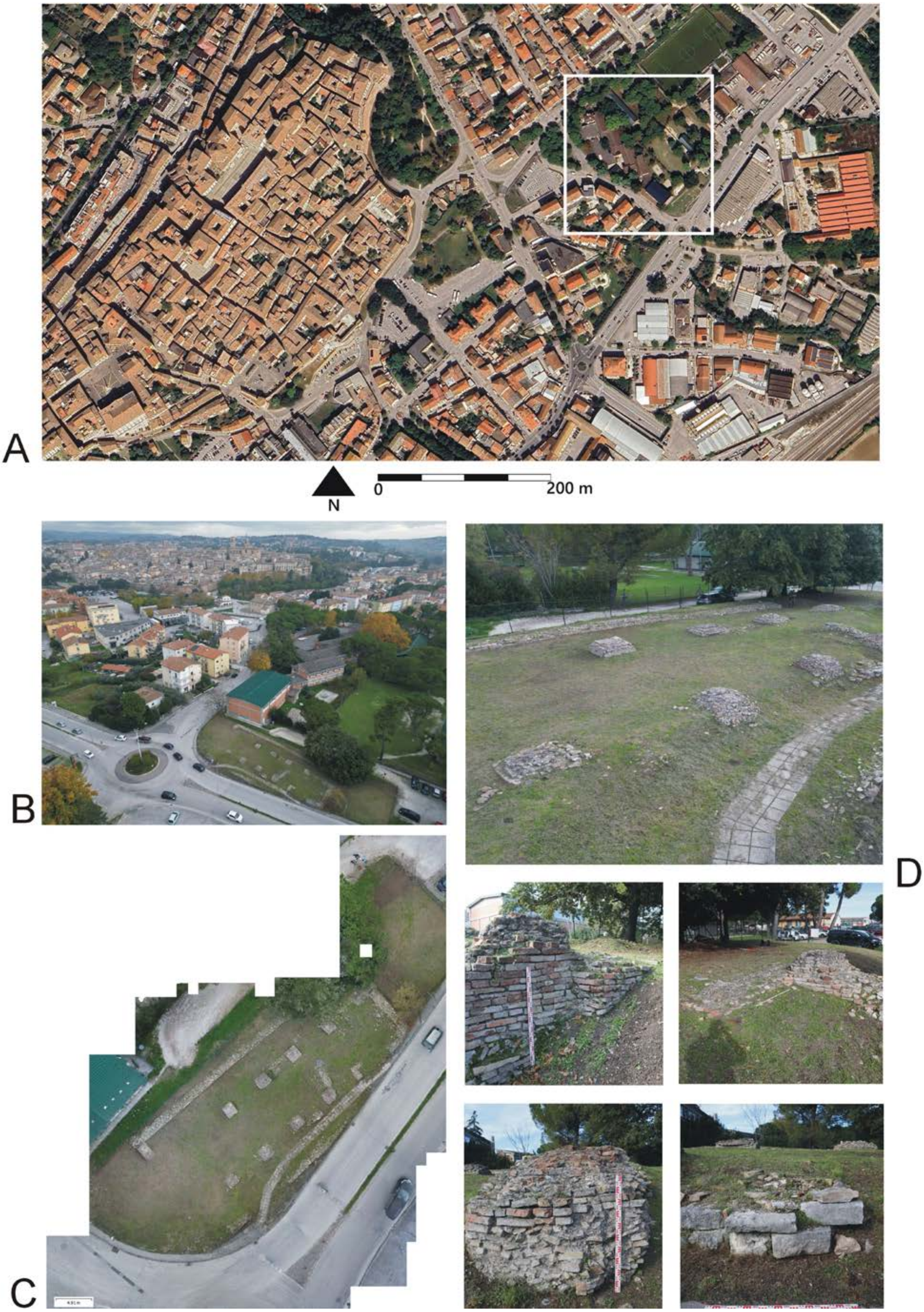

Fig. 2. A: Location of the examined area marked with a white rectangle (drawing: F. Welc). B: View of the relics of the abbey church of San Savino from the south-east (photo: F. Welc). C: Orthophotomap of the relics of the church (photo: F. Welc). D: Relics of the perimeter walls and pillars of the abbey church preserved on the surface of the ground (photo: F. Welc).

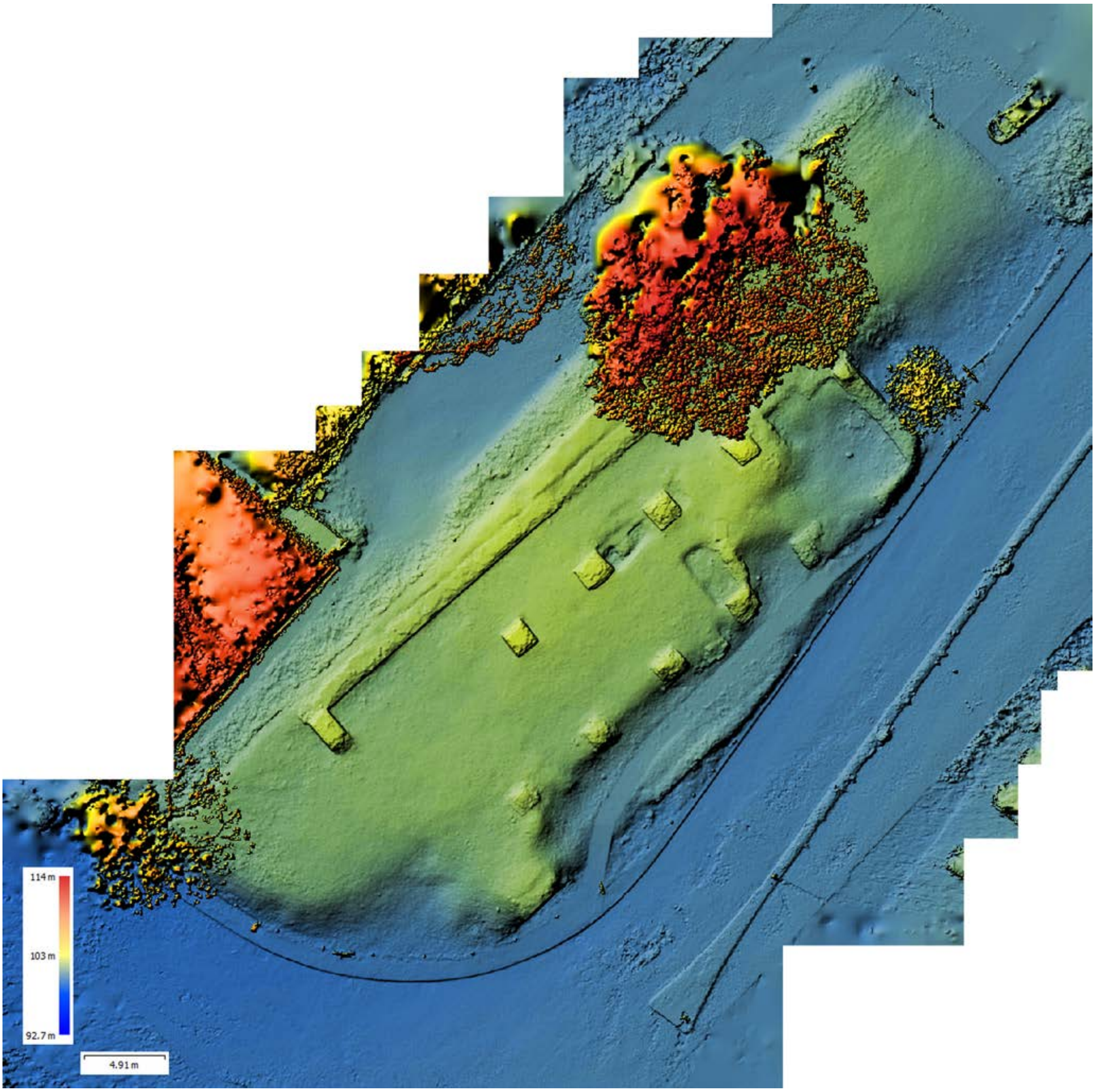

Fig. 3. DEM model of the area occupied by the remains of the San Savino Abbey (drawing: F. Welc). The elevation scale shows ellipsoidal (GNSS) heights and is therefore not directly comparable with the orthometric elevations (m a.s.l.) quoted in the text.

ing to the Sintema di Matelica (MTI), i.e. the Pleistocene coarse-grained fluvial sediments (mainly gravel and sand) deposited under high-energy flow conditions and forming elevated river terraces (Guerrera and Tramontana, 2004).

A detailed reconstruction of the geological structure of the area containing the San Savino church remains was made possible through geotechnical boreholes carried out between 1970 and 1976 in the vicinity of the Federico II school (Accademia Nazionale dei Lincei, 1998) (Fig. 4). These boreholes revealed the presence of a continuous anthropogenic backfill layer (*riporto*) with variable thickness ranging from approximately 0.90 m in the northeastern sector to 4.60 m in the southwestern sector, directly overlying natural Quaternary deposits. This layer contains numerous fragments of ceramics and ancient building materials (primarily fragments of Roman roof tiles), reflecting the use of the area during the Roman period.

Directly beneath the anthropogenic layer, particularly in boreholes S8 and S9, a package of fine-grained sediments was identified, described as clayey colluvial-fluvial deposits and clayey silt with a marly matrix (Fig. 4). Part of this material (colluvium) was transported downslope by gravitational processes from higher-lying terrain, most likely from the edge of the plateau currently occupied by the medieval town of Jesi. The alluvial deposits, in turn, represent material deposited by episodic surface runoff under low-energy flow conditions. The marly matrix indicates that this material originated from the erosion of

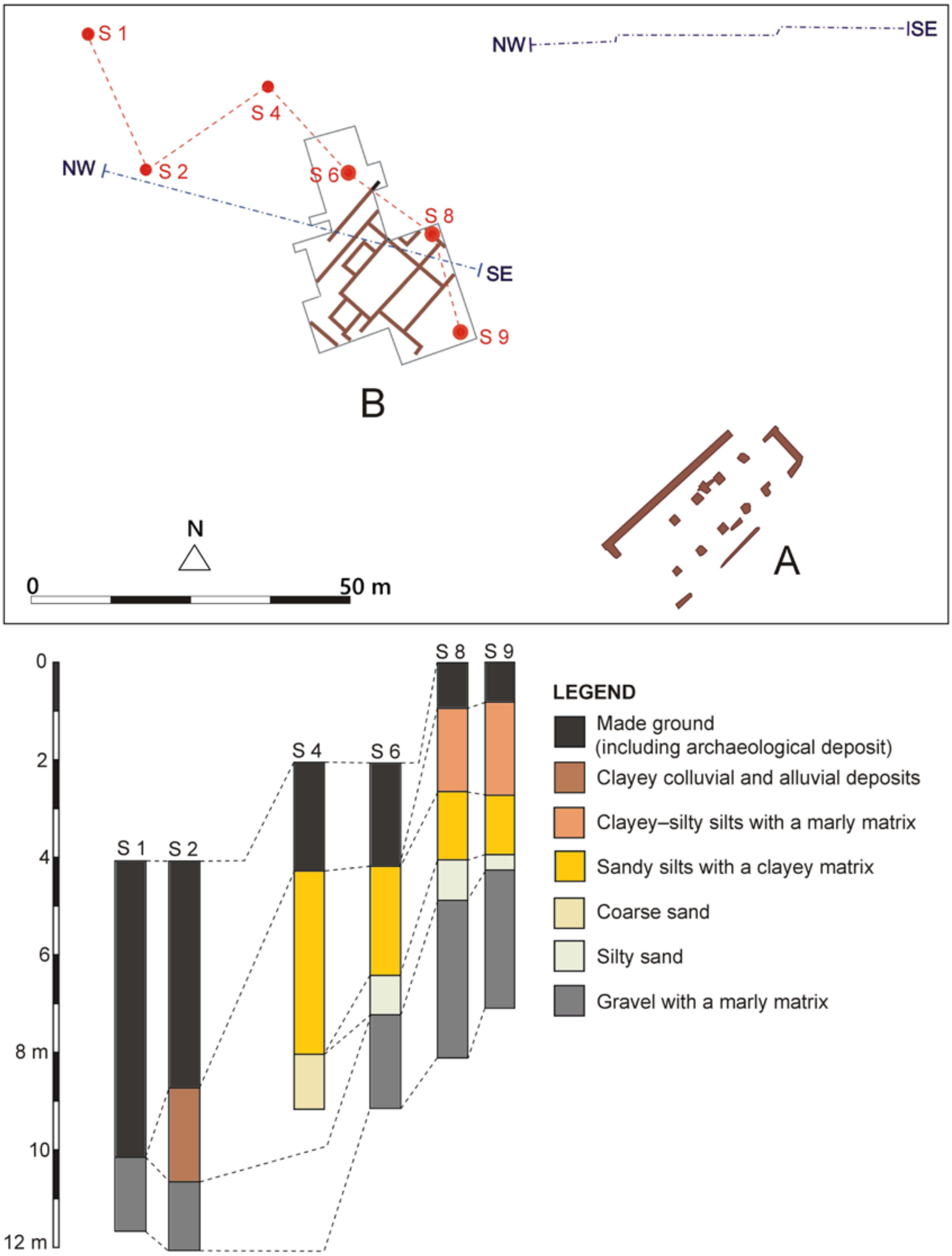

Fig. 4. Location of boreholes (S1–S9) and simplified geological cross-section along the NW-SE transect across the Forum Boario area in Jesi. The upper panel shows the position of the boreholes in relation to the excavated Roman archaeological structures (A) and San Savino church remains (B). The lower panel presents the interpreted stratigraphic sequence based on selected boreholes (S1, S2, S4, S6, S8, S9), illustrating the thickness and lateral variability of anthropogenic deposits (including archaeological deposits) overlying fluvial sediments of the Esino River terrace, composed of clayey silt with a marly matrix, sandy silt with a clayey matrix, sand, and gravel. Depth in metres (after: Accademia Nazionale dei Lincei, 1998; drawing and modification: F. Welc).

clayey-marly formations forming the hill dominating the Esino floodplain from the north and east.

Below the clayey colluvial and fluvial deposits, the boreholes reveal a sequence of natural fluvial sediments related to the fluvial terrace of the Esino River, consisting of sandy silt with a clayey matrix, passing downward into coarse and silty sand, followed by sand and gravel layers, and finally gravel with a marly matrix at greater depths. This succession reflects a gradual increase in grain size and depositional energy, from fine overbank or floodplain sediments to higher-energy channel and channel-proximal fluvial deposits (Accademia Nazionale dei Lincei, 1998).

Fig. 5. The area covered by GPR surveys with the use of a 450 MHz antenna (photo and drawing: F. Welc).

MATERIAL AND METHODS

GPR survey

The investigation of the abbey remains in Jesi began with ground-penetrating radar (GPR) surveys, a non-invasive geophysical method widely used in archaeological and architectural research. GPR operates by transmitting electromagnetic waves into the subsurface using a transmitting antenna; these waves are reflected by layers or objects with contrasting electrical properties, allowing the detection of buried structures and stratigraphic boundaries (Goodman and Piro, 2013; Persico, 2014; Conyers, 2016, 2023; Zhao *et al.*, 2023).

The survey was carried out using the Ground Explorer (GX) system produced by MALÅ Geoscience, equipped with a shielded bimodal antenna operating at a frequency of 450 MHz. A systematic survey grid was established across the study area, with measurement lines arranged in parallel with a spacing of 0.40 m, georeferenced using a GNSS system. The collected data were processed using GPR-Slice software. The processing workflow included: time-zero correction (Move Start Time), amplitude enhancement using Automatic Gain Control (AGC), band-pass filtering, background removal, and migration to collapse diffraction hyperbolas. Depth calibration was performed through geometric fitting of diffraction hyperbolas, resulting in an estimated electromagnetic wave velocity of approximately 0.07 m/ns, consistent with propagation in silty-sandy sediments typical of the investigated area.

The survey area measured approximately 19 m (x) by 58.5 m (y) (Fig. 5), with individual profiles spaced at intervals of 0.40 m. After processing, the radar profiles (radargrams) were compiled into quasi-three-dimensional datasets and amplitude distribution maps (time slices). It should be emphasised that at depths exceeding 1.5 m, the vertical resolution of the 450 MHz antenna is approximately 0.15–0.20 m. Identification of architectural features at these depths, in particular changes in apse form, should therefore be treated with caution, as heterogeneous moisture conditions in anthropogenically disturbed fills may generate amplitude artefacts mimicking structural boundaries. The interpretation of GPR data presented in this paper should be regarded as provisional and subject to validation through future excavation.

Geological drilling

On the basis of GPR results, eight full-core boreholes were drilled (labelled Jesi 1 to Jesi 8) to verify the geophysical interpretations and reconstruct site stratigraphy (Fig. 6). The positioning of the boreholes was carefully planned to avoid damaging subsurface masonry remains. Drilling was carried out using a percussion coring system (Cobra, Eijkelkamp), equipped with tubular samplers of 1 and 2 m in length and diameters ranging from 5 to 10 cm, driven into the ground using a vibratory hammer. This method ensured the recovery of continuous sediment cores with preserved internal structure, suitable for detailed stratigraphic description and sampling. The boreholes yielded diagnostic ceramic fragments used for relative dating. In addition, two samples were subjected to radiocarbon dating at the Radiocarbon Laboratory in Poznań, Poland: a charcoal sample from borehole Jesi 4 (depth 1.10–1.15 m), recovered from a burning horizon (burnt layer) within the middle stratigraphic unit, and a human bone sample from borehole Jesi 5 (depth 0.40–0.45 m).

RESULTS

Ground-penetrating radar

The GPR time slices obtained during processing reveal regularly distributed linear zones of attenuation and areas of enhanced electromagnetic signal amplitude across the surveyed area (Figs. 7, 8). Zones of signal enhancement are interpreted as accumulations of coarse material (bricks, stones) mixed with finer debris. The areas of strong reflections correspond to the physical remains of the abbey church foundations.

Analysis of the anomaly patterns recorded in the time slices allows for the distinction of at least two, and most probably three, phases of the church's development. These phases represent a relative stratification based solely on GPR data and should be regarded as provisional.

Within the depth interval of approximately 0.40–0.90 m, linear anomalies are clearly visible and correspond to the perimeter walls of the church, most likely representing the latest Romanesque-Gothic phase (Fig. 7A). These anomalies show a high degree of correspondence with the course of walls observable at the present-day surface. On the northern side, two linear anomalies connected to the apse wall most likely represent the remains of a tower structure (Fig. 7A: 1). Another notable feature is the presence of irregular anomalies in the area between the main nave and the presbytery, most likely associated with burials dating to the post-medieval period, when the ruins of the church were transformed into a cemetery (Fig. 7A: 2).

At depths exceeding 1 m, the image of the anomalies becomes considerably more complex. Time slices at this level reveal, within the western side aisle, linear anomalies indicating the presence of an earlier architectural structure, most likely a rectangular annex (Fig. 7B: 3). At depths greater than 1.5 m, a significant change in the plan of the apse is observed, which appears rounded rather than rectangular (Fig. 7C: 4). Within the central nave, zones of enhanced GPR signal appear as chaotically distributed reflective surfaces, which may be interpreted either as debris deposits or as the remains of transverse walls belonging to an earlier construction phase. To the east of the structure, an anomaly corresponding to a feature of approximately square plan is visible; its interpretation remains uncertain (possibly a tomb) and further investigation is required (Fig. 7C: 5).

In summary, analysis of GPR time slices between approximately 0.30 m and 2.0 m depth enabled the identification of at least two main phases of the church's development. The remains visible at the surface can clearly be associated with the Romanesque-Gothic phase. The most probable indicators of an earlier architectural phase include the transformation of the apse from a rectangular to a rounded form, as well as the possible presence of transverse walls in the eastern part of the central nave. The spatial distribution of the detected anomalies is presented in the volumetric model shown in Fig. 8.

A cross-section through the volumetric GPR model clearly reveals the presence of transverse walls within the main nave (Fig. 8A: 1) and confirms the presence of a large burial structure located directly north of the church apse (Fig. 8A: 2). The comparison of a selected time slice at approximately 1.7 m depth with a profile obtained along the x-axis at 23 m highlights reflections of perimeter walls

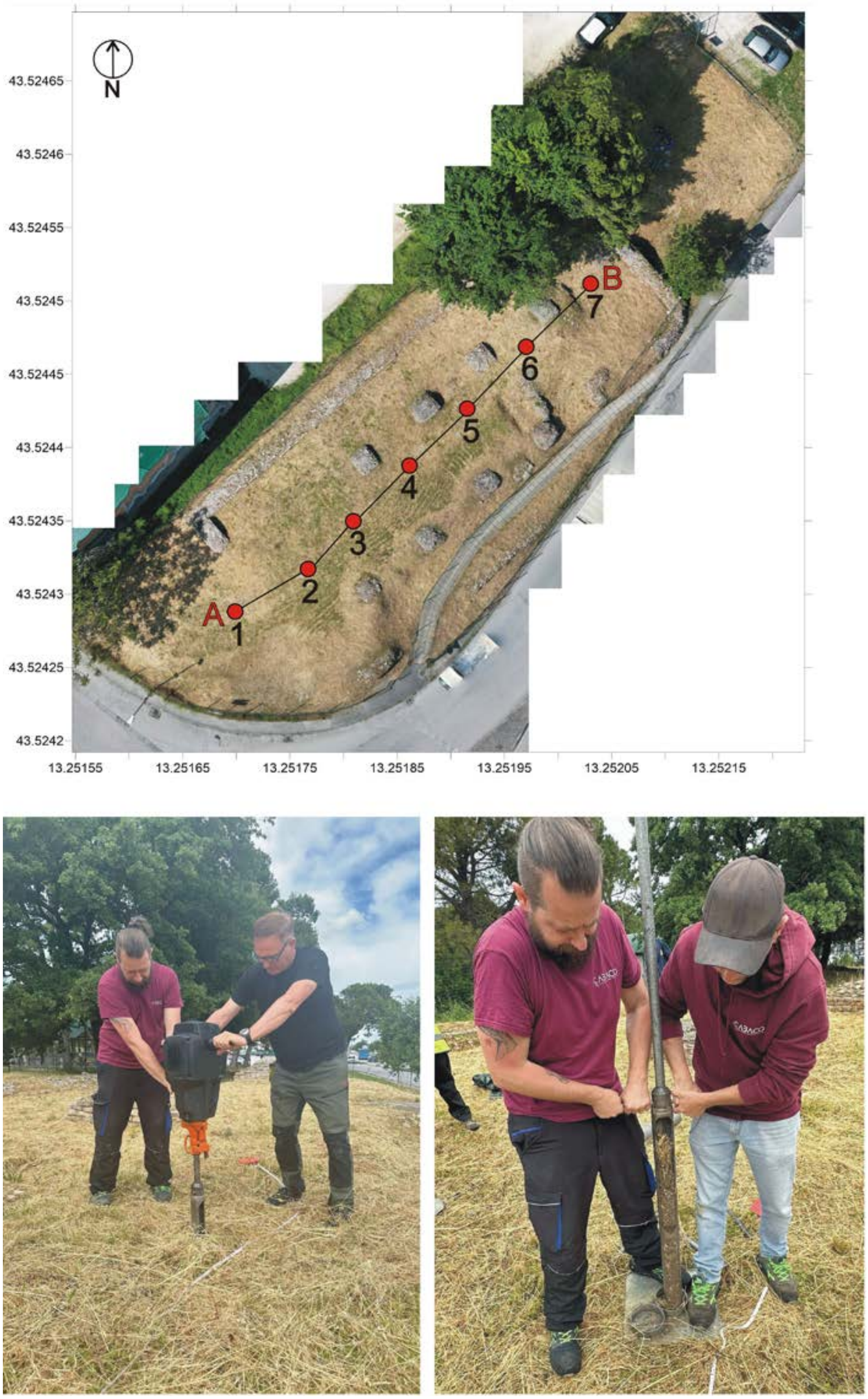

Fig. 6. Top: location of the boreholes (profile A–B) within the relics of the church of San Savino (photo: F. Welc). Coordinates in WGS 84 (decimal degrees). Borehole Jesi 8, located northeast of point B, lies outside the frame of the orthophotomap. Bottom: drilling full-core boreholes using the percussion method (photo: A. Orłowska).

belonging to the Romanesque-Gothic phase (Fig. 8B: 3), graves cut into the nave (Fig. 8B: 4), and deeper-lying walls that may represent an earlier construction phase (Fig. 8B: 5). The complexity of the subsurface structures is particularly well illustrated by the volumetric model of GPR anomalies (Fig. 8C).

Drillings

The boreholes, labelled Jesi 1 to 8, document a stratigraphic sequence composed of anthropogenic deposits, reworked colluvial-fluvial sediments, and natural fluvial substrate (Figs. 6, 9). In all cores, the uppermost part of

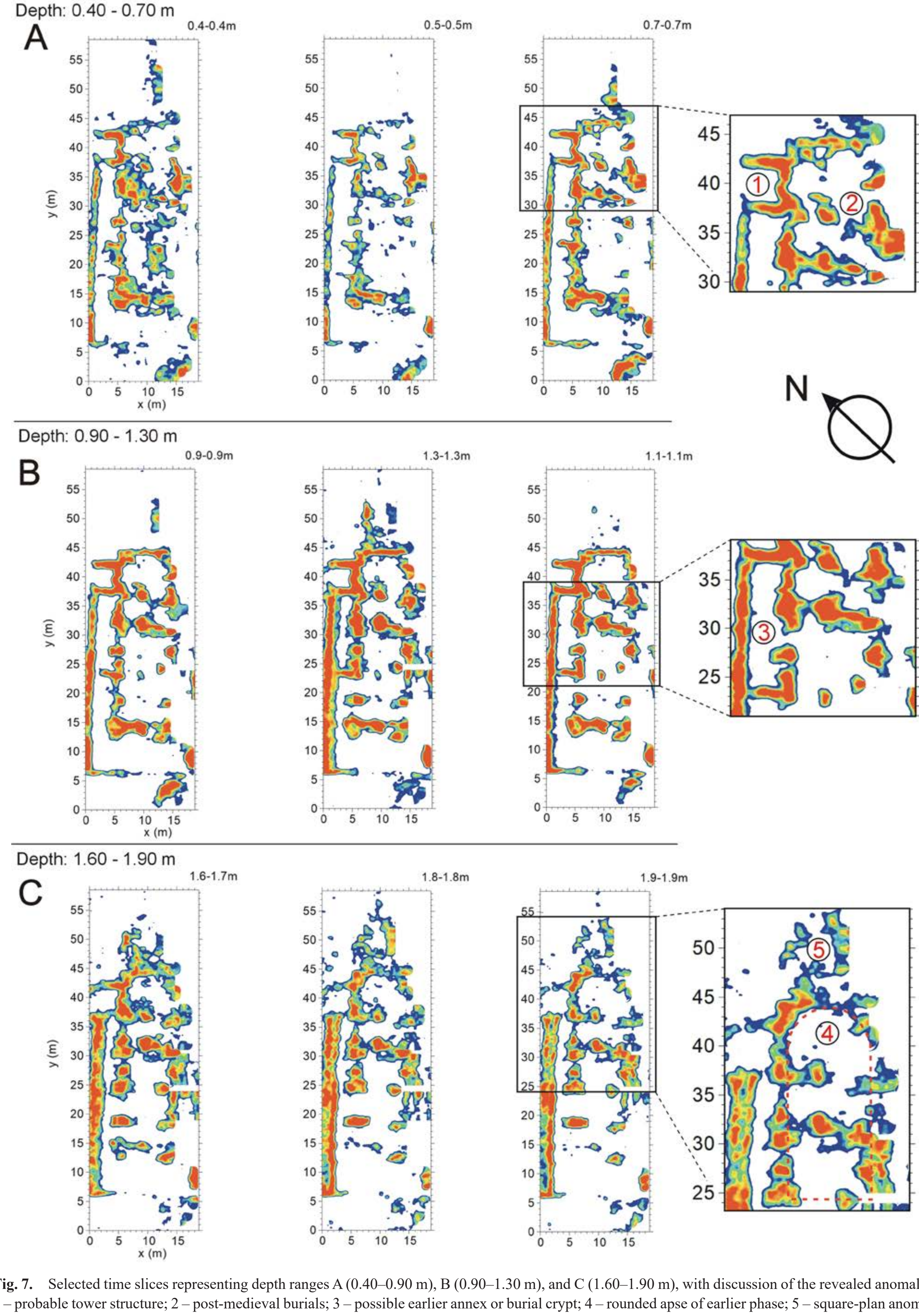

Fig. 7. Selected time slices representing depth ranges A (0.40–0.90 m), B (0.90–1.30 m), and C (1.60–1.90 m), with discussion of the revealed anomalies: 1 – probable tower structure; 2 – post-medieval burials; 3 – possible earlier annex or burial crypt; 4 – rounded apse of earlier phase; 5 – square-plan anomaly of uncertain interpretation. See detailed description in the text (processing and drawing: F. Welc).

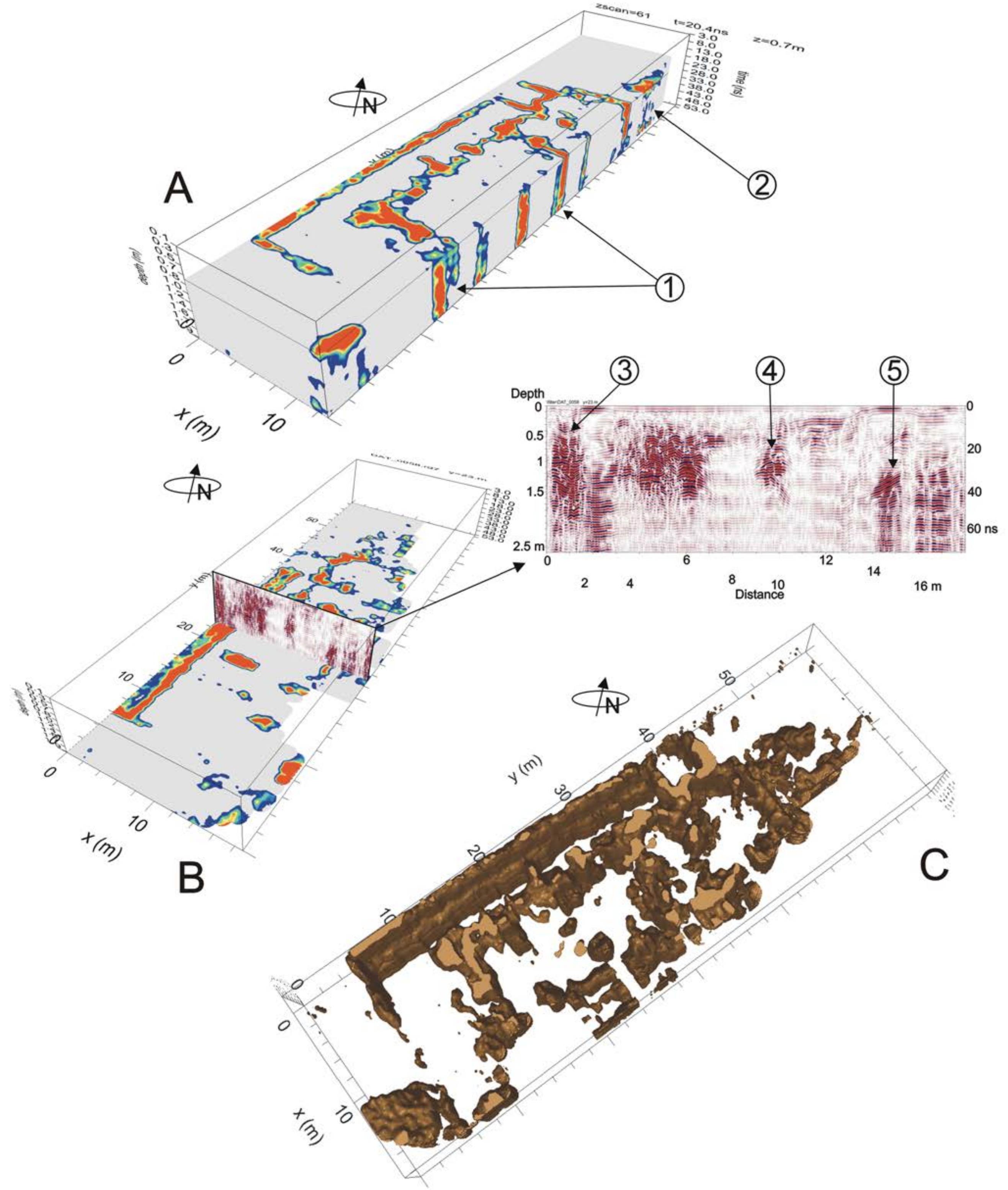

Fig. 8. A: Cross-section of the 3D model of the anomalies: 1 – reflections from probable transverse walls of an earlier chronological phase; 2 – anomaly to the north-east of the church relics. B: Time slice for a depth of approximately 2 m juxtaposed with a selected radargram profile: 3 – reflection from the perimeter wall; 4 – reflection most likely from a grave; 5 – reflection from a deeper wall, possible earlier phase. C: 3D model of the revealed anomalies (processing and drawing: F. Welc).

the profile consists of a thin modern surface layer or humic horizon. In the upper part of core Jesi 1 (drilled outside the church), the interval between 0.20 m and 1.20 m consists of interbedded clayey-sandy and sandy layers containing numerous small fragments of mortar, bricks, ceramics, and charcoal. A similar structure is observed in the near-sur-

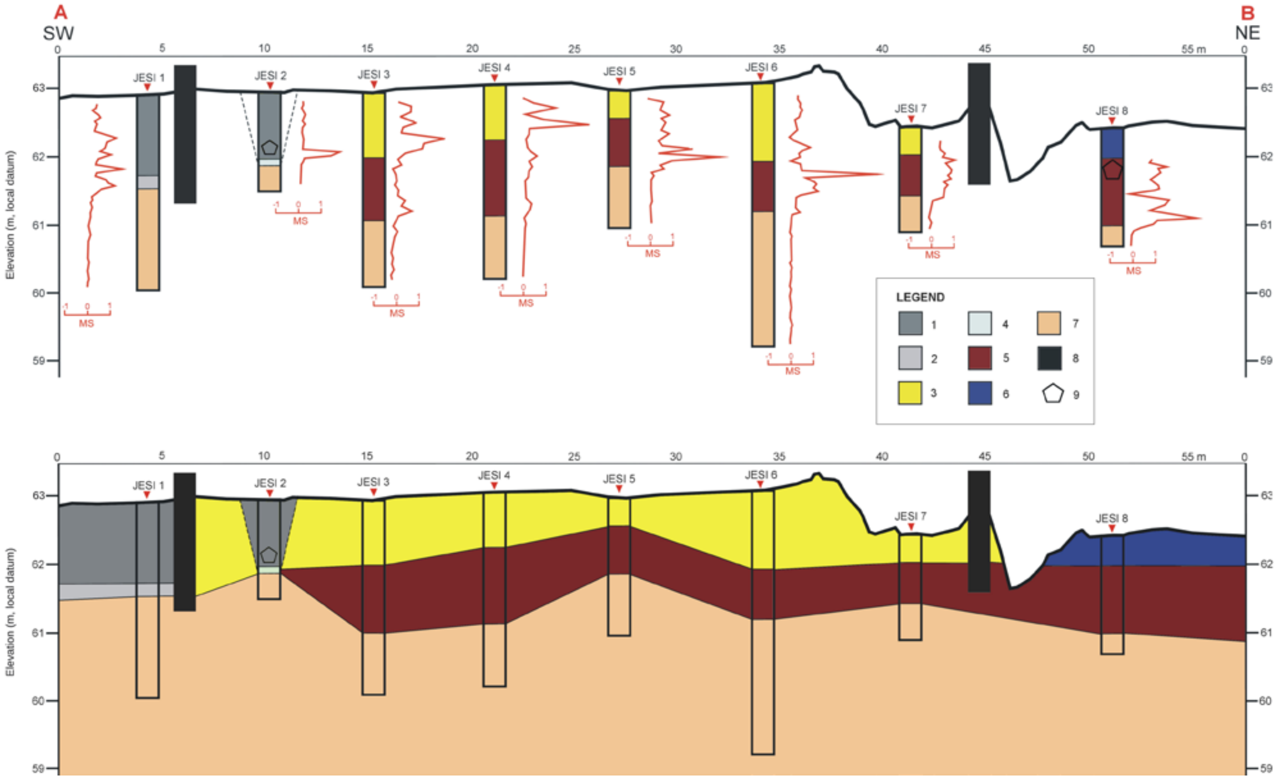

Fig. 9. Geoarchaeological cross-section A–B (SW-NE) across the San Savino site in Jesi, integrating eight cores (JESI 1–8). The upper panel shows the lithology of individual cores and relative variations in magnetic susceptibility (normalised scale from −1 to 1). Legend: 1 – anthropogenic rubble-rich clay-sand layer with mortar, ceramics, and brick fragments; 2 – fine-grained transitional layer, sandy-silty, with admixture of anthropogenic material; 3 – loose sandy-gravelly anthropogenic deposits with abundant construction debris; 4 – human bones; 5 – reworked slope sediments (finer fraction): sandy clays and silts with dispersed anthropogenic material (colluvial origin); 6 – modern embankment; 7 – natural fluvial substrate: massive, plastic silts and silty clays lacking anthropogenic material; 8 – church wall foundations; 9 – burials (drawing and interpretation: F. Welc).

face layer of borehole Jesi 2; however, this unit contains less archaeological material and a significantly higher proportion of human bone remains, with the highest concentration occurring at a depth of approximately 1 m (Fig. 9).

In the central part of profile A–B, encompassing the church interior and its immediate surroundings (boreholes Jesi 1–7), the upper subsurface is dominated by a sequence of unconsolidated deposits with sandy and sandy-gravelly matrices, containing numerous fragments of bricks, mortar, ceramics, charcoal, and small bone fragments, with a thickness ranging from approximately 0.5 to 1 m.

Below this layer occur more compact, plastic, and finer-grained sediments, including sandy clays, clayey sands, and silts of grey to olive-grey coloration, containing dispersed anthropogenic material such as small fragments of mortar, charcoal, brick debris, ceramics, and occasional bone fragments (Fig. 9). In borehole Jesi 4 (at a depth of approximately 0.57 m), interlayers of mortar and accumulations of brick fragments were identified within this unit, possibly representing a floor level.

The lowest and most continuous component of the described lithostratigraphic sequence is the natural fluvial substrate, consisting of massive, structureless, plastic silts, clayey silts, and silty clays of light brown, grey-brown, or grey-yellow coloration, lacking significant anthropogenic inclusions (Fig. 9). Normalised magnetic susceptibility (MS) curves provide an additional vertical characterisation of the sequence (Fig. 9). The highest amplitudes and most pronounced variations are observed within the two upper anthropogenic units, where the highest MS values were also recorded. In contrast, the underlying massive silts display smoother trends, lower variability, and significantly lower MS values. In several cores, particularly Jesi 3, 4, 5, and 6, local maxima and strong fluctuations in MS correspond to layers rich in bricks, mortar, burnt material, or charcoal.

Pottery fragments recovered from the cores

The pottery fragments recovered from the drill cores constitute a small and highly fragmentary assemblage (Fig. 10), yet they provide important evidence for the long-term occupation history of the site. Although limited both in number and in diagnostic value, the material indicates the presence of ceramic finds ranging from the Late Hellenistic/Late Republican horizon through the Roman Imperial period. The small size of most fragments, their secondary deposition within core sediments, and the absence of larger reconstructable forms require considerable caution in chronological interpretation.

Five fragments were recovered from three cores: two

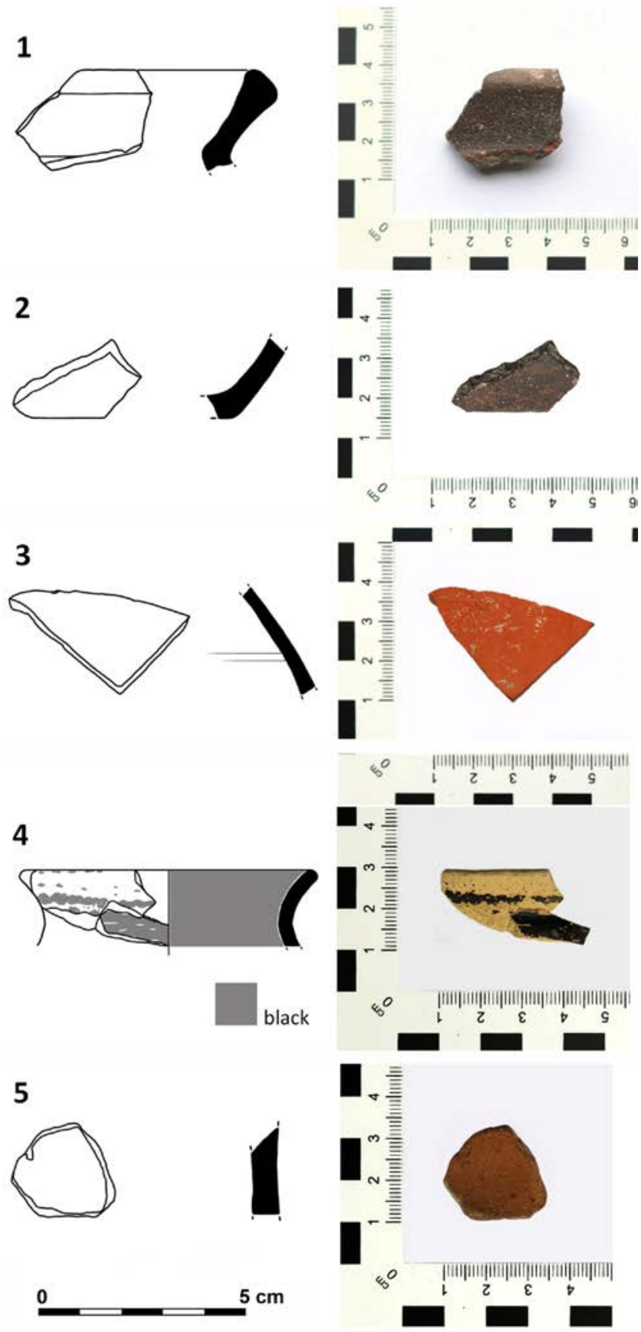

Fig. 10. Pottery fragments from the cores. 1: Jesi 1, depth 0.70 m, rim fragment of early Roman jar (*olla*?). 2: Jesi 1, depth 0.70 m, base fragment of early Roman jar (*olla*?). 3: Jesi 3, depth 0.98 m, thin-walled pottery fragment, 1st century AD. 4: Jesi 3, depth 1.12 m, black-slipped beaker fragment (ceramica a vernice nera), 3rd–1st centuries BC. 5: Jesi 4, depth 1.08 m, fragment of vessel belly, 4th century AD onwards (drawing and photo: B. Nowacki).

from Jesi 1 at a depth of 0.70 m, two from Jesi 3 at depths of 0.98 m and 1.12 m, and one from Jesi 4 at a depth of 1.08 m.

The two fragments from Jesi 1 most probably belong to the same coarse ware pot (*olla*) with a flat base and strongly everted rim. The vessel shows careful surface treatment and well-smoothed surfaces. The colour distribution (dark grey core with brown outer zones) points to uneven firing conditions. Comparisons may be drawn with *ollae* of Olcese type 4b (Olcese, 2003), allowing a tentative dating to the 2nd–1st centuries BC.

Far more diagnostic is the fragment from Jesi 3 (depth 1.12 m), identified as part of a fine ware beaker with black slip on both surfaces, most probably belonging to the class of *ceramica a vernice nera*. The morphology corresponds closely to *bicchieri privi di collo, con bordo espanso* (Brecciaroli Taborelli, 1998), dated to approximately 200–120/110 BC. Similar vessels are attested at Suasa and dated from the second half of the 3rd century BC to the mid-1st century BC (Mambelli, 2014). As a fragment of black-slipped fine ware, this find provides indirect but important evidence for activity in or around the site during the Late Republican period.

The remaining fragments (thin-walled pottery from Jesi 3, dated to the 1st century AD; a body sherd from Jesi 4, tentatively attributed to the 4th century AD onwards) are less diagnostic and should be regarded with caution, given their small size and absence of unequivocal morphological features.

Taken as a whole, the pottery from the cores should be interpreted as evidence of long-term and probably discontinuous activity in the area, rather than as a tightly dated assemblage. Its principal value lies in confirming the presence of residual or redeposited pottery of pre-medieval date – especially of Late Hellenistic/Late Republican date – within the stratified deposits sampled by drilling. Given the secondary depositional context of all finds, they should not be used as precise chronological markers for the stratigraphic units in which they occur.

Anthropological material

Bone material in the form of small fragments was recorded in almost all depth intervals (see Fig. 12). Borehole no. 2 stood out, with the highest concentration of human bones. Selected diagnostic fragments were submitted for anthropological analysis by Prof. J. Tomczyk (Cardinal Stefan Wyszyński University in Warsaw) (Table 1).

Table 1. Anthropological material from borehole Jesi 2.

Borehole	Depth (m)	Material	Anatomical identification	Age	Sex
JESI 2	0.58	human bone	cranial fragment – occipital bone	adult	?
JESI 2	0.70	human bone	probable fragment of the pubic symphysis and fragment of the hip bone (acetabular region)	adult	?
JESI 2	0.95–0.97	human bones	fragment of the right petrous bone and fragments of the right temporal and possibly sphenoid bones	adult	?
JESI 2	1.02–1.04	human bone	cranial fragment – probably parietal bone	adult	?

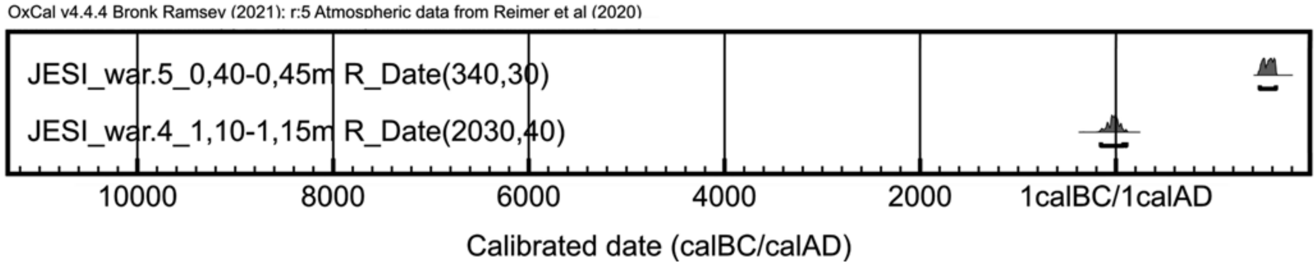

Fig. 11. Calibrated radiocarbon dates: human bone from borehole Jesi 5 (depth 0.40–0.45 m; 340 ± 30 BP; 1474–1638 AD) and charcoal from borehole Jesi 4 (depth 1.10–1.15 m; 2030 ± 40 BP; 153 BC–79 AD, 94.6%, and 100–107 AD, 0.9%). Calibration performed using OxCal v4.4 (Bronk Ramsey, 2009) and the IntCal20 calibration curve (Reimer *et al.*, 2020) at the Radiocarbon Laboratory in Poznań (drawing: F. Welc).

Table 2. Radiocarbon dates from the San Savino site.

Sample name	Material	Core no.	Depth (m)	Lab. no.	^{14}C date	Cal. 95.4% probability
JESI_war.4	Charcoal	4	1.10–1.15	Poz-203744	2030 ± 40 BP	153 BC–79 AD (94.6%) and 100–107 AD (0.9%)
JESI_war.5	Human bone	5	0.40–0.45	Poz-202137	340 ± 30 BP	1474–1638 AD (95.4%)

The osteological analysis of the bone material from borehole Jesi 2 provides important evidence for interpreting the sepulchral context within the area of the former San Savino Abbey. The identified bone fragments, recorded at depths ranging from approximately 0.58 m to 1.04 m, represent both cranial and postcranial elements. In borehole Jesi 2, there is a clear vertical and spatial dispersion of skeletal elements belonging to different anatomical regions, with no observable anatomical continuity. This pattern argues against the interpretation of a single, intact burial and instead strongly suggests that the borehole intersected a zone containing human remains in a disturbed context.

Two main scenarios may be considered: (1) multiple individual burials that, over time, became partially disturbed due to prolonged use of the cemetery space and later transformations; or (2) a collective burial or secondary deposit (ossuary). However, the material does not exhibit typical characteristics of ossuaries, and the assemblage is relatively sparse. The most plausible interpretation is that borehole Jesi 2 intersected an area of a cemetery composed primarily of individual burials that have undergone post-depositional disturbance. A radiocarbon date obtained from a bone recovered in borehole Jesi 5 at a depth of 0.40–0.45 m calibrates to 1474–1638 AD (95.4%) (Table 2),

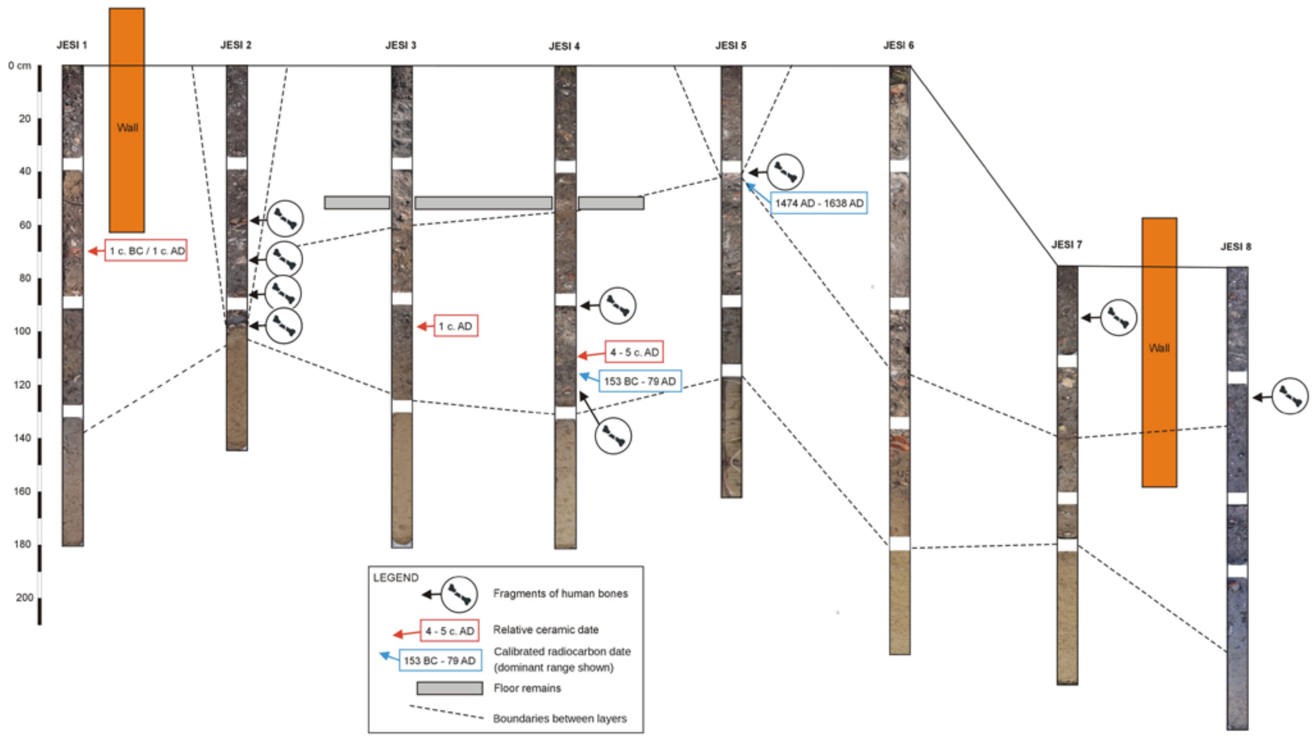

Fig. 12. Correlation of georchaeological logs A–B (SW-NE) across the San Savino site in Jesi, integrating eight cores (JESI 1–8), with stratigraphic position of dated samples and diagnostic ceramic finds. See detailed description in text (drawing: F. Welc).

placing the use of the burial ground in the Late Medieval to Early Modern period.

Relative and absolute chronology

The chronological framework of the San Savino site is based on the combined use of relative dating derived from ceramic material and absolute dating obtained through radiocarbon analysis. Diagnostic pottery fragments were identified in several boreholes (e.g. Jesi 1, 3, and 4) at depths ranging approximately between 0.70 m and 1.12 m, providing a relative chronological indication of Roman-period activity (Fig. 10). Two samples from the cores were selected for radiocarbon dating (Fig. 11, Table 2). The first sample (JESI_war.4, charcoal from core Jesi 4, depth 1.10–1.15 m) yielded a date of 2030 ± 40 BP (Poz-203744), calibrated to 153 BC–79 AD (94.6%) and 100–107 AD (0.9%) within the 95.4% probability range. It should be noted that charcoal is susceptible to the old wood effect, which may result in dates older than the actual depositional event; given the redeposited nature of the sampled horizon, this date should be regarded as a terminus post quem for the accumulation of the middle horizon rather than a precise date of occupation. The second sample (JESI_war.5, human bone from core Jesi 5, depth 0.40–0.45 m) produced a date of 340 ± 30 BP (Poz-202137), calibrated to 1474–1638 AD (95.4% probability). All dated samples and diagnostic finds are indicated in Fig. 12, which illustrates their stratigraphic position within the sequence.

DISCUSSION

Site stratigraphy and architectural phases

The stratigraphy of the San Savino site was reconstructed on the basis of an integrated analysis of geoarchaeological coring, GPR surveys, archaeological material, and radiocarbon dating (Figs. 7, 8, 9, 12, 13). On the basis of the obtained data, three main stratigraphic horizons can be distinguished, composed of packages of layers differing in lithology, origin, and chronology.

The upper horizon extends to a depth of approximately 1.0 m and corresponds to the youngest phase of site use, associated with the functioning and destruction of the church in its Romanesque-Gothic phase and its subsequent use as a burial ground. Lithologically, it consists of loose, poorly consolidated sandy and sandy-gravelly deposits with abundant anthropogenic inclusions (fragments of bricks, mortar, ceramics, charcoal, and small bones). In many places, this layer has a rubble-like, backfill character, corresponding well with the GPR image, where at depths of approximately 0.40–0.90 m clear anomalies corresponding to the remains of the church's perimeter walls are visible, as well as irregular structures interpreted as graves.

On the basis of GPR data and surface observations, the general architectural layout of the church in its Romanesque-Gothic phase can be reconstructed: a building oriented southwest-northeast, approximately 40×19 m, divided into three naves with a central nave approximately 5.72 m wide and side aisles of approximately 3.30 m each. At the north-

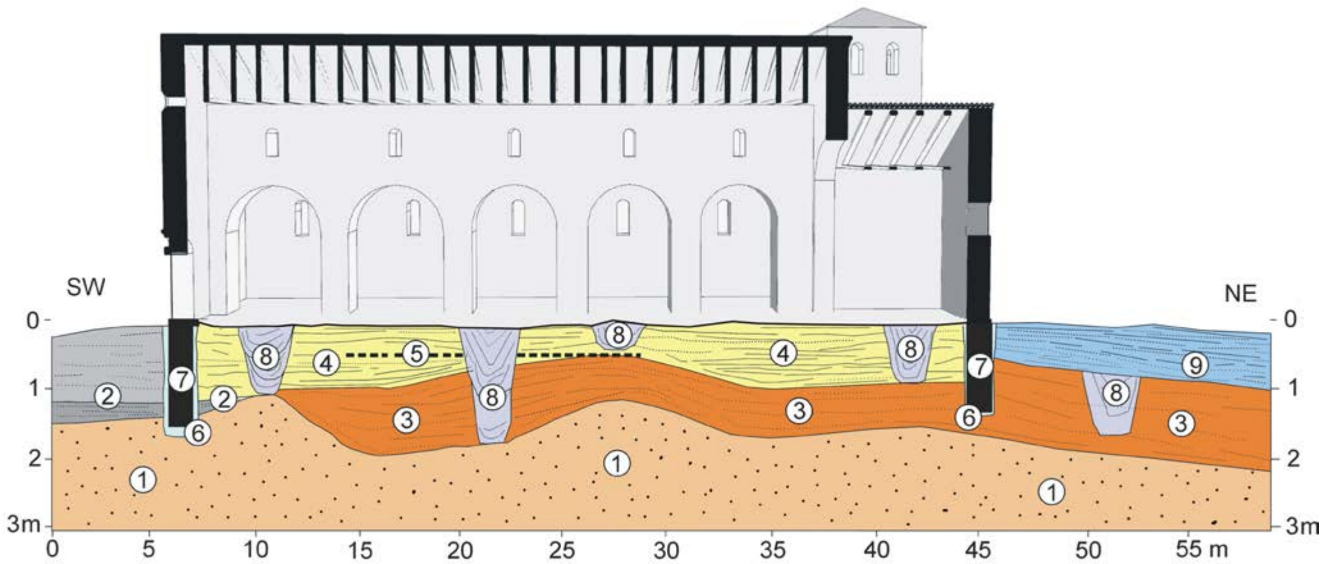

Fig. 13. Final geoarchaeological interpretation of the San Savino site in Jesi: a synthetic SW-NE cross-section combining the hypothetical architectural reconstruction of the Romanesque-Gothic basilica (upper panel) with the integrated lithostratigraphic interpretation along the A–B profile (lower panel; cf. Figs. 9 and 12). The figure illustrates the spatial relationship between the church structure, the burial space, and the underlying stratigraphic sequence, comprising the three main horizons identified in the cores: an upper destruction-sepulchral horizon, a middle redeposited horizon containing Roman-period material, and a lower natural fluvial substrate. Legend: 1 – natural substrate: massive, plastic silts and silty clays lacking anthropogenic inclusions; 2 – fine-grained transitional layer (sandy-silty, with admixture of anthropogenic material) preserved on the SW slope; 3 – loose sandy-gravelly anthropogenic deposits with abundant construction debris (middle horizon, including redeposited Roman material); 4 – anthropogenic rubble-rich clay-sand layer with mortar, ceramics, and brick fragments (upper destruction horizon); 5 – inferred floor level of the Romanesque-Gothic church; 6 – foundation trench; 7 – foundations of the church perimeter walls; 8 – burials cut into the upper and middle horizons; 9 – modern embankment along the NE margin of the site. Vertical scale in metres relative to the present-day ground surface (drawing and interpretation: F. Welc).

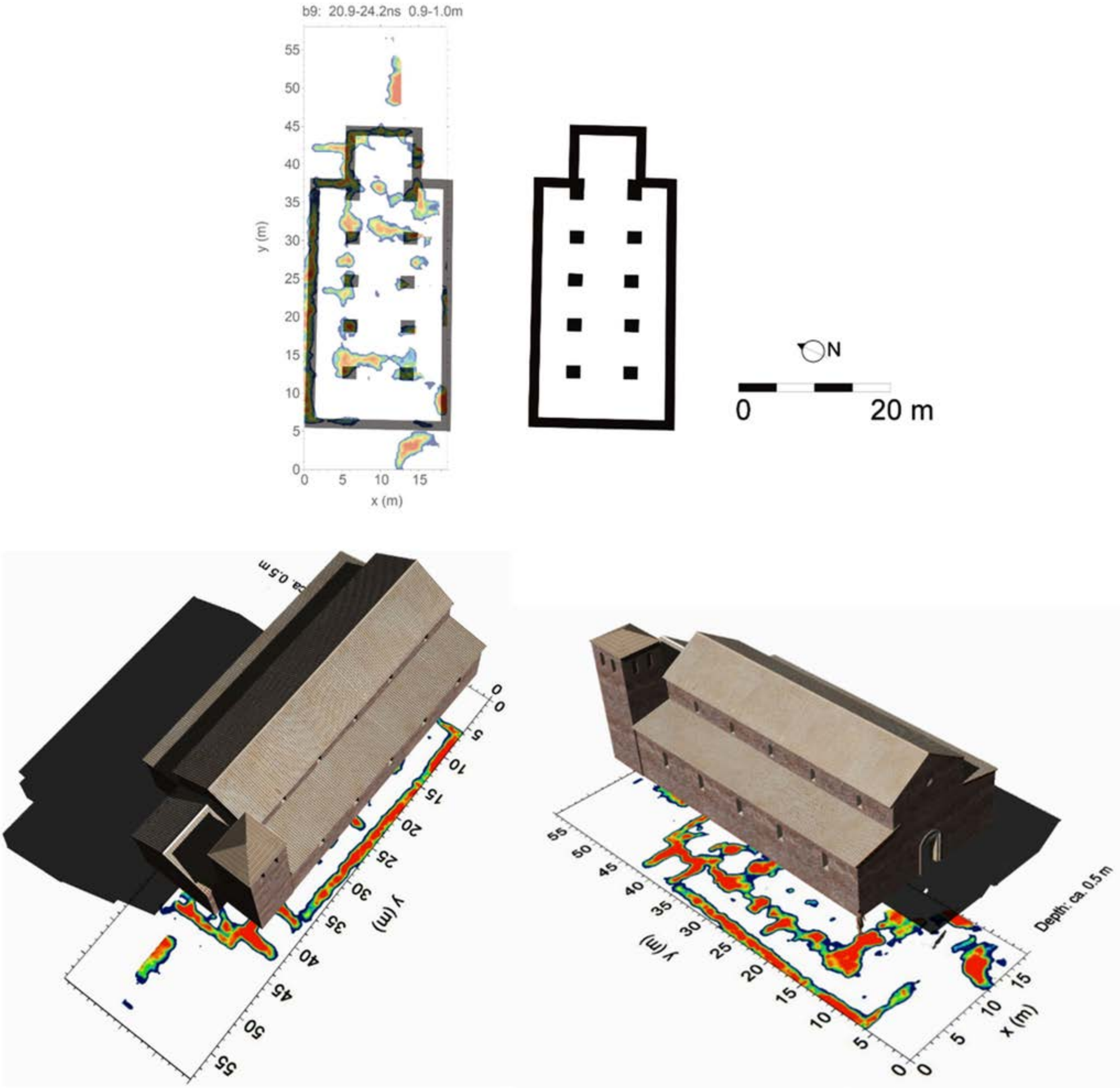

Fig. 14. Hypothetical reconstruction of the youngest Romanesque-Gothic phase of the church of San Savino in Jesi. Upper panel: plan of GPR anomalies at ca. 0.5 m depth with interpreted wall layout. Lower panels: 3D model juxtaposed with selected time slice (drawing: F. Welc).

eastern end, the church was terminated by a rectangular apse approximately 10 m wide. The wall thickness reached approximately 1 m. Adjacent to the apse wall to the north, two linear anomalies most likely represent the remains of a tower (Fig. 14). The upper horizon also contains numerous human remains, particularly concentrated in borehole Jesi 2. A radiocarbon date obtained from a bone sample from borehole Jesi 5 (340 ± 30 BP; 1474–1638 AD) confirms that the ruins of the church were used as a burial ground during the Late Medieval and Early Modern periods.

Below lies the middle horizon, extending to approximately 1.4–1.5 m depth. It consists mainly of fine-grained deposits, including sandy clays, clayey sands, silts, and silty clays of grey to olive-grey coloration, containing dispersed anthropogenic material. A particularly important feature is that at the boundary between the upper and middle horizons, locally in borehole Jesi 4 (at a depth of approximately 0.57 m), layers of mortar and accumulations of brick fragments were recorded and interpreted as possible remains of a floor level associated with the Romanesque-Gothic church. The chronology of the middle horizon is indicated by a radiocarbon date from charcoal from borehole Jesi 4 (2030 ± 40 BP; 153 BC–79 AD, 94.6%, and 100–107 AD, 0.9%, within the 95.4% probability range) and by ceramic material dated to the 1st century AD. However, this evidence must be interpreted with caution: the presence of Early Roman material does not necessarily indicate an in-situ occupation layer of that period, as it may derive from the destruction and redeposition of the earlier Roman villa complex identified in the vicinity. This interpretation is

Fig. 15. Hypothetical artistic reconstruction of the location of the San Savino monastery and its surroundings in the early Middle Ages, based on geomorphological interpretation and regional palaeoclimatic data (drawing by F. Welc, with AI assistance).

consistent with the GPR results, which at greater depths reveal anomalies suggesting an earlier architectural phase.

The lowest horizon represents the natural fluvial substrate, occurring below approximately 1.5 m depth. It consists of massive, homogeneous fine-grained deposits – silts, clayey silts, and silty clays of light brown, grey-brown, or grey-yellow colour – lacking significant anthropogenic inclusions. This horizon corresponds to the natural fluvial-colluvial deposits of the Esino River terrace and forms the geological base of the entire sequence.

GEOMORPHOLOGICAL SETTING AND SITE LOCATION

The results of geoarchaeological coring, combined with GPR data and archival geotechnical investigations, allow for an assessment of the geomorphological factors that may have influenced the location of the complex. The stratigraphic sequence recorded in the cores indicates that both the abbey and the earlier structures (including the Roman villa remains) were founded on a local topographic elevation representing a slightly elevated surface within the fluvial terrace of the Esino River, formed by the accumulation of colluvial-alluvial deposits at the foot of the urban hill (Cilla *et al.*, 1994; Coltorti, 1997).

The lithological characteristics of these deposits correspond to facies typical of colluvial aprons and distal alluvial overbank environments, where fine-grained clayey-silty sediments of mixed colluvial-alluvial origin dominate. These sediments are formed by episodic sheetflood processes and short-distance transport of slope-derived material, typically overlying coarser fluvial deposits of the river terrace surface and characterised by a predominance of silt-clay fractions with admixtures of marly material derived from slope erosion. This vertical arrangement – transitioning from basal gravel and sand to overlying fine-grained clayey-silty units – was clearly identified in the boreholes and is consistent with the colluvial-alluvial geomorphological setting described for Marche river valleys (Coltorti, 1997; Guerrera and Tramontana, 2004).

The gradual accumulation of such deposits formed a slight but distinct elevation within the Esino River valley. At the same time, geomorphological evidence indicates that the distal part of the terrace was later partially incised, resulting in the development of local depressions and a surface slope oriented towards the town. Consequently, the elevated area on which the abbey was constructed was separated from the urban zone by a lower-lying area, likely characterised by periodic or permanent waterlogging.

The hydrological properties of this setting were of potential importance. The substrate, composed of fine-grained colluvial-alluvial deposits with a marly matrix, is relatively impermeable, which limits groundwater infiltration and provides a mechanically stable foundation for construction. The slight elevation above the surrounding floodplain may have offered some protection from inundation during river floods. Notably, the stratigraphic sequence lacks typical floodplain deposits such as laminated alluvial silts, suggesting that this area remained largely outside the active flood zone of the Esino River.

These observations may gain additional significance when considered in a broader palaeoclimatic context. It has been suggested that between the 5th and 9th centuries AD, large parts of Europe experienced a phase of cooler and more humid climatic conditions, associated with increased flood frequency and higher groundwater levels in river valleys (McCormick *et al.*, 2012; Benito *et al.*, 2015; Sadori *et al.*, 2016; Welc, 2019) (Fig. 15). However, it must be emphasised that the absence of local palaeoenvironmental proxies – such as pollen sequences or palaeochannel sediments from the immediate vicinity of the site – precludes a firm reconstruction of the floodplain environment at the time of the abbey's foundation. This aspect requires dedicated future investigation.

It may therefore be hypothesised that the location of the San Savino Abbey was influenced, at least in part, by geomorphological factors – notably the relative elevation and stability of the substrate within an otherwise low-lying floodplain setting. Whether this reflects a deliberate topographic strategy or was primarily conditioned by land ownership and historical continuity of occupation at a site already used in the Roman period remains an open question. In this context, the location of the abbey exemplifies a broader pattern of settlement in slightly elevated but stable zones within floodplain environments, a pattern documented at other early medieval monastic sites in Italy (Wickham, 2005; Castrorao Barba *et al.*, 2021).

CONCLUSIONS

The integrated geoarchaeological investigation carried out at the site of the former San Savino Abbey in Jesi has demonstrated the high interpretative potential of combining non-invasive geophysical methods with minimally invasive geoarchaeological coring. The results provide a coherent, multi-layered reconstruction of the spatial layout, stratigraphy, chronology, and environmental context of the site.

The application of GPR, supported by targeted borehole verification, constituted an exceptionally effective approach for the investigation of buried architectural remains. The GPR survey enabled the identification of a complex system of subsurface anomalies corresponding to walls, internal divisions, burial structures, and earlier construction phases, substantially extending the known plan of the church beyond the preserved surface remains.

One of the most important outcomes of the study is the identification of at least two, and most probably three, main phases of architectural development at the site. The uppermost phase corresponds to the well-documented Romanesque-Gothic church, characterised by a three-nave basilica plan with a rectangular apse and massive perimeter walls. Beneath this phase, the geophysical results reveal a more complex and previously unrecognised architectural arrangement, including anomalies tentatively interpreted as a possible rounded apse-like feature and wall-like reflections within the nave; the existence and chronology of this earlier phase remain hypothetical pending excavation.

The geoarchaeological data clearly demonstrate that the stratigraphic sequence reflects a dynamic history of construction, destruction, reuse, and redeposition. The middle stratigraphic horizon is characterised by a complex mixture of materials of different chronological origin, including Roman-period ceramics and radiocarbon-dated charcoal. The site should therefore be interpreted as a palimpsest of successive human activities extending from at least the Late Republican period through the Roman Imperial period and into the Middle Ages. The ceramic assemblage, although limited and fragmentary, confirms the presence of pre-medieval activity in the area, while the redeposited nature of the finds underscores the necessity of cautious interpretation.

The results of the anthropological analysis indicate that the site retained its sepulchral function long after the destruction of the monastic complex, with a radiocarbon date of 1474–1638 AD confirming the use of the area as a burial ground during the Late Medieval and Early Modern periods.

From a geomorphological perspective, the site was established on a slightly elevated colluvial-alluvial surface within the Esino River floodplain, a position offering relative stability and some protection from flooding. The influence of geomorphological factors on the choice of location, while plausible, cannot be definitively demonstrated without local palaeoenvironmental data, and alternative explanations – including historical land ownership and the continuity of earlier Roman occupation – must be considered equally.

Methodologically, the research demonstrates the advantages of a non-invasive or minimally invasive approach to archaeological investigation. The combination of GPR and coring allows for the reconstruction of both horizontal and vertical aspects of the archaeological record without the need for extensive excavation, which is particularly important in the context of heritage conservation. The results remain, to a certain extent, provisional, and future research should focus on carefully planned, limited excavations aimed at verifying the key hypotheses proposed in this study, particularly concerning the existence and dating of earlier architectural phases.

Acknowledgements

The authors wish to thank Prof. Jacek Tomczyk (Cardinal Stefan Wyszyński University in Warsaw) for the anthropological analysis of bone material from borehole Jesi 2. Radiocarbon dating was carried out at the Radiocarbon Laboratory in Poznań, Poland. The authors are grateful to ABACO Società Cooperativa for facilitating access to the site and for logistical support during fieldwork. Thanks are also due to A. Orłowska for photographic documentation of the drilling campaign. The authors declare no conflict of interest. The fieldwork, including drilling and GPR scanning, was financed by the Polish National Science Centre grant: "The fall, crisis, or transformation? Correlation of the late antique settlement pattern changes with environment and climate fluctuations in the northeastern Adriatic region based on results of geoarchaeological and palaeoclimatic research" 2020/37/B/HS3/02458.

REFERENCES

Accademia Nazionale dei Lincei, 1998. Notizie degli Scavi di Antichità, Serie IX, Volume VII–VIII (1996–1997). Roma: Azienda Grafica Eredi Dr. G. Bardi.

Barone, P.M., Ruffell, A., Tsokas, G.N., Rizzo, E., 2019. Geophysical surveys for archaeology and cultural heritage preservation. Heritage 2, 2814–2817.

Benito, G., Macklin, M.G., Panin, A., Rossato, S., Fontana, A., Jones, A.F., Machado, M.J., Matlakhova, E., Mozzi, P., Zielhofer, C., 2015. Recurring flood distribution patterns related to short-term Holocene climatic variability. Scientific Reports 5, 16398.

Bini, M., Fornaciari, A., Ribolini, A., Bianchi, A., Sartini, S., Coschino, F., 2010. Medieval phases of settlement at Benabbio castle, Apennine mountains, Italy: evidence from ground penetrating radar survey. Journal of Archaeological Science 37(12), 3059–3067.

Brecciaroli Taborelli, L., 1998. Jesi (Ancona). L'officina ceramica di Aesis (III secolo a.C. – I secolo d.C.). In: Notizie degli Scavi di Antichità, Serie IX, Volume VII–VIII (1996–1997), 5–250. Roma.

Bronk Ramsey, C., 2009. Bayesian analysis of radiocarbon dates. Radiocarbon 51(1), 337–360.

Bullarium Romanum, 1739. Bullarium Romanum, Tomus V. Romae.

Capizzi, P., Martorana, R., Messina, P., Cosentino, P., 2012. Geophysical and geotechnical investigations to support the restoration project of the Roman "Villa del Casale", Piazza Armerina, Sicily, Italy. Near Surface Geophysics 10, 145–160.

Capozzoli, L., Mutino, S., Liseno, M.G., De Martino, G., 2019. Searching for the history of the ancient Basilicata: archaeogeophysics applied to the Roman site of Forentum. Heritage 2, 1097–1116.

Castrorao Barba, A., Speciale, C., Miccichè, R., Pisciotta, F., Aleo Nero, C., Marino, P., Bazan, G., 2021. The Sicilian countryside in the Early Middle Ages: Human-Environment Interactions at Contrada Castro. Environmental Archaeology 26(4), 369–385.

Cilla, G., Coltorti, M., Dramis, F., 1994. Holocene fluvial dynamics in mountain areas: the case of the Esino River. Geografia Fisica e Dinamica Quaternaria 17(1), 163–174.

Coltorti, M., 1997. Human impact in the Holocene fluvial and coastal evolution of the Marche region, Central Italy. Catena 30, 311–335.

Conyers, L.B., 2006. Ground-penetrating radar for archaeological mapping. In: Wiseman, J., El-Baz, F. (Eds), Remote Sensing in Archaeology. Berlin/Heidelberg: Springer.

Conyers, L.B., 2011. Discovery, mapping and interpretation of buried cultural resources non-invasively with ground-penetrating radar. Journal of Geophysics and Engineering 8, 13–22.

Conyers, L.B., 2016. Ground-Penetrating Radar for Geoarchaeology. Chichester: John Wiley and Sons.

Conyers, L.B., 2023. Ground-Penetrating Radar for Archaeology. 4th ed. London-New York: Bloomsbury Academic.

Costantini, C. (Ed.), 1986. Storia di Jesi. 2 vols. Jesi.

Costanzo, A., Pisciotta, A., Pannaccione Apa, M.I., Bongiovanni, S., Capizzi, P., D'Alessandro, A., Falcone, S., La Piana, C., Martorana, R., 2021. Integrated use of unmanned aerial vehicle photogrammetry and terrestrial laser scanning to support archaeological analysis: the Acropolis of Selinunte case (Sicily, Italy). Archaeological Prospection 28, 153–165.

Cozzolino, M., Di Giovanni, E., Mauriello, P., Piro, S., Zamuner, D., 2018. Geophysical Methods for Cultural Heritage Management. Berlin/Heidelberg: Springer.

Deiana, R., Leucci, G., Martorana, R., 2018. New perspectives on geophysics for archaeology: a special issue. Surveys in Geophysics 39, 1035–1038.

El-Qady, G., Metwaly, M., 2018. Archaeogeophysics: State of the Art and Case Studies. Berlin/Heidelberg: Springer.

Gaffney, C., 2008. Detecting trends in the prediction of the buried past: a review of geophysical techniques in archaeology. Archaeometry 50, 313–336.

Goodman, D., Piro, S., 2013. GPR Remote Sensing in Archaeology. Berlin/Heidelberg: Springer.

Grizi, P., 1578. Il ristretto delle istorie di Jesi. Jesi.

Guerrera, F., Tramontana, M. (Eds), 2004. Note illustrative della Carta Geologica d'Italia alla scala 1:50,000 – Foglio 292 Jesi. Servizio Geologico d'Italia.

Kehr, P.F., 1909. Italia Pontificia. Regesta pontificum Romanorum. Umbria et Picenum. Berlin.

Leucci, G., Masini, N., Rizzo, E., Capozzoli, L., De Martino, G., De Giorgi, L., Marzo, C., Roubis, D., Sogliani, F., 2015. Integrated archaeogeophysical approach for the study of a medieval monastic settlement in Basilicata. Open Archaeology 1, 236–241.

Mambelli, M., 2014. Ceramica a vernice nera. In: Mazzeo Saracino, L. (Ed.), Scavi di Suasa 1. I reperti ceramici e vitrei della Domus dei Coiedii, 115–159. Bologna.

Martinho, E., Dionísio, A., 2014. Main geophysical techniques used for non-destructive evaluation in cultural built heritage: a review. Journal of Geophysics and Engineering 11, 053001.

McClendon, C.B., 1987. The Imperial Abbey of Farfa: Architectural Currents of the Early Middle Ages. New Haven-London.

McCormick, M., Büntgen, U., Cane, M.A., Cook, E.R., Harper, K., Huybers, P., Litt, T., Manning, S.W., Mayewski, P.A., More, A.F.M., Nicolussi, K., Tegel, W., 2012. Climate change during and after the Roman Empire: reconstructing the past from scientific and historical evidence. Journal of Interdisciplinary History 43(2), 169–220.

Olcese, G., 2003. Ceramiche comuni a Roma e in area romana: produzione, circolazione e tecnologia (tarda età repubblicana – prima età imperiale). Mantova: SAP.

Paoli, U. (Ed.), 1976. Le carte dell'abbazia di San Vittore delle Chiuse (secoli XI–XIII). Roma.

Persico, R., 2014. Introduction to Ground Penetrating Radar: Inverse Scattering and Data Processing. Hoboken, NJ: John Wiley and Sons.

Pressutti, P. (Ed.), 1888. Regesta Honorii Papae III (1216–1227). Tomus I. Romae.

Ranalli, D., Scozzafava, M., Tallini, M., 2004. Ground penetrating radar investigations for the restoration of historic buildings: the case study of the Collemaggio Basilica (L'Aquila, Italy). Journal of Cultural Heritage 5, 91–99.

Reimer, P.J., Austin, W.E.N., Bard, E., Bayliss, A., Blackwell, P.G., Bronk Ramsey, C., Butzin, M., Cheng, H., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Hajdas, I., Heaton, T.J., Hogg, A.G., Hughen, K.A., Kromer, B., Manning, S.W., Muscheler, R., Palmer, J.G., Pearson, C., van der Plicht, J., Reimer, R.W., Richards, D.A., Scott, E.M., Southon, J.R., Turney, C.S.M., Wacker, L., 2020. The IntCal20 Northern Hemisphere radiocarbon age calibration curve (0–55 cal kBP). Radiocarbon 62(4), 725–757.

Sadori, L., Giraudi, C., Masi, A., Magny, M., Ortu, E., Zanchetta, G., Izdebski, A., 2016. Climate, environment and society in southern Italy during the last 2000 years. Quaternary Science Reviews 136, 173–188.

Urbini, S., Cafarella, L., Marchetti, M., Chiarucci, P., Bonini, D., 2007. Fast geophysical prospecting applied to archaeology: results at "Villa ai Cavallacci" (Albano Laziale, Rome) site. Annals of Geophysics 50, 291–299.

Welc, F., 2019. Geoarchaeological evidence of late and post antiquity (5th–9th c. AD) climate changes recorded at the Roman site in Plemići Bay (Zadar region, Croatia). Studia Quaternaria 36(1), 3–17.

Welc, F., 2024. Geophysics for architecture: non-invasive inventory of the buried relicts of a medieval monastery in Poland with application of the Amplitude Data Comparison Method (ADCM). Bulletin du centre d'études médiévales d'Auxerre 28.1, 2–18.

Welc, F., Mieszkowski, R., Lipovac Vrkljan, G., Konestra, A., 2017. An attempt to integrate different geophysical methods (magnetic, GPR and ERT): a case study from the late Roman settlement on the Island of Rab in Croatia. Studia Quaternaria 34(1), 47–59.

Welc, F., Rabiega, K., Brzostowska, I., Wagner, A., 2022. From field survey to 3D model – application of ground-penetrating radar for studies of historical architecture: a case study of the Wyszyna Castle in Poland. International Journal of Conservation Science 13(3), 793–808.

Wickham, C., 2005. Framing the Early Middle Ages: Europe and the Mediterranean 400–800. Oxford: Oxford University Press.

Zhao, W., Forte, E., Levi, S.T., Pipan, M., Tian, G., 2023. Ground penetrating radar for archaeological prospection: review and perspectives. Remote Sensing 15(3), 716.