3 Exploring with GPR the Frigidarium of the Byzantine Baths in Ostia Antica after Excavation, Backfilling and Floor re-tiling

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A GPR survey was conducted in the frigidarium *of the Byzantine baths in 2017 almost 50 years after the area had been excavated, backfilled and re-tiled using a black and white mosaic. GPR signals are interpreted using photographs of the excavation provided by courtesy of Archivio di disegno as well as drawings and texts produced by scholars to retrace the multiple functions that the site had until the Late Antiquity. It is shown that some ancient reticulated wall structures can be recognised in the GPR data, but not all! There are also prominent GPR features which cannot be identified. We conclude that the partial excavation of the site and the backfilling operation have further complicated the structure of the ground below the mosaic of the Byzantine baths.*

3.1 INTRODUCTION

Can we image again structures that were excavated and backfilled in Ostia Antica during the last century using a Ground Penetrating Radar (GPR) survey? To answer this question, Hanna Stöger proposed that our TU Delft Geoscience & Engineering team carry out a GPR survey in the spring of 2017 in the large *frigidarium* of the Byzantine baths located in Regio IV, *Insula* iv. The site had been excavated (and backfilled) three times – in 1940, 1958 and 1970-1971 (Stöger pers. comm. 2017). Photographs of the last excavation (Archivio di Designo) and drawings of the site's lay-out (Lorenzatti 1998; Poccardi 2006) were available and we could use them to compare with our GPR data.

3.2 THE *FRIGIDARIUM* TODAY

The *frigidarium* of the Byzantine baths is currently accessible via two entrances: at its north-west corner from Via del Tempio Rotondo, along a corridor and stairs; and at its north-east corner through an opening between the remains of the Domus di Giove Fulminatore and a large *natatio*. At its southern end the *frigidarium* is characterised by two cold baths with apses (Fig. 3.1, labels 1 and 2). The floor of the *frigidarium* is partly tiled using white and black mosaics (Fig. 3.1, label 3). Vegetation has invaded the walls fringing the *frigidarium* and colonised the adjacent floor. Grass, mowed shortly before our survey, covers the parts of the floor where the mosaic no longer exists.

Four column bases (Fig. 3.1, labels 4, 5, and 6) are visible in the *frigidarium*. They had been part of a *palaestra*. The south-east column base (Fig. 3.1, label 5) has drifted from its initial location. Two short parapets, more or less aligned with the southern end of the *palaestra*, emerge from the ground surface, and are used to separate the *frigidarium* into two spaces: the southern space, at a slightly lower elevation, and the northern space. This division is relevant, as we explain below.

At the time we performed the survey, the east cold bath at the southern end of the *frigidarium* was mostly free of vegetation and could be inspected (Fig. 3.2, left). The west cold bath was still covered by vegetation and could not be inspected. The inspection of the bath showed, to our surprise, that the inner face of the more recent north-south wall of the bath is covered by an "anachronistic" reticulated brick pattern that we associated with Hadrian's time (Fig. 3.2, left and middle, label 7). We also saw a rectangular duct opening at the north-west corner of the bath (Fig. 3.2, right). The duct appeared to go in the direction of the west bath.

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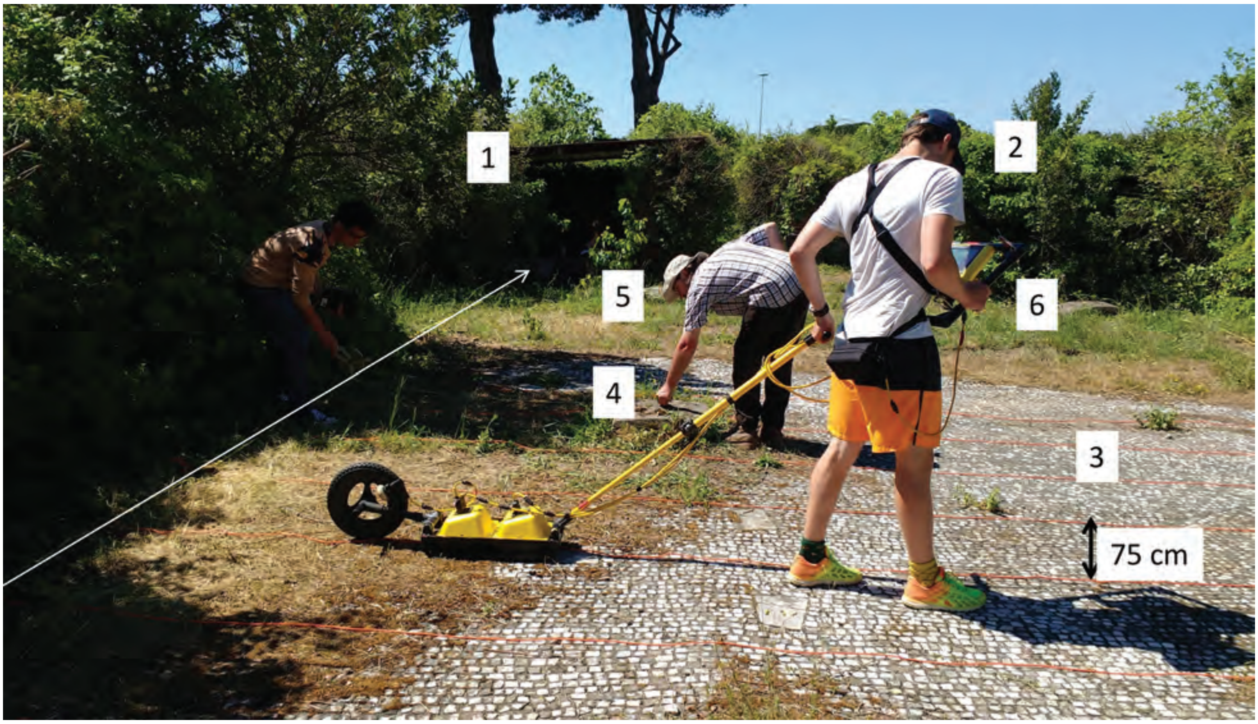

Fig. 3.1 The *frigidarium* during the recording of ground penetrating radar (GPR) data using 500-MHz antennae. The data were recorded along a direction perpendicular to the long axis of the *frigidarium*. 1: east cold bath, 2: west cold bath, 3: mosaic floor, 4-5: bases of *palaestra* columns. The white arrow indicates the base line of the surveys

Fig. 3.2 View from the east cold bath towards the west cold bath (left). Anachronistic reticulated wall (left and middle, label 7) and water duct at the north-west corner of the bath (right). The water duct is 24 cm wide and 30 cm high. It is located 50 cm below the floor of the frigidarium

3.3 SITE HISTORY

The *frigidarium* belongs to the Byzantine baths erected *c.* AD 390-425. Before being used as a cold bathing place, the site fulfilled several functions, partly revealed by the excavations carried out in 1970-1971.

While the targets and outputs of the excavations conducted in 1940 and 1958 are unknown, at least to us, the 1970-1971 excavation clearly aimed to investigate levels anterior to the baths (Poccardi 2006); it is documented with black and white photos provided by courtesy of the Archivio di Designo. After completion of the excavation, the site was entirely backfilled and the fifth-century AD mosaic floor re-laid. Unfortunately, we have not come across a sketch of the 1970-1971 findings nor photos taken during the backfilling of the excavation.

From observations made on the excavation photos and on the remains still standing today, it is clear that the site not only had multiple functions but was also reconstructed several times. Such conclusions can be drawn from observing for example the walls, because walls present construction patterns characteristic of the time they were built, thus helping to retrace the biography of the site and its connections to adjacent constructions (Stöger pers. comm. 2015; 2018).

At an early time, the site of the *frigidarium* formed part of the peristylium of the Domus di Giove Fulminatore (Lorenzatti 1998). The first phase of this house, called in English the House of Jupiter the Thunderer, dates back to the second century BC (Poccardi 2006). Then, the site was "a large rectangular area flanked by long corridors or rows of rooms" with walls covered by characteristic reticulated facing (Poccardi 2006). Lorenzatti (1998) superimposed the lay-out of the reticulated walls onto the drawing of the Byzantine baths (Fig. 3.3). One reticulated wall (Fig. 3.3, label H) was incorporated within the west wall of the east cold bath and continues to the north, as shown by the 1970-1971 photographs (Fig. 3.4, label c). Today, this wall is visible only from inside the east cold bath (Fig. 3.2, label 7). Elsewhere, it has been re-buried and covered by the mosaic floor. Labels on the photographs of the 1970s excavation (Figs 3.4-3.7, labels h to l) highlight the reticulated walls drawn by Lorenzatti and labelled H to l on figure 3.3. Note that we could not track back wall K on the 1970-1971 photographs.

According to Poccardi (2006), the *frigidarium* was developed in two phases. The first baths were erected in the southern space in the second century AD and were private. They were named "Byzantine" by mistake due to their curved apses which made them appear like later Byzantine constructions (DeLaine 2006). From the end of the third century to the fifth century, the baths developed into public baths by being extended to the north. The expansion of the baths reflected the dynamics of the neighbourhood and the fact that the Ostia political centre and also the main thermal establishment were situated close by. It did cost, though, the Domus di Giove Fulminatore its peristylium! The slight elevation difference in the floor of the *frigidarium* marks the northern limit of the former baths. The *palaestra* (Fig. 3.3, label G) was erected in the extension. The alignment of its long walls with the north-south walls of the cold baths should be noted (Fig. 3.3, labels E, F and G). Four of its six column bases still stand on the mosaic floor. The four column bases marking the corners of the *palaestra* are used as geo-references in our GPR survey (Fig. 3.1, labels 4-6).

More recently, archaeologists have re-evaluated the photographs of the 1970-1971 excavation and reckoned that in the third century AD the site could have been occupied by a fullery, *i.e.*, a laundry. With its numerous small-sized chambers and earthenware vessels (Fig. 3.5, labels n and o), the space excavated under the mosaic floor of the Byzantine baths in fact resembles Roman workshops which have been proved to be fulleries (Stöger pers. com. 2017; Flohr 2013). De Ruyt (2001) depicted fullers in action in Ostia. On her drawing, some slaves are soaking, cleaning or rinsing cloths in a very large basin, while others are trampling on cloths for further cleaning in large pressing-bowls; the slaves are supporting themselves by placing their hands on short walls on either side of the pressing-bowls or are pouring liquids into smaller bowls. The large basin and the pressing-bowls are all built into the floor of the fullery.

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Fig. 3.3 Drawing of the *frigidarium* surveyed by TU Delft in April 2017 (from Lorenzatti, 1998). The *frigidarium* is delineated by green lines. A: entrance with stairs from Via del Tempio Rotondo. B: entrance between the remains of the Domus di Giove Fulminatore (C) and the large *natatio* (D). E and F: east and west cold baths, respectively. G: *palaestra* delineated by thin black lines. Only one of the *palaestra* corner column bases is drawn. H to K: reticulated walls anterior to the *frigidarium*. Wall H has been incorporated in the construction of the east cold bath. The areas of the fullery and baths surveyed by TU Delft are marked in red dashed lines. The present article focusses on the largest fullery grid

As a conclusion, the subsurface under of the *frigidarium* is more complex than is shown on the drawing by Lorenzatti (1998). Apart from the ancient walls built in Hadrian's time and transformed or added to in Antonine's time, the subsurface certainly contains subterranean ducts leading to the cold baths or connecting basins of the fullery as well as the remains of many hand-support walls and buried bowls of various sizes.

Fig. 3.4 Assemblage of photographs taken during the 1970-1971 excavation. Letters a to l correspond to features highlighted with the letters A to L in figure 3.3, respectively. The three square column bases on top of wall k might belong to the columns at the corners of the *palaestra*. Note the presence of many walls and columns that have not been drawn by Lorenzatti and possibly date from the use of the site as a fullery. The function of the large square construction noted m, situated next to the point where several reticulated walls intersect, is unknown to us. Note also the high number of small excavations dug to various depths. Courtesy of Archivio di Designo

3.4 GPR SURVEYS

3.4.1 GPR METHOD

One of the aims of a GPR survey is to map contrasts in electromagnetic properties (magnetic permeability, electrical storage capacity and electrical conductivity) present in the subsurface. The electromagnetic properties of subsurface objects are a function of the material type, moisture and fluid salinity if they contain fluids. Thus, a GPR survey can highlight walls buried under the mosaic floor of the Byzantine baths if the wall structure and/or wall materials are sufficiently different from those of the backfilled material. The walls can also be highlighted if they are characterised by trapped humidity different from the humidity of the walls' surrounding.

During a GPR survey a grid of lines is laid down, and data are recorded by pulling the GPR along each line (Fig. 3.1). The spacing between lines should be sufficiently short (a few decimetres apart) to avoid shadow zones (*i.e.*, not imaging) between the lines. A so-called radargram (Fig. 3.6) is produced for each survey line. The radargram is composed of a number of vertical recordings (traces) representing the recording of electromagnetic signals at consecutive points along the GPR line. The recording points along a line should also be closely spaced (a few centimetres apart). At each survey point the GPR

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Fig. 3.5 Artefacts, photographed during the 1970-1971 excavation, next to reticulated wall (label J and j in figure 3.3 and 3.4, respectively). Earthenware bowls (n) and jars (o). Courtesy of Archivio di Designo

transmitter antenna sends a pulse of a high-frequency electromagnetic energy into the subsurface, while the GPR receiver antenna records the signals that reach it as a function of time. Each trace shows the arrival time of a recorded signal, its amplitude (in grey scale) and polarity (white or black colours). Even though the aim is to send a signal only into the subsurface, part of the transmitter energy propagates to the receiver directly through the air. Another part propagates directly to the receiver through the ground. The rest of the emitted energy propagates through the subsurface. When it reaches a contrast in the subsurface electromagnetic properties, part of the energy is scattered in the form of reflection, refraction or diffraction. The part of the energy scattered back to the surface in the direction of the receiver is recorded by it. Along its travel path in the subsurface the emitted pulse also loses energy because of various physical processes. As a result, the investigation depth of the GPR is limited. This is especially the case in conductive materials such as wet clays, soils saturated with salty waters, but also very heterogeneous soils.

A GPR radargram (also called GPR section) can be used for interpretation already after quick and limited signal processing. What one looks for in such radargrams is strong reflectors (Fig. 3.6, orange arrow) and hyperbolas (Fig. 3.6, blue arrow), which could be indicating a subsurface layer and a relatively small object in the subsurface (or an abrupt end of a relatively bigger object), respectively.

To convert the timescale of a radargram to depth, one uses the propagation velocity of the electromagnetic waves in the subsurface. Because this velocity is unknown beforehand, it is usually estimated using radargrams themselves. The common method of estimation in archaeogeophysics is hyperbolae fitting (Goodman & Piro 2013). Hyperbolae are assumed to correspond to reflections from a point object and are fitted with theoretically calculated hyperbolic responses of such an object. The best fit obtained gives an estimate of the velocity of the subsurface above the object, while the apex of the hyperbola indicates the location (including depth) of the object. The estimation method is limited in its accuracy because the objects that generate the hyperbolae are not points but have shape and final dimensions. Even more importantly, the subsurface of an archaeological site is often heterogeneous at

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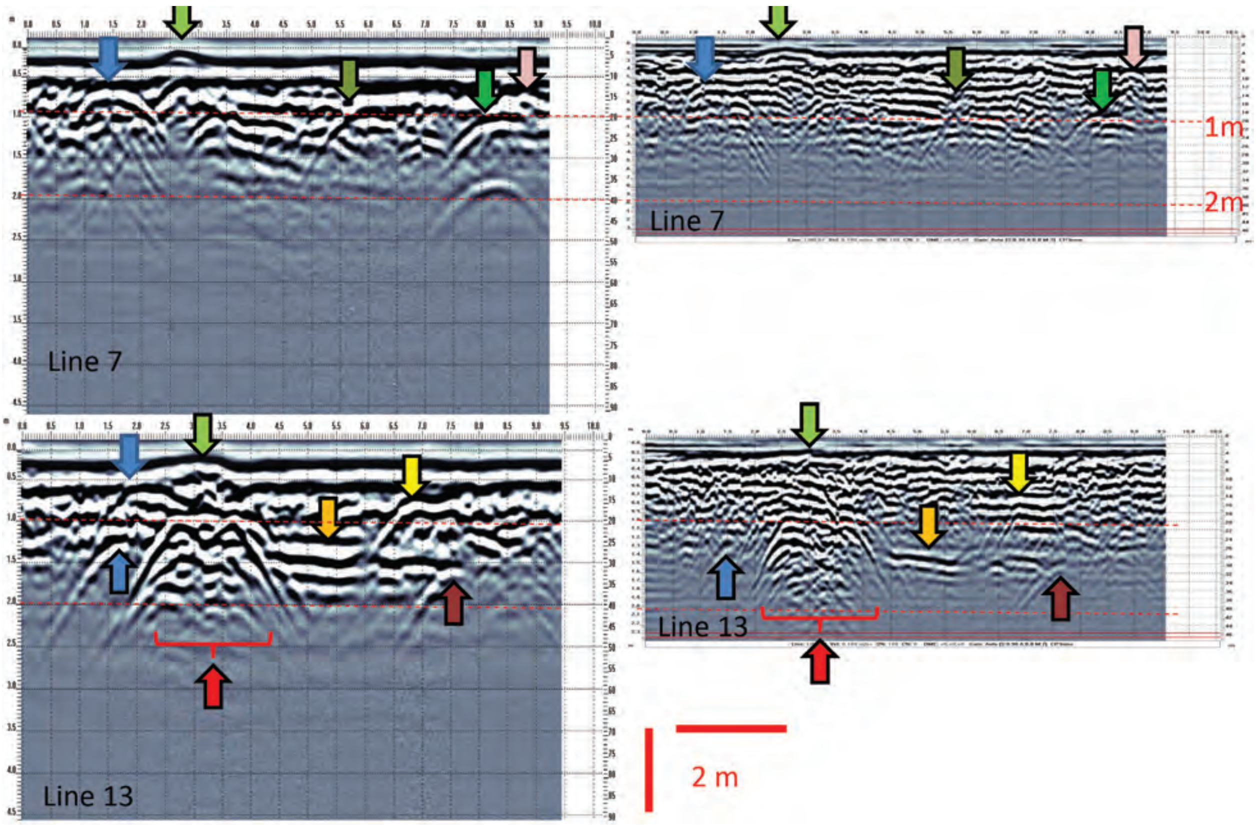

Fig. 3.6 Radargrams recorded during the 250 and 500 MHz surveys perpendicular to the long axis of the *frigidarium* along lines 7 and 13. See figure 3.7 for the position of the lines. Arrows of different colour highlight most obvious GPR features (hyperbolas or reflectors). Green arrows point to the bump on the mosaic floor, blue arrows to the Hadrian wall that has been partially re-used in the east cold bath, red arrows and brackets to the square construction next to a spot where many walls converge. Orange, yellow and brown arrows mark clear GPR features that have yet to be identified

the scale of the survey, and thus the ground velocity varies in all directions.

GPR surveys can be conducted using antennae emitting pulses of various frequencies (250 and 500 MHz, for example). The higher the frequency the higher the resolution of the survey, the resolution being a fraction of the wavelength of the emitted signal. A compromise has to be found when selecting the GPR frequency since the higher the frequency the lower the depth of investigation due to the frequency-dependent signal-attenuation processes. Moreover, the higher the frequency the narrower the spatial "sensing" of the antennae and, thus, the closer the survey lines of the GPR grid should be.

To track walls or ducts in the subsurface the radargrams recorded along parallel lines are combined to form a survey grid. Then, the amplitude of all signals recorded along the lines between two times (or depth levels) are represented on the survey grid in a time or depth slide (Fig. 3.7). To interpret walls or ducts one should look for high-amplitude features of an elongated shape.

3.4.2 GPR SURVEY SET-UP

We carried out the GPR survey using a PulseEkko Pro GPR instrument. The survey consisted of three grids, each grid constructed of parallel lines with a 0.25 m spacing between the lines. Such a spacing should have allowed us to resolve possible Roman

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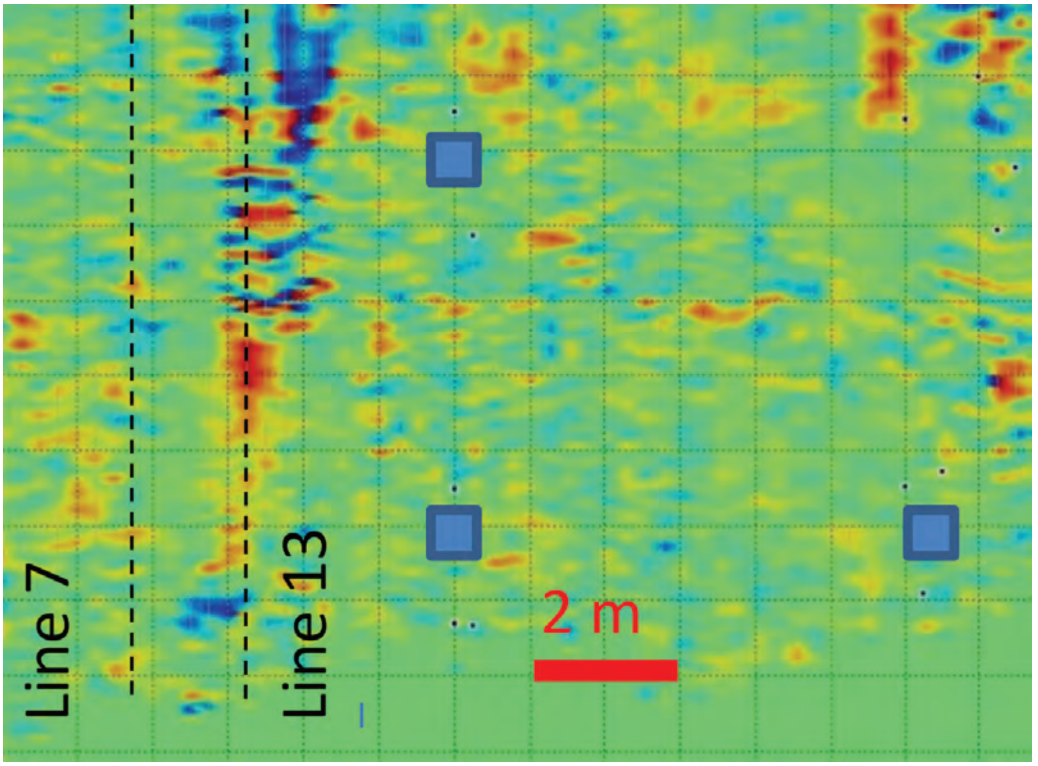

Fig. 3.7 Time slice showing the most prominent feature of the 250 MHz GPR survey recorded along line 13 and adjacent lines. The blue squares mark the column bases of the *palaestra*

walls in the subsurface; the walls are up to 0.6 m thick. The lines were marked on the ground by nylon ropes. We recorded data along the lines in a zigzag mode, meaning that after recording along a line from its beginning to its end we recorded along the neighbouring line from its end to its beginning. The first survey was conducted with 500-MHz antennae along lines sub-parallel to the long axis of the *frigidarium*. The second and third surveys were performed along lines perpendicular to the long axis of the *frigidarium* using 250- and 500-MHz (Fig. 3.1) antennae, respectively. The spatial sampling along the lines was set at 2.0 cm and 2.5 cm for the 250- and 500-MHz surveys, respectively; the recording time window was 130 ns and 50 ns for the 250 MHz and 500 MHz surveys, respectively. To ensure sufficient signal-to-noise ratio of the recordings along all lines, the number of stacks at each recording point was set to DynaQ mode and was kept high because we adopted a slow walking pace.

The invasive vegetation crawling down the walls of the *frigidarium* prevented us from covering the whole area with the GPR survey. The poor reception of satellite signals by the GPS of the GPR compromised the accurate geo-referencing of the survey. Instead, we used as references the bases of the *palaestra* columns marked as fiducials during the GPR survey. Lesson learned: always make many manual records of distances between notable features inside and outside the survey area; include in the geodetic survey landmarks with known coordinates.

3.5 DATA PROCESSING

The data processing was limited to just a few standard steps: Dewow, Time-zero alignment and Automatic Gain Control (Sensors & Software 2009). Next, we estimated the subsurface velocity applying hyperbola fitting (as explained above). Because the subsurface of the survey area is heterogeneous

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with heterogeneities of various shapes and sizes, the hyperbolae do not exhibit ideal shapes, which rendered the estimation of the velocity inaccurate. We estimated velocities between 0.07 m/ns and 0.10 m/ns. We then converted the radargrams from travel time to depth assuming a constant velocity of 0.10 m/ns for the sake of simplicity – using multiple velocity values estimated with low certainty does not improve the chances of the interpretation. With the chosen velocity, the penetration depth was on average limited to 1.5 and 2.0 m for the 500- and 250-MHz surveys, respectively. We did not migrate the radargrams nor did we correct them for topography effects before producing the time slices. We chose not to combine the two 500-MHz surveys into one series of time slices because the surveys' extent was different and their orientation was not exactly perpendicular.

3.6 RESULTS AND INTERPRETATIONS

We found the data recorded with the 500- and 250-MHz antennae to be consistent (Fig. 3.6). We can observe that the 250-MHz radargrams are less cluttered than the 500-MHz ones, and consequently highlight better interesting signals from the background noise. On the other hand, the higher-resolution 500-MHz radargrams depict in more detail the organisation of the reflections associated with the interesting features detected by the 250-MHz survey. The 500-MHz radargrams also provide information where the ground wave in the 250-MHz data covers useful signals.

The shallowest time slices are found to reflect differences in ground coupling, surface elevations and the dependence of the recorded signal on the frequency (Fig. 3.7). For example, the extent of the mosaic floor appears clearly on the 500-MHz grids but not on the 250-MHz grids.

Slight surface-elevation differences produce a jump in colour on the time slices. This is the case at the northern extension of the baths where walls are slightly protruding above the surface. This is also the case where the tiled surface presents a bump (Fig. 3.6). The bump is subparallel to the west wall of the east cold bath but not aligned with it. It is unclear what caused this bump.

The long continuous reticulate walls drawn by Lorenzatti (1998) are the most noticeable on the radargrams. For example, one of these walls should be the culprit causing the hyperbolae present on most radargrams of the 250-MHz antennae (Fig. 3.6 blue arrow) at about 1.75 m from the base line.

The most outstanding feature of all three surveys is a large cluster of hyperbolae (Fig. 3.6, red arrow and bracket). The cluster falls in the neighbourhood of the intersection between four reticulate walls (Fig. 3.3, labels H, I, K, and L), and might very well have been generated by the square structure located between the wall intersection and the north-east corner of the *palaestra*; on photographs taken during the 1970-1971 excavation the structure is capped by a plank (Fig. 3.4, label m). The exact function of this structure is unknown to us. The cluster appears to be a very clear squared zone of high-energy signals on the time slices of the three surveys and is connected at its base via an elongated feature to a second, smaller square structure. The elongated feature is formed by a flat hyperbola and a long reflector on adjacent radargrams of the 500-MHz survey that we conducted parallel and perpendicular to the long axis of the *frigidarium*, respectively. What could this be? Possibly the wall K (Fig. 3.3) that intersects with the other walls next to the main square structure? An overview of the main features extracted from the GPR survey in the northern part of our survey areas is under construction.

3.7 DISCUSSION AND CONCLUSIONS

We were expecting that the Hadrian and Antonine walls would show up without ambiguity in our GPR data. This is not exactly the case even if many elongated features could be spotted on the radargrams. It is also unclear why one structure is so prominent in the radargrams and time slices compared to others. Several factors could explain these ambiguities. First, the site of the *frigidarium* has fulfilled several functions which required the demolition of old walls, the construction of new walls and the partial re-use of existing walls. When the area was transformed into a fullery, many basins, small chambers and pressing-bowls must have been built, increasing greatly the complexity of the site.

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Second, based on the archive photographs, the site looks like a patchwork of small excavations dug down to various depths and bordering many Roman walls and objects of various shapes and sizes. It is not known with what materials the backfilling under the reconstituted mosaic floor was done. Using brick, stones or other small objects to backfill would blur the radargrams – such small objects give rise to multiple diffraction signals, which will make the picture appear of high noise level and might thus mask the presence of diffractions and reflections from the walls. Zones not excavated during the last century excavations are probably stiffer than backfilled zones. They might have reflected/diffracted the GPR signals just like walls would do during the GPR survey. Lesson learned: both the excavation and backfilling works should be documented very well with images, drawings and, nowadays, 3D digital models. This would simplify future excavations or geophysical investigations. Alternatively, the difficulty in interpreting expected features in the results of the GPR survey highlights the fact that, if possible, it would be better not to excavate buried structures, but to investigate them with multiple non-invasive techniques.

Acknowledgements
The survey in the *frigidarium* of the Byzantine baths was conducted in parallel to the 2017 main geophysics survey performed by TU Delft to reveal the functions of the unexcavated part of Ostia at the fringe of Region IV, *Insula* iv and contributes to Hanna Stöger's research. The research of the TU Delft team was supported in kind by TU Delft Department of Geosciences and Engineering. Deyan Draganov's contribution was supported by the Division for Earth and Life Sciences (ALW) with financial aid from the Netherlands Organisation for Scientific Research (NWO) with grant no. VIDI 864.11.009. Martijn Waarnaar's involvement was supported by a personal scholarship awarded by the Molengraaf fund.

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