Lancaster Priory Geophysics Report

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Survey Personnel

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Dates	
Fieldwork:	20 December 2021 - 18 July 2022 (8 days in total)
Report:	26 March 2024
NGR	SD 47328 61929
Location	The grounds of Lancaster Priory, bounded by Castle Parade and Hillside. SAM No. 1020668. Part of a Roman fort and its associated vicus and remains of a pre-Conquest monastery and a Benedictine Priory on Castle Hill.
Survey Methods	Ground penetrating radar (GPR).
Study Area	0.7 ha.
Report DOI:	https://doi.org/10.5281/zenodo.10876766
Associated data DOI:	https://doi.org/10.5281/zenodo.10877390

Licences

The survey was mobilised by the lead archaeologist for the project, Jason Wood, and undertaken in accordance with Historic England section 42 licences in his name: Case No: SL00234215 (granted 9 December 2021); Case No: SL00234232 (granted 24 January 2022); Case No:SL00234332 (granted 4 July 2022).

Aims

An extensive set of geophysical surveys were carried out in order to: (1) help interpret the wider context setting of archaeological remains found during excavation following the uprooting of a large Wych Elm tree (see separate report by Jason Wood: Wood (2024)); (2) assess potential presence of subsurface voids in the car park adjacent to the Priory; (3) determine the location of any underground services and identify any possible areas of archaeological significance to assist with planned future ground works.

Summary of results

The surveys reveal a highly heterogenous shallow subsurface within the estate, in part due to the extensive historical use and development of the site. However, a number of key findings have resulted from the surveys, most notably: (1) evidence that the previously speculated presence of voids beneath the Priory car park may, in fact, be due to localised electrically conductive shallow subsoil (e.g. patches of dense clay); (2) the location of a series of underground services (cables, drains, etc.) is proposed; (3) a relatively deep (2m) feature consistent with the footprint of a former structure is suggested, alongside evidence of a significant superficial geological boundary at this depth; (4) the route of the path (now not present) connecting the former grammar school to the Priory is evident at a depth of 0.75m; (5) potential features consistent with former structures are apparent in the southwest churchyard, and warrant further investigation.

Method

Georeferencing: Several permanent features were surveyed with a Trimble R8 GNSS system in RTK survey mode to establish coordinates relative to the British National Grid. A Trimble S6 DR Robotic Total Station was then used for each GPR survey to georeference to these fixed points.

GPR: MALA ProEx 800MHz, 500MHz, 250MHz and 100MHz antenna. Most surveys in 3D mode with 0.3m or 0.4m line separation (depending on antenna). Some surveys only carried out as 2D transects (where access to a suitable area for a 3D survey was not possible). Technical details in Appendix A.

Data Processing

GPR: Radar velocity estimated from hyperbola matching in *ReflexW*. *GPRPy* used for GPR data processing: time-zero correction, survey length correction, dewow, power-law gain. *GPRPy* used to generate 3D model in vts format for viewing in *ParaView*.

Survey conditions

Site cover: grass cover in places, some paved and other hardstanding cover. Topography variable.

1. Site description and context

1.1 Lancaster Priory lies within the site of a series of Roman Forts dating from the 1st to 4th centuries AD. The site was formerly a pre-Conquest monastery, later developed to the medieval Priory of St Mary. Few archaeological investigations have taken place within the grounds of the Priory. The only previous geophysical surveys conducted were by Oxford Archaeology North in 2014 as part of the *Beyond the Castle* project (Wood, 2021), although these covered very little of the Priory estate and revealed very little of archaeological significance.

1.2 Uprooting of the Wych Elm tree within the ground of Lancaster Priory during storm Arwen (November 2021) prompted archaeological investigations of the area. On the suggestion of the lead archaeologist, Jason Wood, a request was made to Historic England for licences to conduct geophysical surveys adjacent to the excavation to help interpret the wider context setting of any finds.

1.3 The Oxford Archaeology North geophysical survey in 2014 revealed the possible presence of subsurface voids adjacent to the western wall of the Priory building (region marked “Area 1” in Oxford Archaeology North (2014)). Given concerns about possible settlement, a further investigation of this area was requested.

1.4 Proposals are underway to develop part of the Priory land for erection of a monument/statue acknowledging Lancaster’s role in the slave trade. Geophysical surveys were requested to assist in any future ground works required for such works.

1.5 Given the above, a series of ground penetrating radar (GPR) surveys were carried out within the Priory estate. Figure 1 shows the area covered. Surveys were designed to cover as much of the estate as possible. 3D (grid) surveying was used for the majority of the work, although in some areas 2D (single transect) survey was necessary due to access constraints. The 3D surveys were designed as a patchwork of rectangular grids bounded by above ground features (trees, walls, paths, etc.), resulting in an irregular arrangement of survey plots, some of which were far from ideal in geometry (e.g. long but narrow). Furthermore, the heterogeneity of surface cover (grass, paved stone, asphalt - see examples in Figure 2) meant that coupling of the GPR antenna to the ground was variable. This has little effect on surveys on individual plots but it does mean that when composite images are produced from multiple plots, variation in results due to different surface cover is inevitable.

1.6 The higher the frequency of the GPR antenna, the greater the spatial resolution, but the weaker the depth of investigation. A 250MHz GPR antenna was used for the majority of the surveys to balance resolution and depth of investigation. In some areas 800MHz and 500MHz antenna were also used for comparison. For a number of transects a 100MHz antenna was used in an attempt to sense deeper into the subsurface. The 18 3D survey areas are labelled “A”, “B”, … “R” (see Table A1). The 2D surveys are labelled “yymmdd(xx)”, where “yy”, “mm” and “dd” refer to year, month and day, respectively and “xx” is a unique numerical identifier for the survey date.

1.7 The location of surface features (trees, tree stumps, lampposts, floodlights, drain covers) were surveyed to aid interpretation of the geophysical data. The boundary of the excavation within the area of the former Wych Elm tree was also surveyed.

1.8 Figure 3 to 6 show the locations of the 3D and 2D surveys, along with key features in the estate. The photographs in Figure 2 illustrate some of the survey conditions.

2. Priory car park (Plot A)

2.1 Extensive surveys were carried out within the Priory car park (Plot A) as the 2014 GPR survey in this area by Oxford Archaeology North revealed a number of anomalies with ‘ringing’ behaviour. The term ringing is typically used to describe repeated reflections. These observations had been interpreted as possible subsurface voids (Oxford Archaeology North, 2014), which, if correct, could have implications on the stability of the Priory structure. In fact, the surface cover (asphalt) of the car park shows distinct degradation in places (see Figure 2a), adding further support to this interpretation of the 2014 survey.

2.2 Oxford Archaeology North had used a 400MHz antenna; to investigate this further we selected a range of antenna frequencies (250MHz, 500MHz, 800MHz), covering an area 13m by 14m. Figure 7 shows the position of the survey in detail, along with its orientation.

2.3 Figure 8 shows example horizontal slices through the 3D model derived from the 250MHz dataset. A linear feature orientated approximately in the Y direction is clearly visible in the 0.5m deep slice. In addition, a set of localised anomalies are evident.

2.4 The linear feature noted above suggests an underground service is present in the plot. In fact, a downpipe on the western wall of the Priory aligns with this feature (see Figure 9), although no drain is visible. It appears that a former drain (now redundant) may be present in the plot.

2.5 Individual GPR transects can be analysed to assess the nature of reflections. An image of an individual transect consists of a sequence of signal amplitudes over an interpreted depth. In a greyscale plot (as used in this report) each reflection at depth is shown as a white-black-white (or black-white-black) pattern. Several of the localised anomalies identified above show ‘ringing’ behaviour, as illustrated by two individual surveys shown in Figure 10 (see Line 042 between X=7m and X=12m; Line 066 between X=1m and X=3m and also X=7m and X=11m). These are consistent (character and location) with features observed by Oxford Archaeology North in their 2014 survey (their “Area 1”).

2.6 A number of hyperbolae reflection patterns (upside down V shape) are also evident in the plot for Line 042 in Figure 10. These are shown again in Figure 11 along with the plot for another line (Line 047) and the deeper horizonal slices of the 3D model. Hyperbolae result from traversing across localised features. The continuity of these features spatially is not apparent from the horizontal slices.

2.7 Figure 12 shows example horizontal slices based on the higher resolution 500MHz GPR data. The overall patterns are similar to the 250MHz data but notice now that at 0.4m depth a reasonably continuous reflection is seen to follow a curved path through part of the plot. This is even more evident in the 800MHz data (Figure 13). We interpret this continuous feature as an underground service line (e.g. electrical cable).

2.8 Ringing of GPR signals could be a result of subsurface voids, particularly if the voids are capped (as interpreted by Oxford Archaeology North): the void leads to a kind of electromagnetic reverberation of the signal. However, other subsurface characteristics can also manifest themselves with ringing behaviour in GPR data. Furthermore, the ringing of the 250MHz data (e.g. Figure 10) also shows other characteristics – there is an apparent reduction in frequency of the reflected signals where the ringing occurs (i.e. the spacing of the white-black-white patterns appears longer where the ringing occurs). We carried out surveys using three different antenna frequencies in order to investigate this further.

2.9 Figure 14 shows a comparison of 0.5m deep horizontal slices from the 250MHz, 500MHz and 800MHz data, along with example individual surveys along the same line. Note that the horizontal slices show some contrasting behaviour; in particular, note that the large strong apparent reflective anomalies (black/dark red features) in the 250MHz data (e.g. at X=9m, Y=11m) are not visible in the 500MHz data and in the 800MHz data appear a very low reflective 'strength' (white/light yellow colour in the image). Such attenuation (in the 800MHz data) is likely a result of high electrical conductivity of the subsurface. Notice also how the individual transects show different behaviour when crossing the apparent anomaly (e.g. between X=7m and X=11m in the individual transects in the lower part of Figure 14): the attenuation of the 800MHz data is very clear, as is the apparent reduction in signal frequency in the 500MHz data. What this suggests is that the antennas are behaving differently when crossing the feature. If the shallow (say upper 0.3m) of the ground contains material that has high electrical conductivity (e.g. steel reinforcement or wet clay) then the ground can begin to act as an antenna (depending upon the GPR antenna used) and features, such as those seen in Figure 14, can result. The consequence is that the anomalies previously interpreted at subsurface voids are more likely to be a result of shallow elevated electrical conductivity (e.g. wet clay rich soil).

2.10 Figure 15 shows another comparison of data from the three antennas. In this example the three individual transects show similar behaviour. The datasets reveal that the anomaly at (X=6m to X=8m; Y=9m; Z=0.5m) appears to be a localised deformation under the asphalt cover.

2.11 Figure 16 summarises the main features observed in Plot A.

3. Plot B.

3.1 Figure 17 shows the position of the Plot B survey, along with its orientation (see also Figures 2e, 3 and 4). Both 500MHz and 250MHz surveys were carried out. We focus here on the 250MHz results (the 500MHz data show similar behaviour). In Figure 18 the survey area is superimposed on a section of the Priory's current record of former gravestone sites (approximately georeferenced).

3.2 The GPR surveys of Plot B were carried out in an attempt to identify features associated with the Roman fortification. Figure 19 shows example horizontal slices of the 250MHz 3D model. Numerous anomalies are present in the data, although all appear localised and likely consistent with graves, particularly the regularly aligned rectangular shaped features of similar size noted at relatively shallow depths (<1m). The low signal rectangular feature (white/light yellow anomaly; X=0m to X=2; Y=12m to Y=14m) is the stone paved area (visible in the aerial image in Figure 3 and 4). No features of archaeological significance appear to be present in Plot B.

4. Southern churchyard (Plots A,C,D,I,J,K,L,M,R,Q)

4.1 The surveys of the southern churchyard were constrained by the range of ground cover (asphalt, stone paving, grass) and surface features (walls, trees, tree stumps, lampposts, etc). As a result, a collection of small rectangular plots was selected. In all cases except Plot H (see Figure 3) the ground cover was the same in each plot (this was unavoidable in Plot H due to the triangular shape of the grassed area it covered). We focus here in the 250MHz data. Note that the results from Plot A are included here but as they have been discussed already we will not repeat discussion of these data.

4.2 Each dataset was processed individually using the same processing steps and parameters. A composite plot was then produced. In this composite plot a common colour scale was used, i.e. the same colour represents the same reflected signal strength for each plot. This is worthy of note as different ground cover (grass, paved stone, etc.) will have different antenna coupling characteristics and thus the strength of signal transmission will vary. Figures 20 to 25 show selected horizontal slices of the composite plot.

4.3 Figure 20 shows the horizontal slice at a depth of 0.5m. A number of underground services are clearly visible in the image, and align with surface infrastructure (lampposts, drains, etc.). Figure 21 (depth: 1.0m) illustrates the challenge of working with data collected over different ground cover. The long thin Plot D (see Figure 4 for location) with paved stone cover shows contrasting behaviour to the adjacent grass covered plots – a likely consequence of the different antenna coupling. Figure 26 shows an interpretation of possible underground services within the area surveyed.

4.4 The collection of composite images shows numerous localised anomalies and given the extent of burials at the site and inevitable disturbance it is difficult to interpret each one. However, the horizontal slice at 1.75m (Figure 23) is potentially of interest. In this figure a number of rectangular anomalies, assumed due to be graves adjacent to the southern wall of the Priory, are visible. More significant, perhaps, is the apparent right-angled anomaly, given that its orientation (20 degrees N /110degrees N) aligns well with that of the Roman fort boundary (and assumed buildings within). We note, however, that a similar alignment of significant graves could lead to the same geophysical anomaly and that the Priory follows the same alignment.

4.5 To investigate the anomaly noted above we designed an additional set of surveys focussing on the area of interest. For the composite image in Figure 23 the surveys had been carried out using only one orientation of GPR measurement (the longest axis of each rectangular plot) simply because several of the plots were too narrow to be able to conduct orthogonal surveys, or trees/trees stumps restricted access in one orientation. In order to investigate the feature in Figure 23 we created a new survey area (Plot Q) that covered much of Plots I and K, but could be surveyed on its long and short axis (see Figure 27).

4.6 Figure 28 to 31 show horizontal slices of the composite images from plots I, Q and R for depths 1.5m, 1.75m, 2.0m and 2.25m, respectively. The angular feature noted earlier is more prominent (particularly in Figure 29 for a depth of 2m), a likely result of conducting surveys in two orthogonal directions for Plot Q. Additional linear anomalies with the same alignment are now also more visible. Figure 32 summarises the key features noted over the depth interval 1.75 to 2.25m. However, we must stress again that the presence of substantial graves could result in the same observed anomalies.

4.7 The ground surface of the southern churchyard will clearly have changed significantly since Roman occupation. If the features noted above are due to remains of earlier buildings or foundations then they exist approximately 2m below current ground level. An additional survey carried out offers some additional support that a contrast in soil horizon may exist at such a depth. The survey was conducted along the southern wall boundary with Castle Parade (see Figure 33). It was prompted by observations of water seeping out of the south face of the wall (see Figure 34) in December 2021. The seeps appeared above the base of the wall and appeared to follow a clear upper boundary, which would be consistent with the presence of a low permeability soil horizon impeding vertical flow. A single GPR transect was surveyed with a 500MHz antenna adjacent to the wall on its northern side (i.e. within the churchyard). This survey is labelled 211221(71). Then, on 12 January 2022 the vertical and horizontal position of individual seeps were surveyed using the Trimble S6 DR Robotic Total Station, georeferenced to British National Grid. Figure 34 shows the results from this topographic survey. Processing of the 211221(71) GPR dataset involved vertical correction using ground elevation survey recorded during the GPR data acquisition. This then permits the display of the GPR data with elevations corrected to Ordnance Datum alongside the position of observed seeps (see Figure 35). Interestingly, the GPR data shows a number of semi-continuous reflection patterns (consistent with a contrasting soil horizon) and these appear to align well with the position of the observed seeps. At the summit, the depth to this horizon is 1.5m. This is not inconsistent with the earlier remarks concerning plots I and Q.

5. Southwest churchyard (Plots N, O, P and transects).

5.1 Plots N, O and P were designed to cover the grassed area of the southwestern region of the churchyard (see Figure 36 and Figure 2g). Figure 37 to 42 show example horizontal slices through the 3D model derived from the 250MHz surveys. At a depth of 0.5m (Figure 37) numerous distinct localised anomalies are evident, some of which have a clear rectangular shape. We interpret these to be graves where horizontal gravestones are still in place. At 0.75m and 1.0m (Figure 38 and 39, respectively) a clear east-west linear anomaly runs in the northern section of Plot N. In Figure 43, a georeferenced 1846 map of the area is shown, revealing the position of a path connecting the former grammar school to the Priory. The anomaly noted in Figures 38 and 39 align exactly with this path and thus explain the origin of the feature.

5.2 At 1.5m depths (and below) a linear anomaly appears parallel to the path on the eastern edge of Plot N. This is a result of interference from the path edging (which is why is shows an apparent migration west with depth) and thus of no archaeological significance.

5.3 The horizontal slices at depths 1.5m, 2.0m and 2.25m (Figures 40 to 42) reveal a number of localised reflection anomalies. At a depth of 1.5m there is potential evidence of a linear anomaly (marked in Figure 40) that runs in a 20 degree N direction (i.e. aligns with the Roman fortification). However, this anomaly is weak. The presence of multiple graves and the inevitable disturbance of the soil will have a significant effect on resolution of relatively deep features, but the apparent anomaly is worthy of note. Other anomalies to the east of this feature are also evident at depths of 1.5m and deeper but any interpretation of subsurface structures is speculative. The surveys in Plots N,O and P were conducted in one orientation – future targeted surveys, in the area highlighted above, using surveys in orthogonal directions may offer more insight but the disturbance of the plot given its former use will always be a constraint in interpretation.

5.4 A number of individual 100MHz surveys were also carried out in the southwest churchyard (see Figure 6 for their locations) in an attempt to obtain greater signal at depth. These surveys do reveal significant variation in reflection patterns but, unfortunately, offer little additional value. Figure 44 shows the position of three 100MHz transects selected for illustration. These surveys, with topographic correction applies, are shown in Figure 45 (the 10m and 20m markers in Figure 44 are useful to aid referencing against the 250MHz 3D data). The three transects have some consistent behaviour, specifically the deep (~3m) reflection over sections of the transects (e.g. transect 220222(10) between 20m and 30m). This probably indicates the position of an original slope topography, or a significant superficial geological boundary. Note that in transect 220222(10) some undulation of a continuous reflector can be seen between 10m and 20m. No similar pattern is seen in the two adjacent transects, making interpretation extremely speculative. The transects also show a number of significant hyperbolic reflection patterns (see 220222(09) at 23m, for example). We interpret these as substantial grave anomalies. The three transects also show rather chaotic reflection patterns in the upper 1.5m – this is no doubt a consequence of numerous burials in the surveyed area (the 100MHz signal has a wavelength of approximately 1m and so small features will not be resolved individually but will still perturb the signal).

6. West churchyard (transects)

6.1 A number of individual transects were surveyed in the western region of the churchyard (see Figure 5 and 6). Access was constrained preventing the use of grid (3D) type surveys. We focus here on selected 250MHz surveys (no additional information was evident in the 100MHz surveys). Figure 46 shows the location of the 250MHz surveys in relation to the Roman fort boundaries (Wood, 2021). The surveys were carried out to determine any evidence of subsurface features consistent with former fortification.

6.2 Figure 47 shows the topography along survey lines 220718(01) and 220718(03), which flank the outdoor theatre area. In Figure 48 a sub-section of the survey lines are marked to aid interpretation. Figure 49 shows a 25m section of the two GPR surveys that should cross the 1st/2nd century fort western boundary. Figure 50 also shows a 25m section of the two transects, this time crossing the 4th century fort boundary. The surveys reveal a series of subsurface reflections, but there is no evidence of specific structure that aligns with the estimated fortification.

7. Relationship to other surveys

7.1 In February/March 2022 a series of GPR surveys were carried out within the grounds of nos. 4,5 & 6 Hillside, to the west of the Priory. The results of these surveys are documented in Binley (2023). Figure 51 shows the area surveyed at Hillside using 500MHz radar antenna, along with the approximate positions of Roman Fort boundaries (after Wood (2021)). The insert image in Figure 51 is an example result from the Hillside surveys – the most striking feature is a linear high attenuation (white in the image) feature in the south of the survey area running in a similar orientation to the fort boundaries. High attenuation is typically a result of high clay content in the subsoil, leading Binley (2023) to conclude that one explanation could be the result of remobilised clay presumably installed as part of the western defences (e.g. Jones and Shotter, 1988). Unfortunately, this feature is not seen to extend further north in the survey area and is not apparent in the 250MHz transects shown earlier (Figures 49 and 50).

8. Summary and recommendations

8.1 An extensive set of ground penetrating radar surveys have been carried out within the grounds of Lancaster Priory. The surveys included 14 grids in 3D mode using a 250MHz antenna, and a number of replicate surveys using 500MHz and 800MHz antenna. Surveys on a set of individual (2D) transects using 250MHz and 100MHz antennas were carried out to supplement the 3D surveys.

8.2 The surveys reveal a highly heterogenous shallow subsurface within the estate, in part due to the extensive historical use and development of the site. However, a number of key findings have resulted from the surveys.

8.3 In the car park west of the Priory building the results of our surveys suggest that the previously proposed occurrence of subsurface voids is unlikely to be correct and that localised patches of very shallow electrically conductive material (e.g. clay or steel reinforcement) are more likely to be the cause of ‘ringing’ behaviour observed in the radar signals. At least one small patch within the car park does, however, appear to have experience some settlement of the subbase. The car park survey also revealed two possible underground service routes, one of which appears to be a (possibly redundant) drain, given that it connects (in plan) with an existing downpipe. See Figure 16 for summary.

8.4 Surveys to the west of the car park (Plot B) did not reveal any features of archaeological interest. The images do reveal a substantial array of anomalies associated with graves. See Figure 19.

8.5 A patchwork of surveys in the southern churchyard provides a map of shallow underground services (see Figure 16), which may be useful for planning future groundworks at the site. The surveys also revealed some features at depth that may be of archaeological significance. A potential subsurface structure is interpreted at a depth of 2m, with alignment to the Roman fortification (see Figure 32). We should note, however, that disturbance above this depth (in particular, graves) has potentially constrained the resolving capability of the radar. Surveys along the walled boundary with Castle Parade have shown that observed water seeps along the southern face of the wall marry with a near-continuous radar reflection in the churchyard adjacent to the wall at an approximate depth of 2m (see Figure 34 and 35). This suggests that a significant superficial geological boundary may exist at this depth, which is not inconsistent with the depth of the interpreted feature closer to the Priory building mentioned above.

8.6 Surveys in the southwestern churchyard show high heterogeneity, almost certainly due to its use as a graveyard. At a depth of 0.75m – 1m a clear linear anomaly was noted running in an east-west direction. The feature aligns perfectly with the historic route of the path between the Priory and (former) grammar school shown in the 1846 map of the area (see Figures 38 and 43). Despite the high heterogeneity of radar signals, some relatively strong reflections at depth were observed (e.g. Figure 40).

8.7 In the western churchyard surveys were constrained to the use of individual transects. The results of the surveys show substantial variation in radar reflection patterns but no signals consistent with the alignment of the Roman fortification are apparent (e.g. Figures 49 and 50).

8.8 We recommend the following further investigations: (1) shallow (say 300mm) small bore (say 10mm) drilling of the interpreted electrically conductive anomalies in the car park should confirm the origin and nature of the source of 'ringing' behaviour in a minimally invasive manner; (2) in Plot N (southwestern churchyard) a repeat GPR survey (with a suite of antenna and done in orthogonal directions) should provide greater insight into the deep anomalies in this area (a 20m by 20m survey area should be sufficient for this). Excavation in the southern churchyard where the anomaly in Figure 32 is situated is clearly highly unlikely to be possible. However, we do believe that this area does warrant further investigation of some sort in order to build a much clearer picture of former structures at the site.

8.9 Finally we should add that whilst a great deal of information has been gathered by the geophysical survey, the results presented here and their interpretation should not be relied upon as a sole and complete record of subsurface features present at the site.

8.10 This report should to read in conjunction with that by Jason on the results of the archaeological excavation in the area of the uprooted Wych Elm tree (Wood, 2024).

9. Data availability

All the raw GPR data, along with coordinates of surveyed plots (to British National Grid) are available at https://doi.org/10.5281/zenodo.10877390. Any use of the data or results should acknowledge this report.

10. References

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Appendix A. Technical information: Ground Penetrating Radar (GPR).

Instrumentation: MALA ProEx unit with 800MHz, 500MHz, 250MHz and 100MHz shielded antenna.

The shielded GPR system typically operates in reflection mode: a transmitter antenna provides a pulse of high frequency electromagnetic energy and a receiver antenna records signals travelling directly from the transmitter and from reflections in the subsurface. Surveys were conducted along transects using an odometer to trigger measurements every 2cm. The odometer recorded distance for each transect was compared to the known survey length and corrections made, when necessary, to adjust the recorded position, assuming a linear drift. Such errors can occur due to odometer wheel slippage on wet ground, but are typically of the order of a few percent.

Most surveys were carried out in a rectangular grid (3D) layout (see Table A1). These are sometimes referred to as C-scan surveys. In some cases, e.g. where site access restricted the use of a grid, individual transects (2D) were surveyed (see Table A2). Transect surveys are sometimes referred to as B-scan. A C-scan survey consists of multiple B-scan surveys. For grid surveys, the corners were first positioned and georeferenced using a Trimble S6 DR Robotic Total Station. Then survey lines were marked using a length of nylon cord, at equal intervals along the shortest axis of the rectangle. For the 250MHz antenna, the lines were positioned every 0.4m (the width of the antenna). For 500MHz and 800MHz antenna, the lines were positioned every 0.3m. No grid surveys were conducted with the 100MHz antenna. For selected grids surveys were also conducted in an orthogonal orientation (see Table 1) to enhance detection of subsurface features. Given that several of the grids had a 'long thin' rectangular shape, orthogonal surveys were not feasible.

For 2D (i.e. individual transect) surveys, the position of the start, end and several intermediate positions along the survey line, were recorded using the Trimble S6 DR Robotic Total Station. This allowed corrections to be made for topography.

GPR data were recorded over an appropriate time window to ensure capture of all detectable reflections. The length of the time window depends upon the antenna use; the following were used: ~20ns (800MHz); ~70ns (500MHz); 90ns (250MHz); 100ns (100MHz).

For both 2D and 3D surveys, each transect dataset was processed individually in *GPRPy* (Plattner, 2020) using the following steps: (1) odometer correction to known survey length; (2) time-zero correction; (3) dewow (low frequency filter); (4) time window truncation (to remove later sections of the trace where no reflections are present); (5) application of a gain function (to amplify signals at later times in the trace); (6) translation of time window to an effective depth using an appropriate velocity. In order to obtain a velocity measure, a number of transect datasets with visible hyperbolic reflections were selected for velocity analysis in *ReflexW* (*GPRPy* has this feature too but *ReflexW* has much greater flexibility and user control). The inferred velocity from such analysis was 0.085 m/ns. This is characteristic of a relatively moist soil. Most of the observed hyperbolae occur at shallow depth and yet the velocity may vary with depth. Consequently, the computed depths of GPR reflections but be treated with some caution. For example, a two way (i.e. from transmitter to reflector and return to receiver) of 30ns equates to a reflector depth of 1.275m (assuming a velocity of 0.085m/ns) and a depth of 1.5m (assuming a velocity of 0.1m/ns, which was assumed in the Priory surveys conducted by Oxford Archaeology North (2014)).

For 2D surveys a topographic correction was also applied, using linearly interpolated position and elevation data. For 3D surveys no topographic correction was applied (thus all results from these surveys indicate reflections relative to ground level).

For 3D (grid) surveys, once each transect was processed in *GPRPy*, they were combined to create an interpolated 3D volume of signal strength (higher signals equating to strong reflections). The interpolation was done typically on a 10cm (horizontal) x 10cm (horizontal) x 3cm (depth) grid (for 800MHz survey the discretisation over depth is much less). The resultant 3D volume was then viewed in *ParaView*, allowing horizontal slices to be extracted. As signal weakens with depth a colour scale was uniquely assigned for each depth slice. It is, therefore, important to recognise that a colour for one slice does not necessarily equate to an equivalent signal strength on another slice.

Table A1: 3D GPR surveys at Lancaster Priory

Plot	**Survey date**	**Antenna frequency (MHz)**			**Dimensions (L x W in metres)**	**Survey direction**	**Notes**
		800	**500**	**250**			
A	20/12/2021		✓		14.4 x 13	W	Car park
A	12/01/2022	✓	✓	✓	14 x 13	L & W	Car park
B	20/12/2021		✓	✓	17 x 8	L	Grass cover
C	20/12/2021		✓	✓	37 x 2.4	L	Path
D	20/12/2021		✓	✓	30 x 2.4	L	Path
E	21/12/2021		✓		15 x 11.2	L	Grass
F	21/12/2021		✓		17 x 8	L	Grass
G	21/12/2021		✓		10 x 6.4	L	Grass
H	21/12/2021		✓		18 x 9.6	L	Grass/path mix
I	18/01/2022			✓	15 x 11.2	L	Similar to plot E
J	18/01/2022			✓	17 x 7.2	L	Similar to plot F
K	18/01/2022			✓	10 x 6.4	L	Similar to plot G
L	18/01/2022			✓	18 x 9.6	L	Similar to plot H
M	18/01/2022		✓	✓	6.5 x 5.6	L	Adjacent to excavation
N	02/02/2022			✓	26 x 22.4	L	Grass
O	02/02/2022			✓	18 x 15.2	L	Grass
P	02/02/2022			✓	10 x 9.6	L	Grass
Q	09/02/2022			✓	17.6 x 8	L & W	Part of I and K
R	09/02/2022			✓	20 x 5.6	L	Path

Table A2: 2D GPR transects at Lancaster Priory

Line	Survey date	Antenna frequency (MHz)			Length in metres	Notes
		500	250	100		
211221(71)	21/12/2021	✓			45	Adjacent to Priory wall
220222(01)	22/02/2022			✓	23	Grass
220222(02)	22/02/2022			✓	35	Grass
220222(03)	22/02/2022			✓	28	Grass, across slope
220222(04)	22/02/2022			✓	30	Grass, downslope
220222(05)	22/02/2022			✓	50	Grass, across slope
220222(06)	22/02/2022			✓	35	Grass, across slope
220222(07)	22/02/2022			✓	40	Grass, across slope
220222(08)	22/02/2022			✓	28	Grass, downslope
220222(09)	22/02/2022			✓	31	Grass, upslope
220222(10)	22/02/2022			✓	30	Grass, downslope
220222(11)	22/02/2022			✓	65	Grass, downslope
220222(12)	22/02/2022			✓	77	Extended reverse of 220222(11)
220209(90)	09/02/2022		✓		76	Grass, downslope
220209(91)	09/02/2022		✓		81	Extended reverse of 220209(90)
220718(01)	18/07/2022		✓		145	Grass, downslope
220718(02)	18/07/2022		✓		145	Reverse of 220718(01)
220718(03)	18/07/2022		✓		146	Grass, downslope
220718(04)	18/07/2022		✓		146	Reverse of 220718(03)
220718(05)	18/07/2022		✓		68	Grass, downslope
220718(06)	18/07/2022		✓		67	Upslope

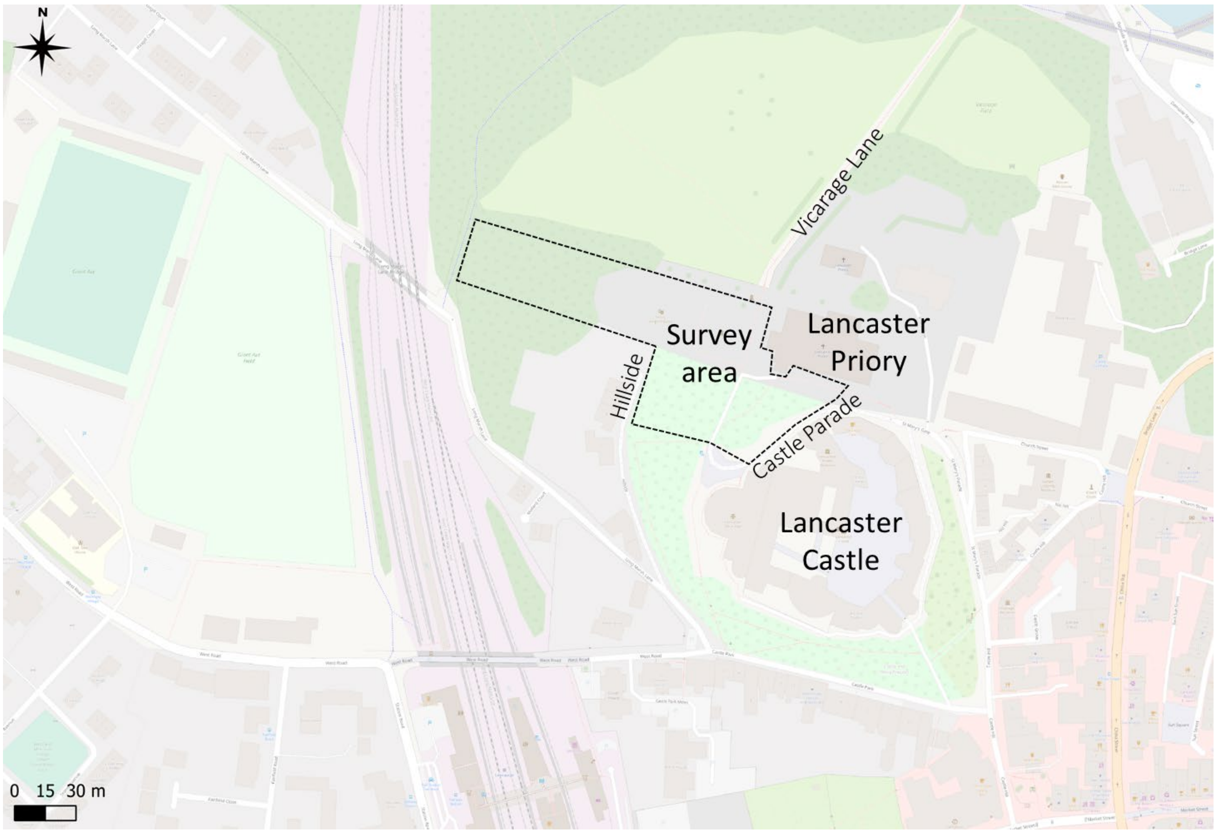


Figure 1: Survey areas.

(a) 800MHz PlotA
(b) 100MHz Transect 220222(12)
(c) 250MHz PlotR
(d) 500MHz PlotD
(e) 250MHz PlotB
(f) 500MHz PlotM
(g) 250MHz PlotN

Figure 2: Example photographs taken during surveys, illustrating different surface cover and conditions.

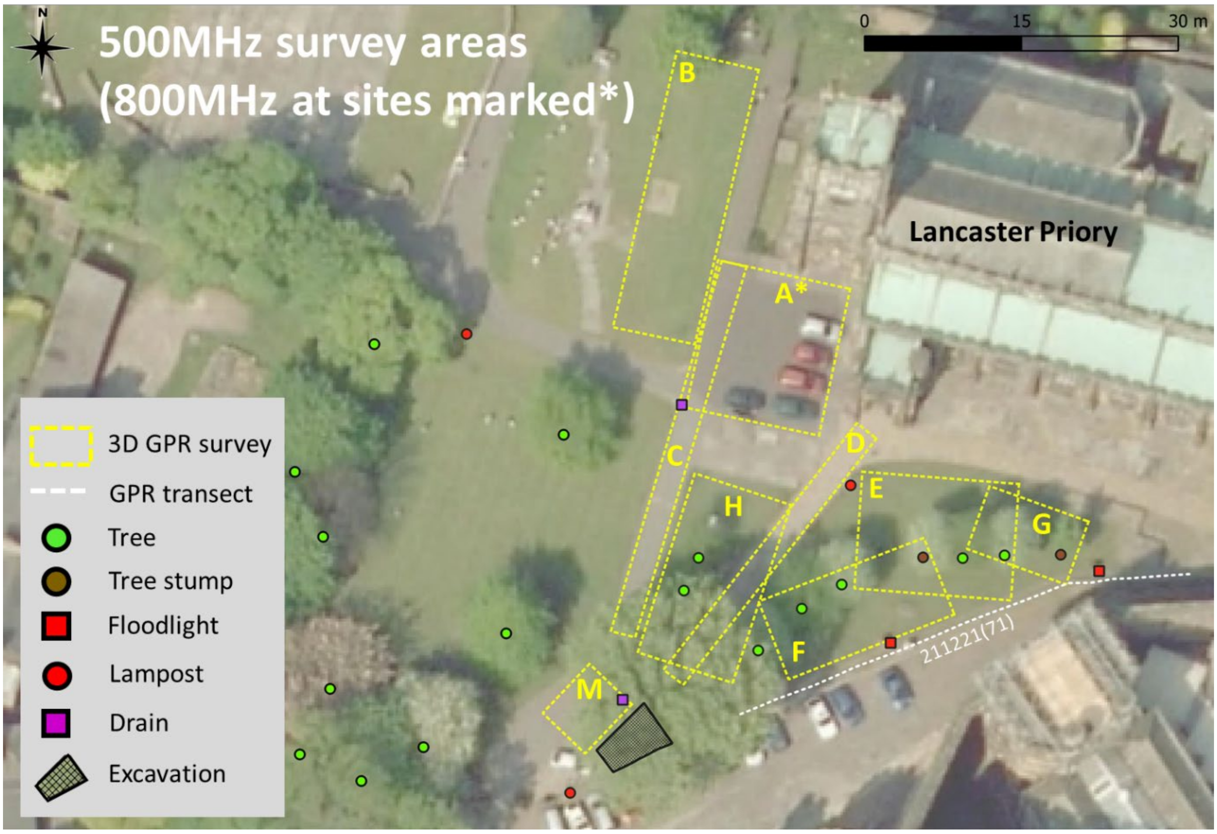


Figure 3: Coverage of 500MHz and 800MHz surveys.

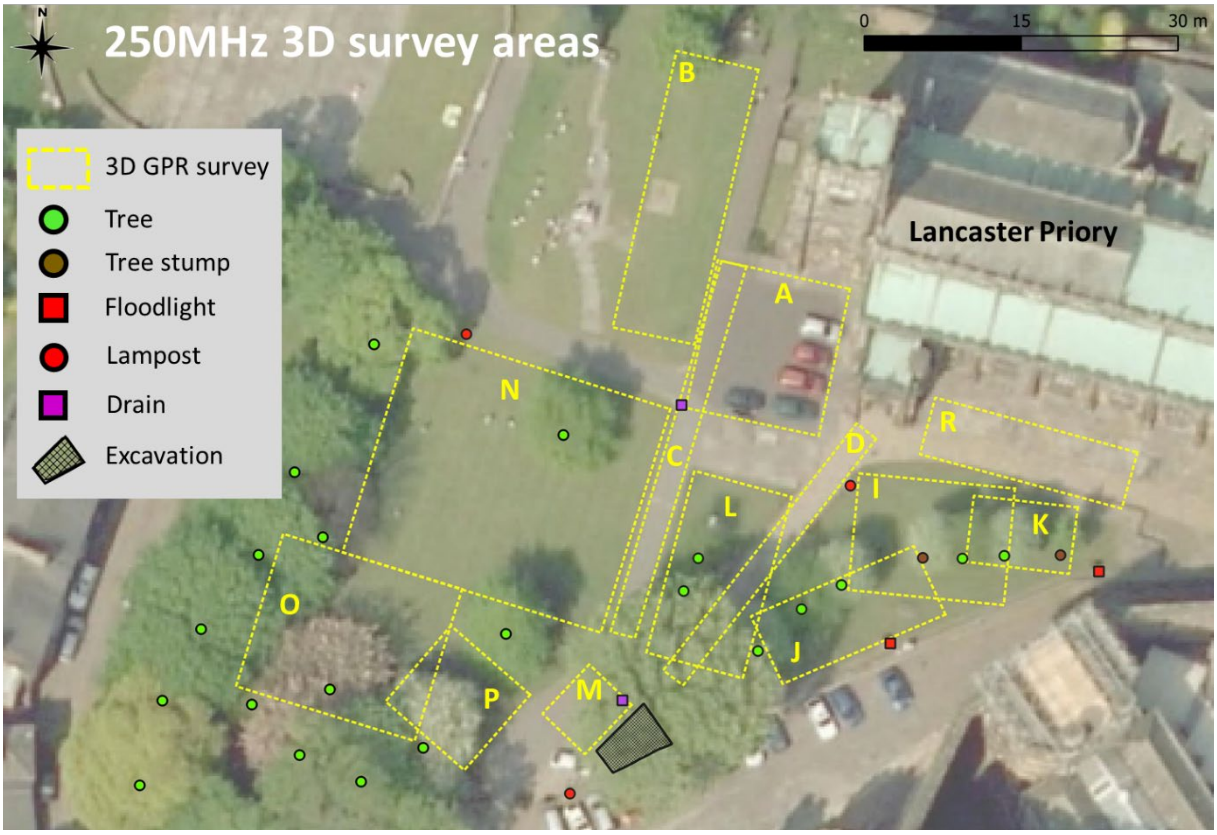


Figure 4: Coverage of 250MHz 3D surveys. An additional plot (plot Q) was also surveyed with 250MHz antenna, covering parts of plots I and K (see Table A1).

Figure 5: Coverage of 250MHz 2D surveys.

Figure 6: Coverage of 100MHz 2D surveys.

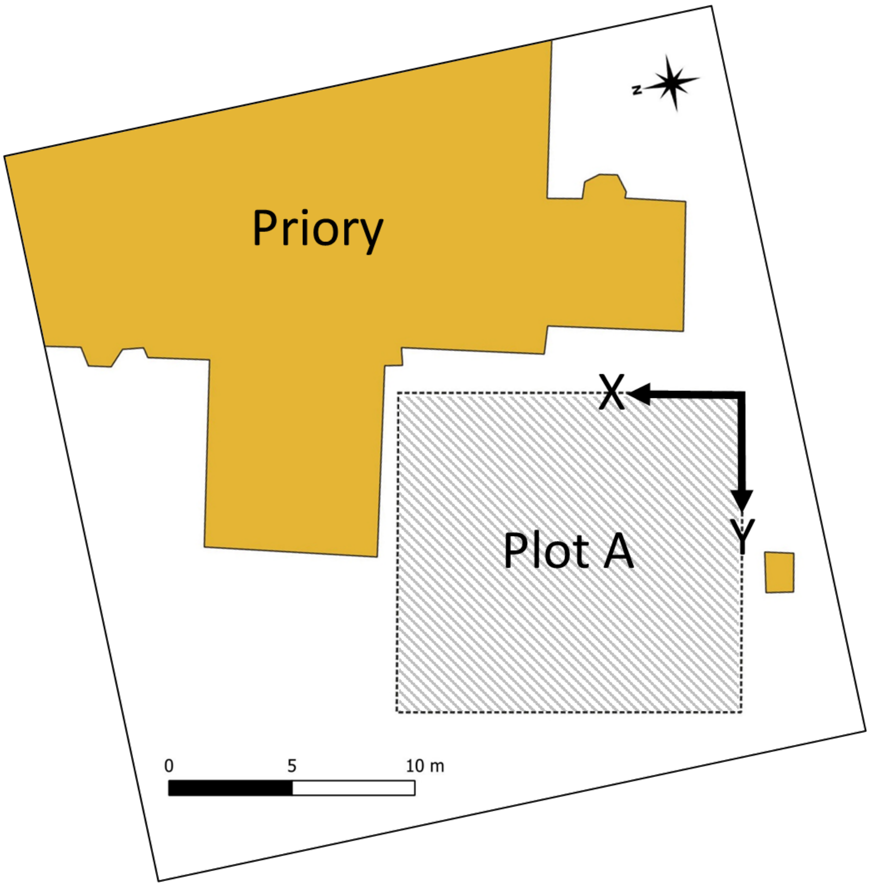


Figure 7: Layout of the Plot A surveys.

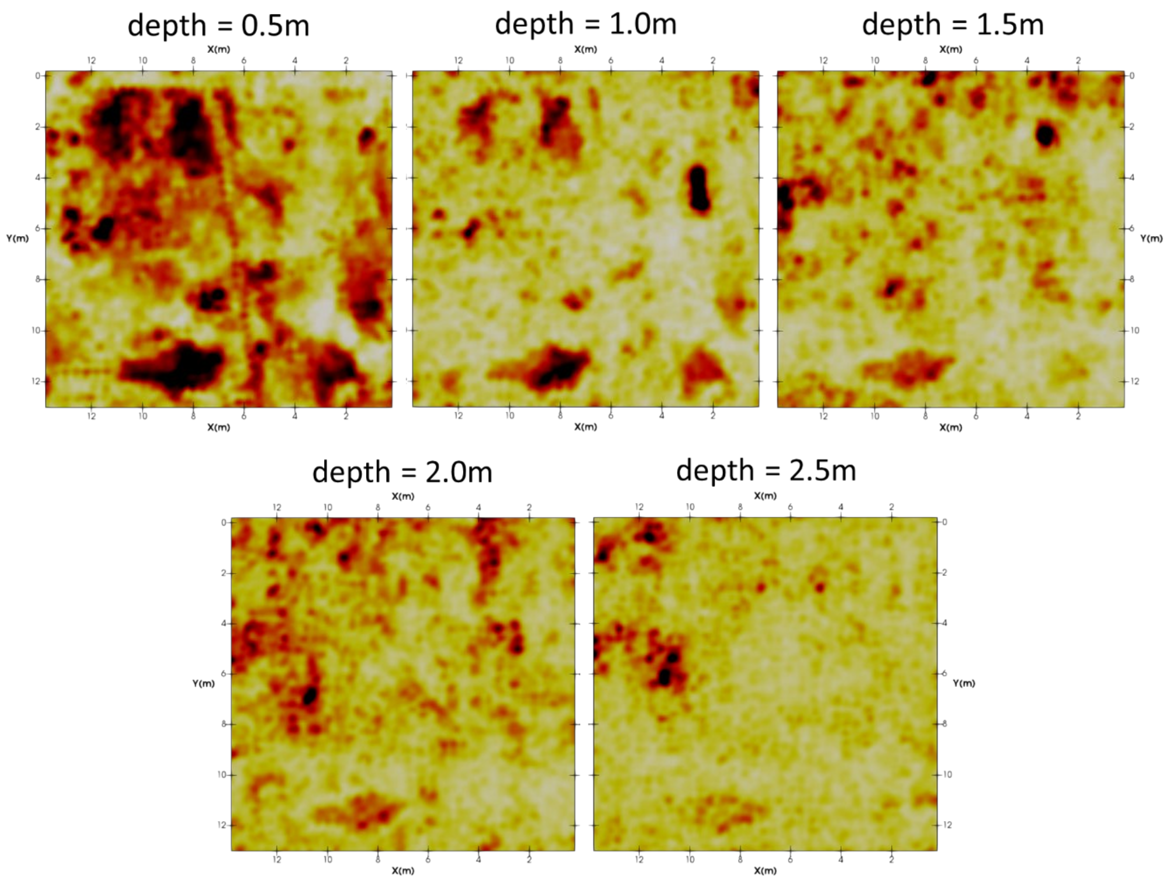


Figure 8: Example horizontal slices of 250MHz data from Plot A. Dark colours indicate reflections.

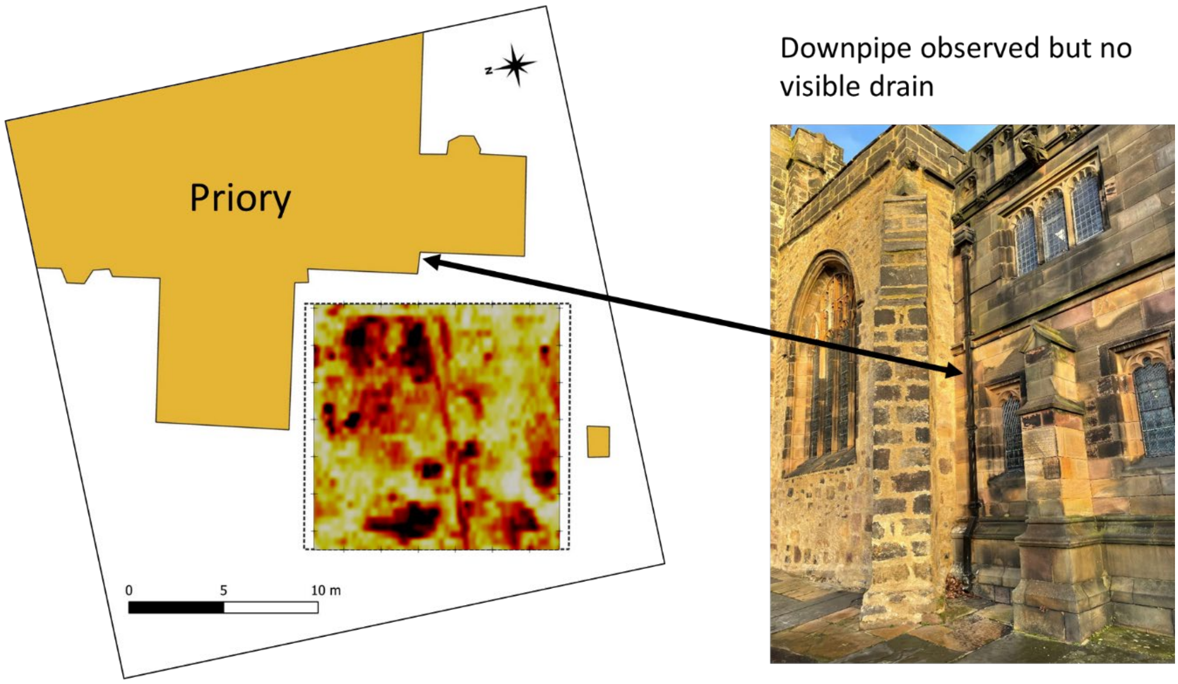


Figure 9: Linear anomaly in Plot A 250MHz horizonal slice at 0.5m depth in relation to existing downpipe.

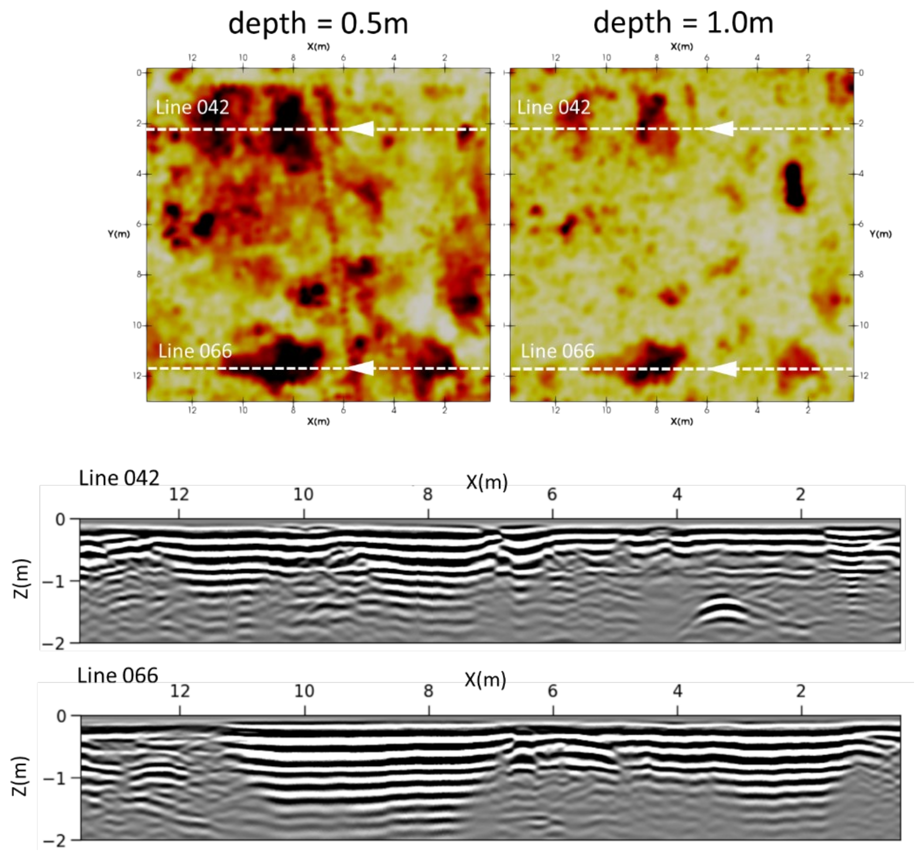


Figure 10: Evidence of 'ringing' behaviour in Plot A 250MHz surveys, illustrated by two individual transects.

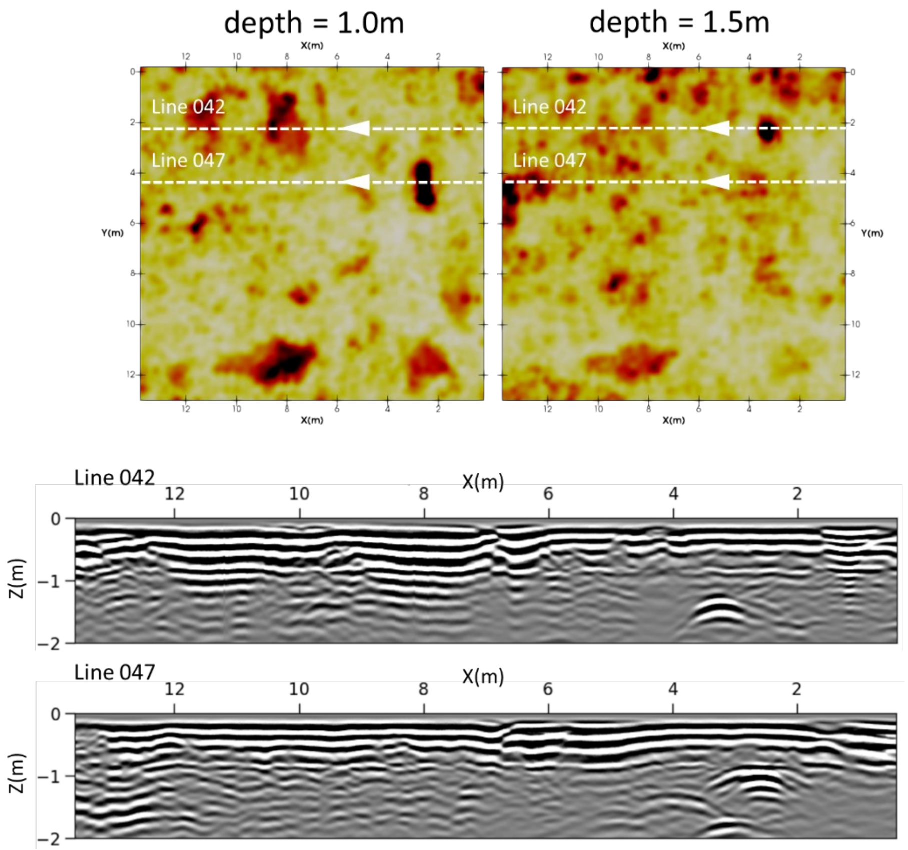


Figure 11: Illustration of localised reflection hyperbolae at depth (250MHz survey for Plot A)

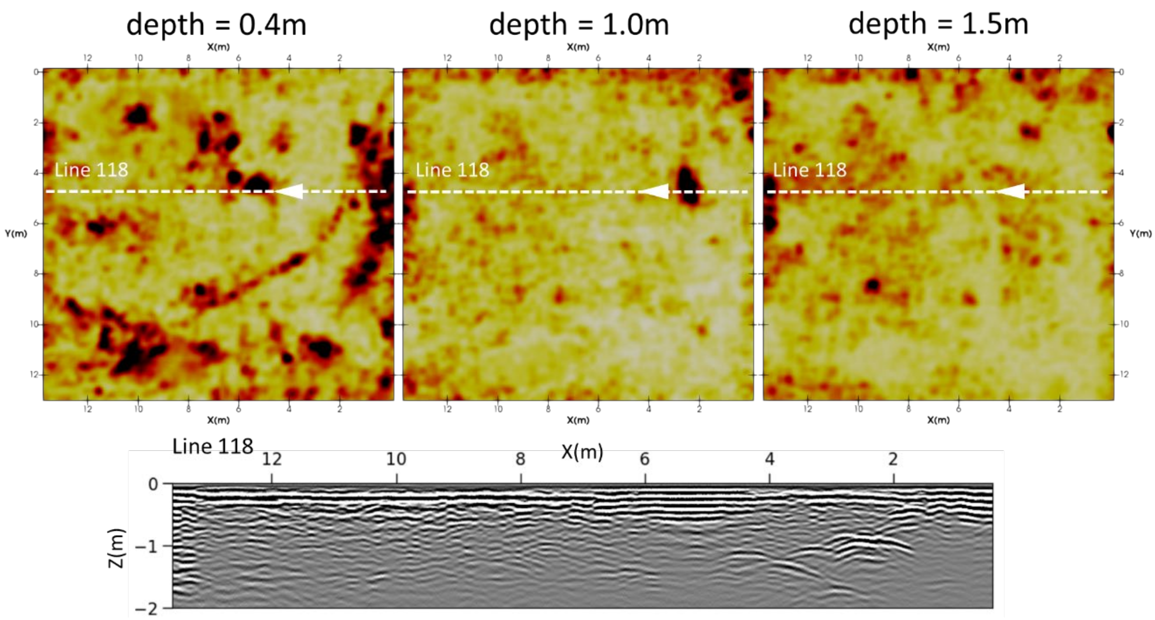


Figure 12: Selected horizontal slices of the 500MHz data, along with an example GPR transect.

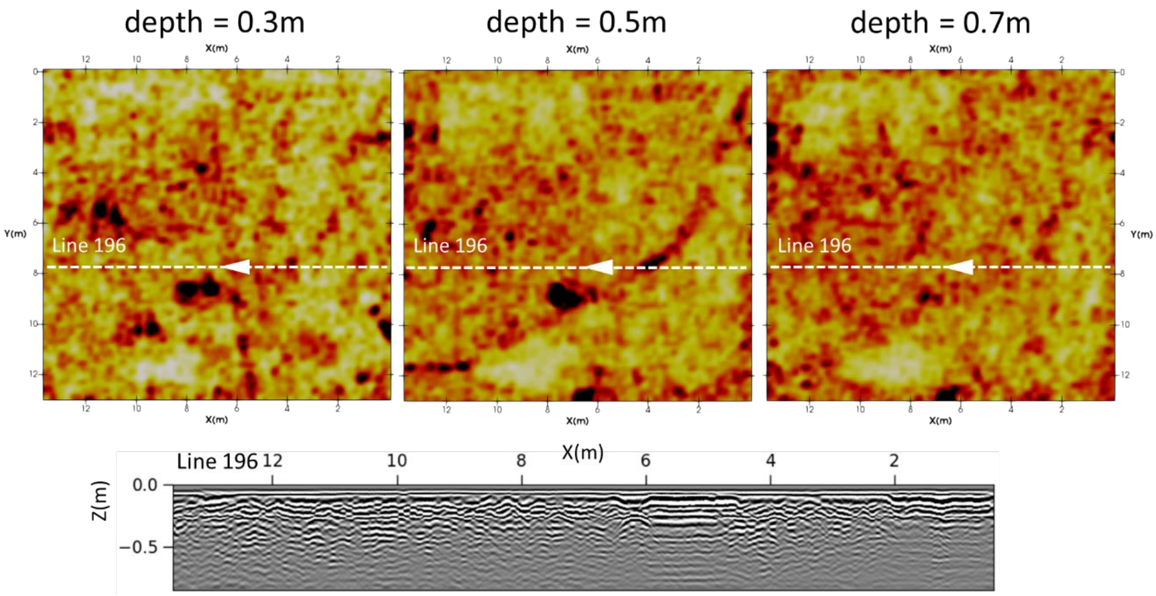


Figure 13: Selected horizontal slices of the 800MHz data, along with an example GPR transect.

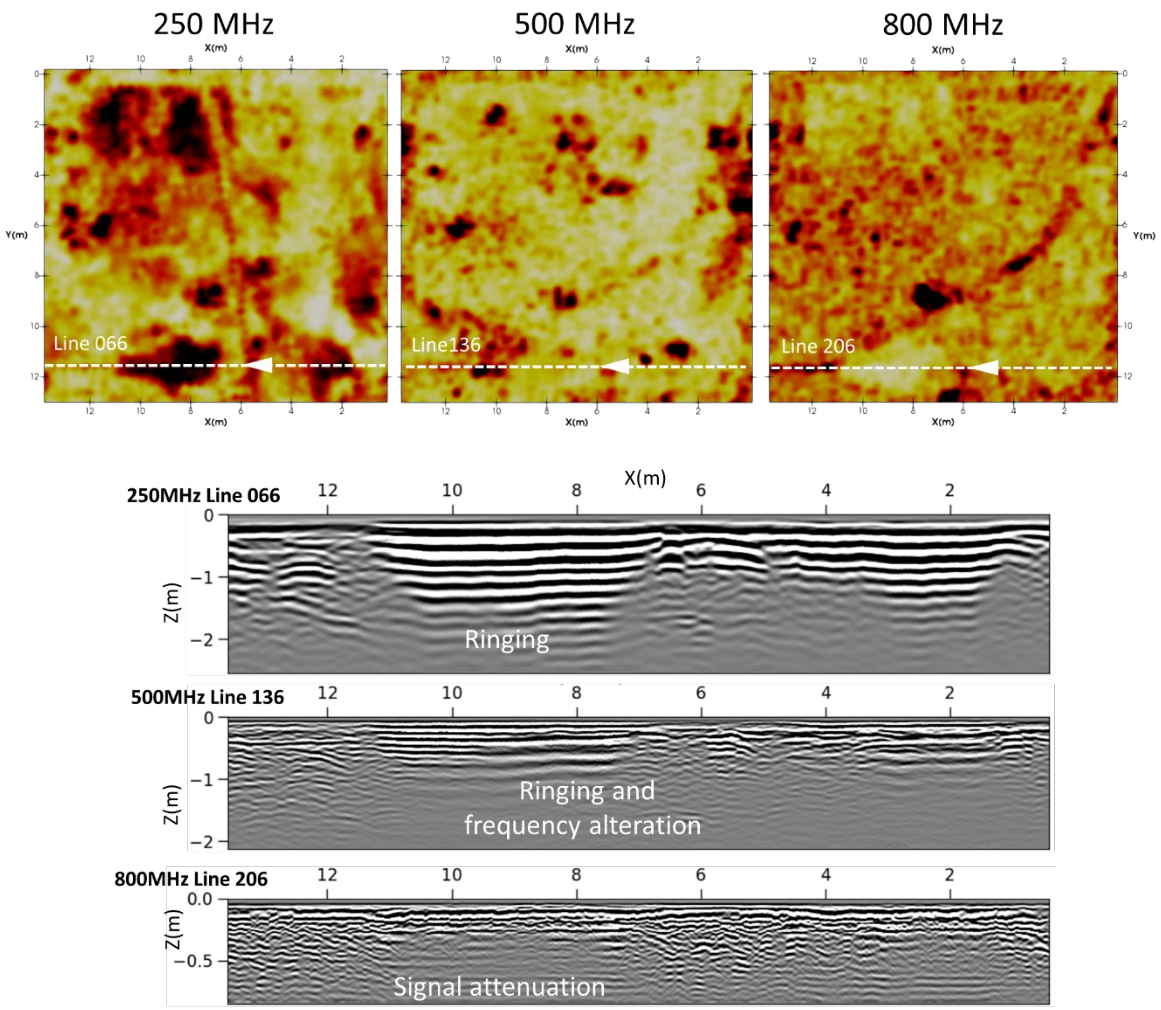


Figure 14: Comparison of 250MHz, 500MHz and 800MHz data. Upper image shows horizontal slice at 0.5m depth. The lower images show an individual trace across the same line for the three antenna frequencies.

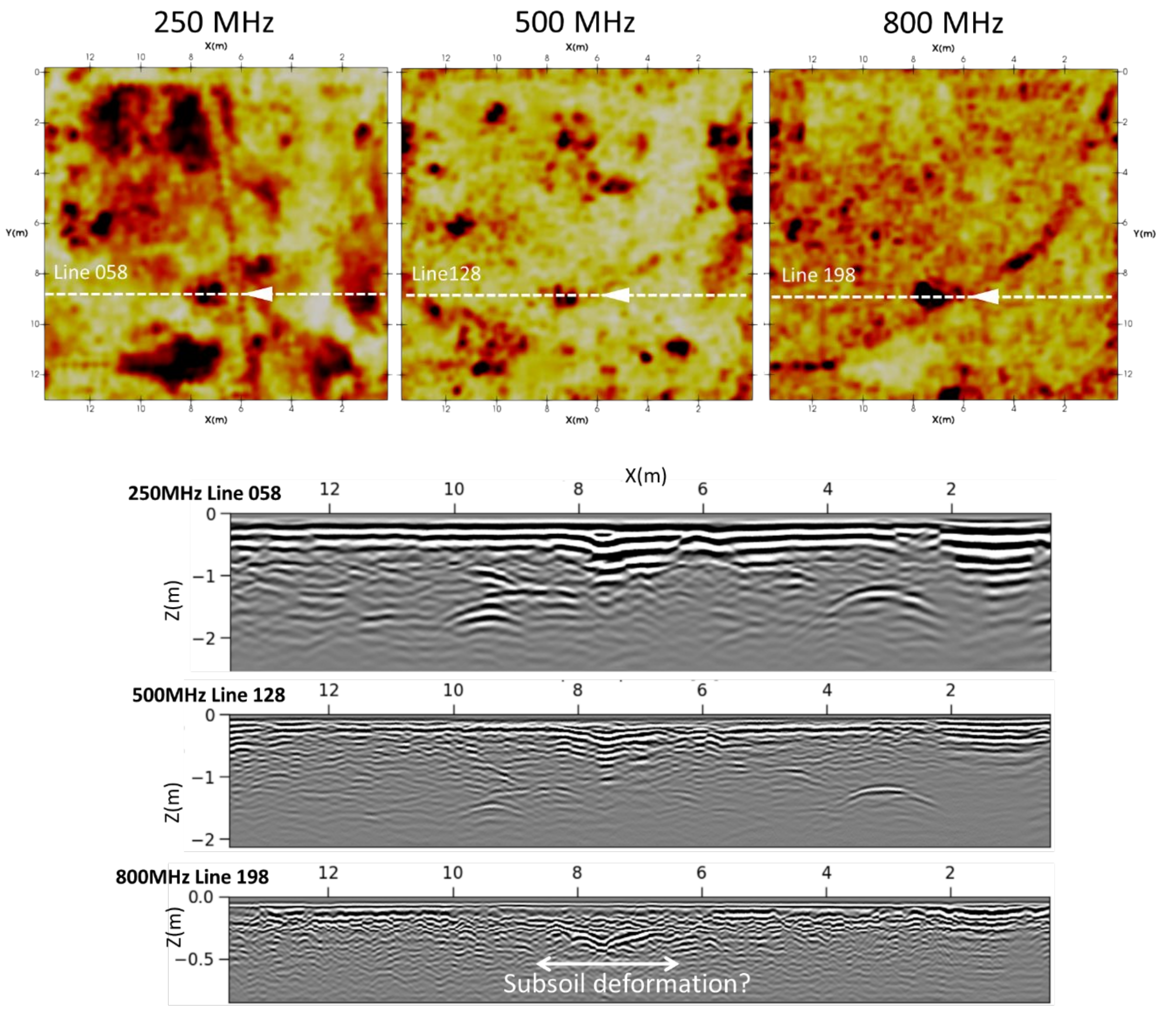


Figure 15: Comparison of 250MHz, 500MHz and 800MHz data. Upper image shows horizontal slice at 0.5m depth. The lower images show an individual trace across the same line for the three antenna frequencies.

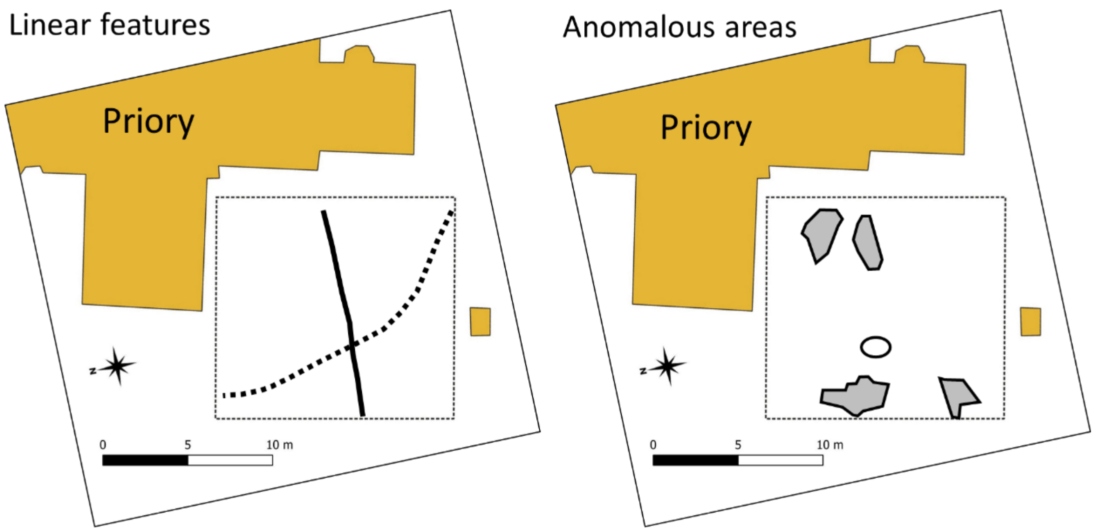


Figure 16: Summary of Plot A features. Left hand image shows linear features. Right hand image shows anomalous zones (grey filled indicate potentially electrically conductive shallow subsoil; white filled symbol shows area with potential subsoil deformation).

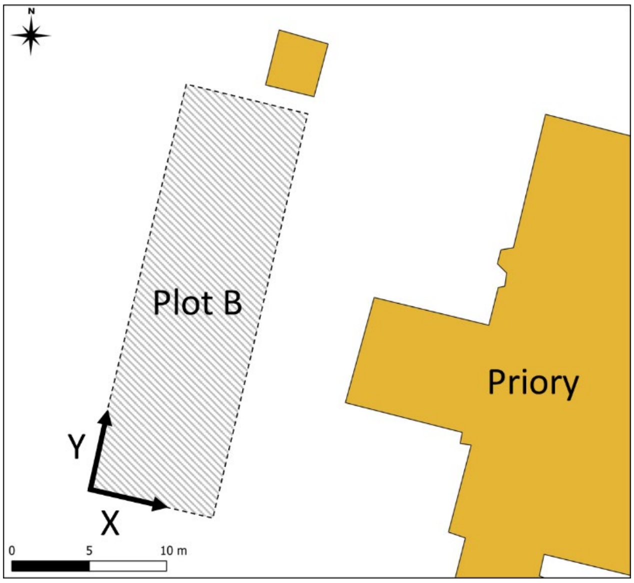


Figure 17: Location of Plot B surveys.

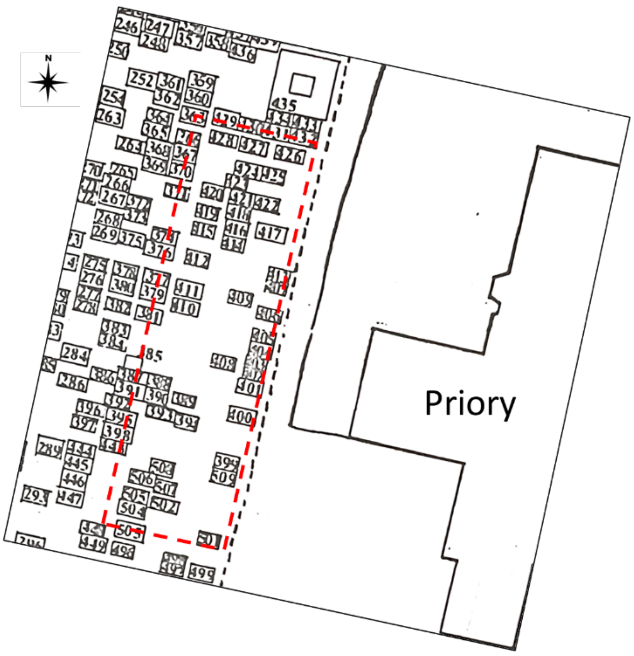


Figure 18: Location of Plot B surveys (red dashed line) and recorded grave sites.

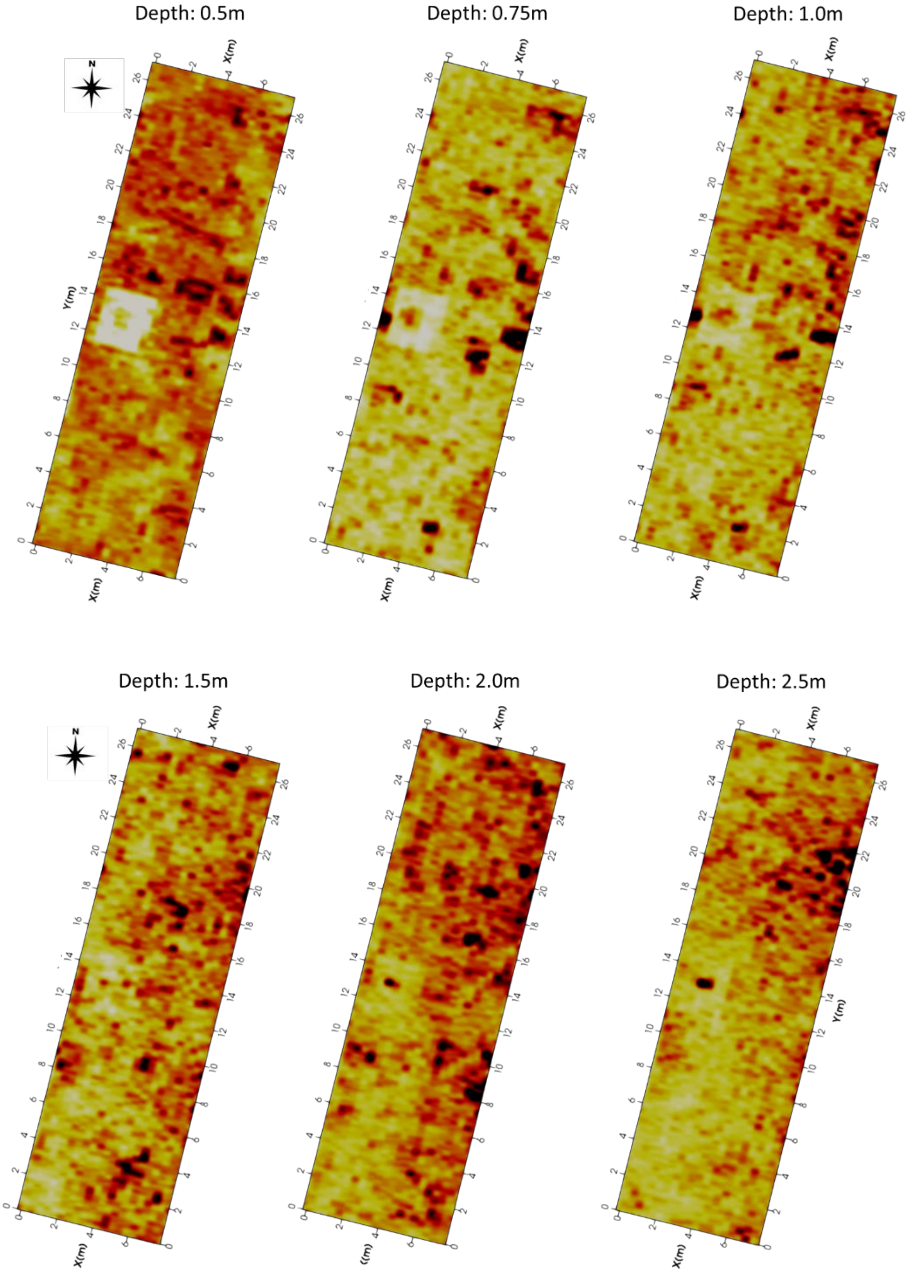


Figure 19: Example horizontal slices for the Plot B 250MHz data.

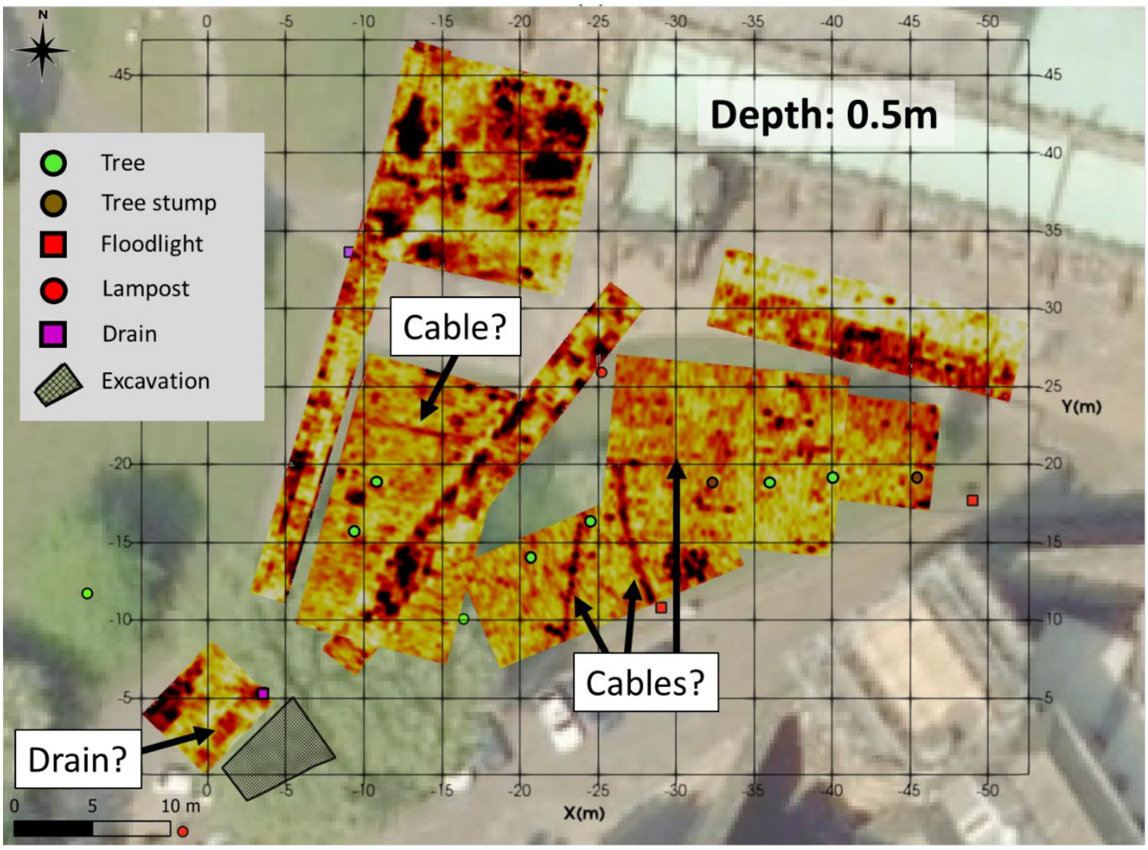


Figure 20: Southern churchyard 250MHz results, depth: 0.5m.

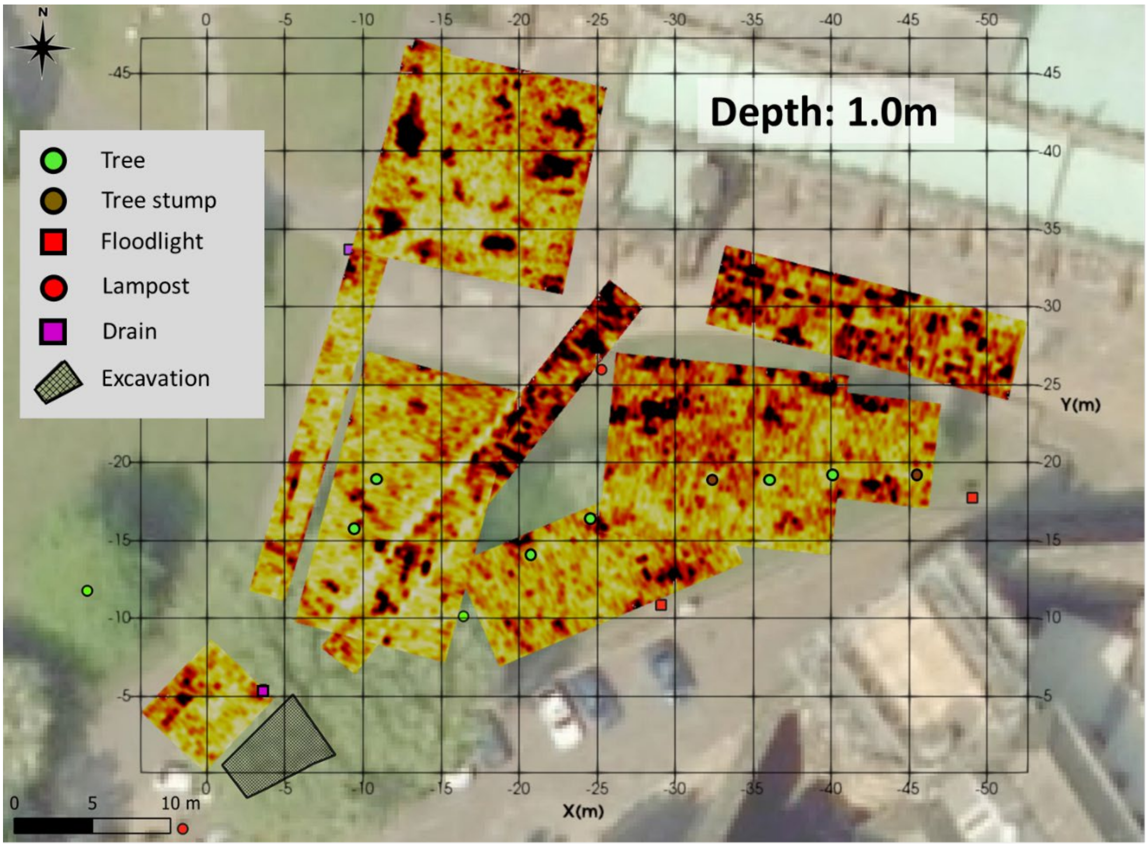


Figure 21: Southern churchyard 250MHz results, depth: 1.0m.

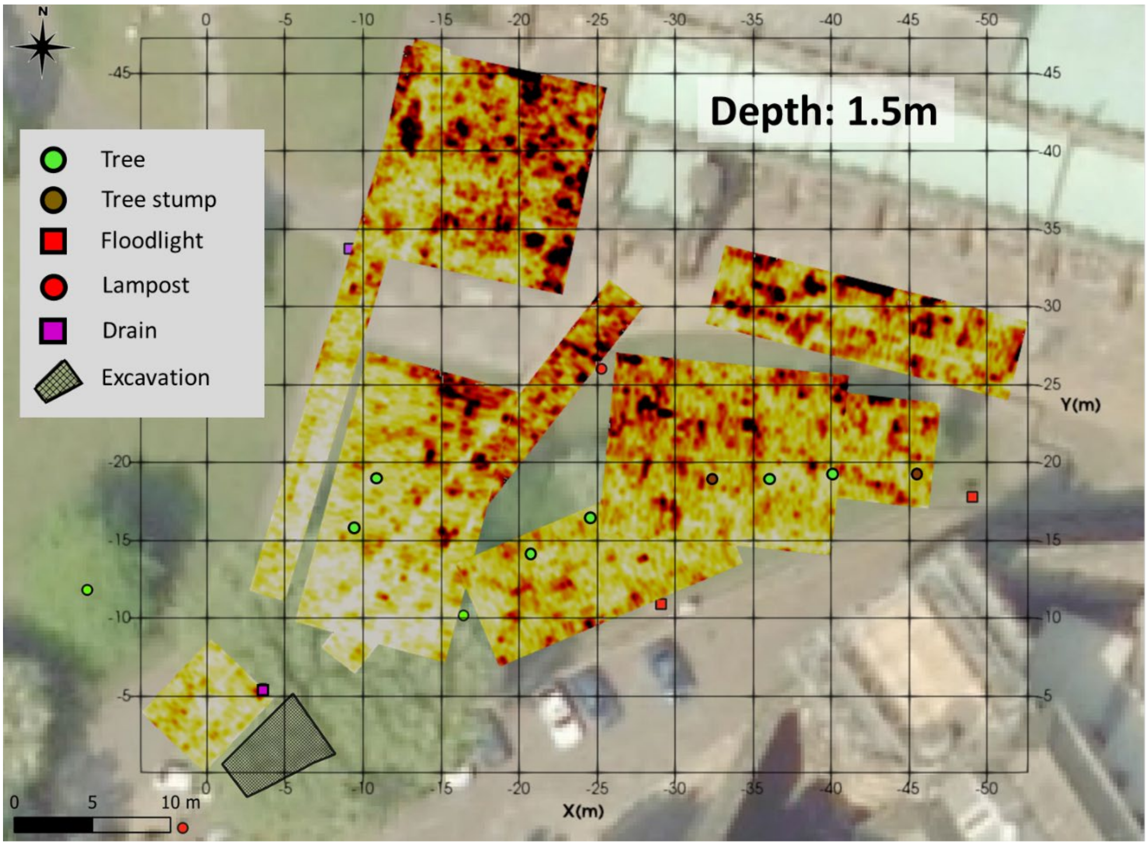


Figure 22: Southern churchyard 250MHz results, depth: 1.5m.

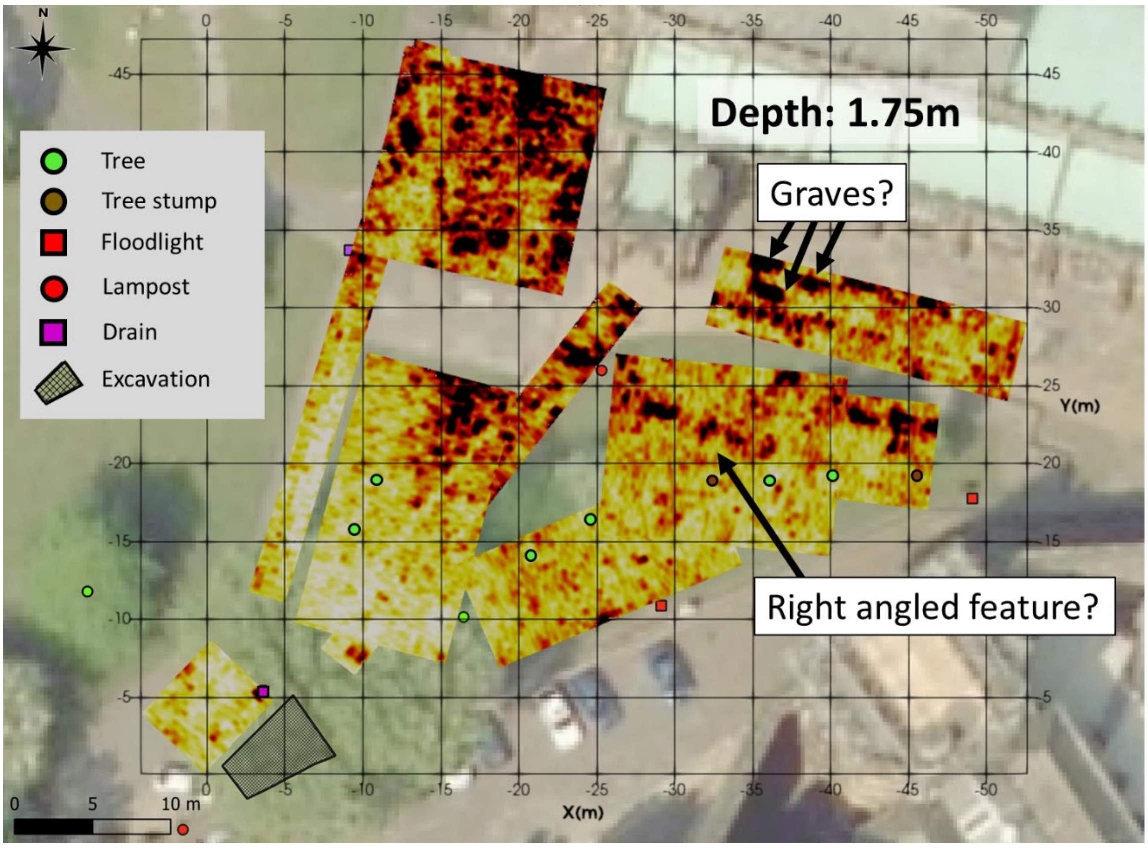


Figure 23: Southern churchyard 250MHz results, depth: 1.75m.

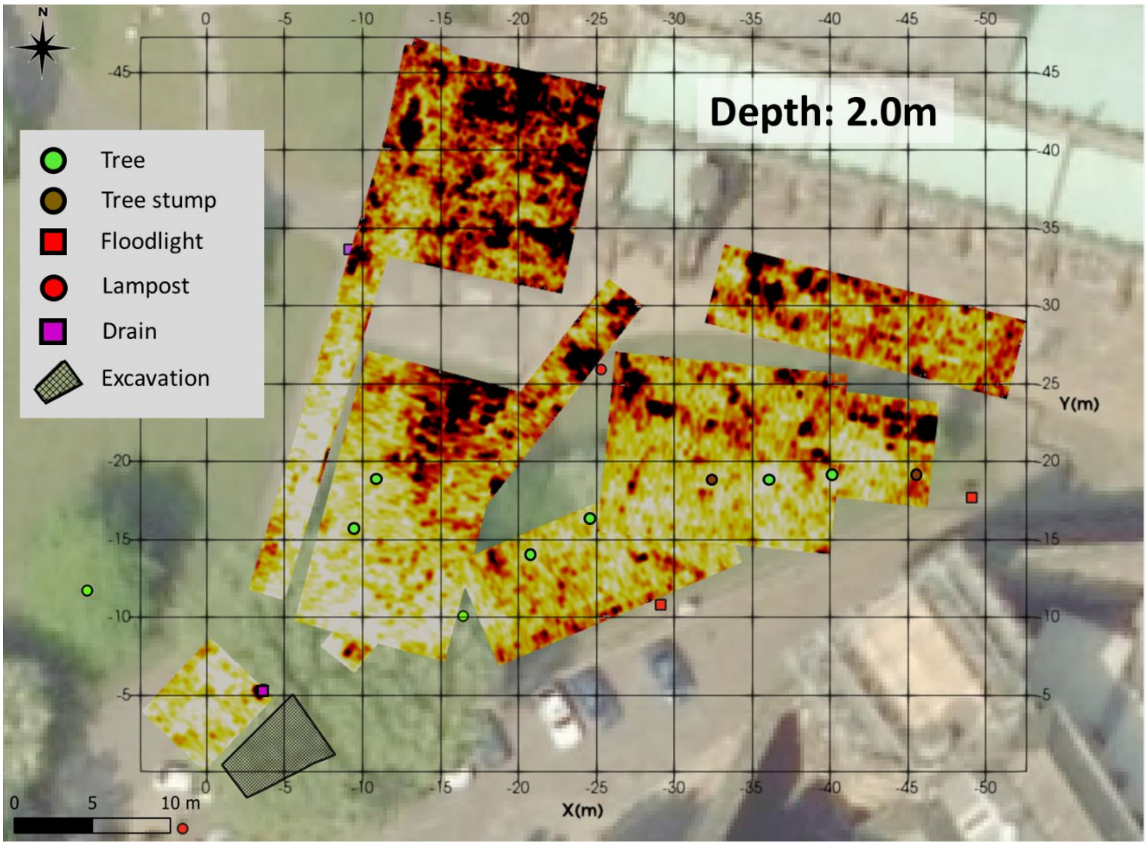


Figure 24: Southern churchyard 250MHz results, depth: 2.0m.

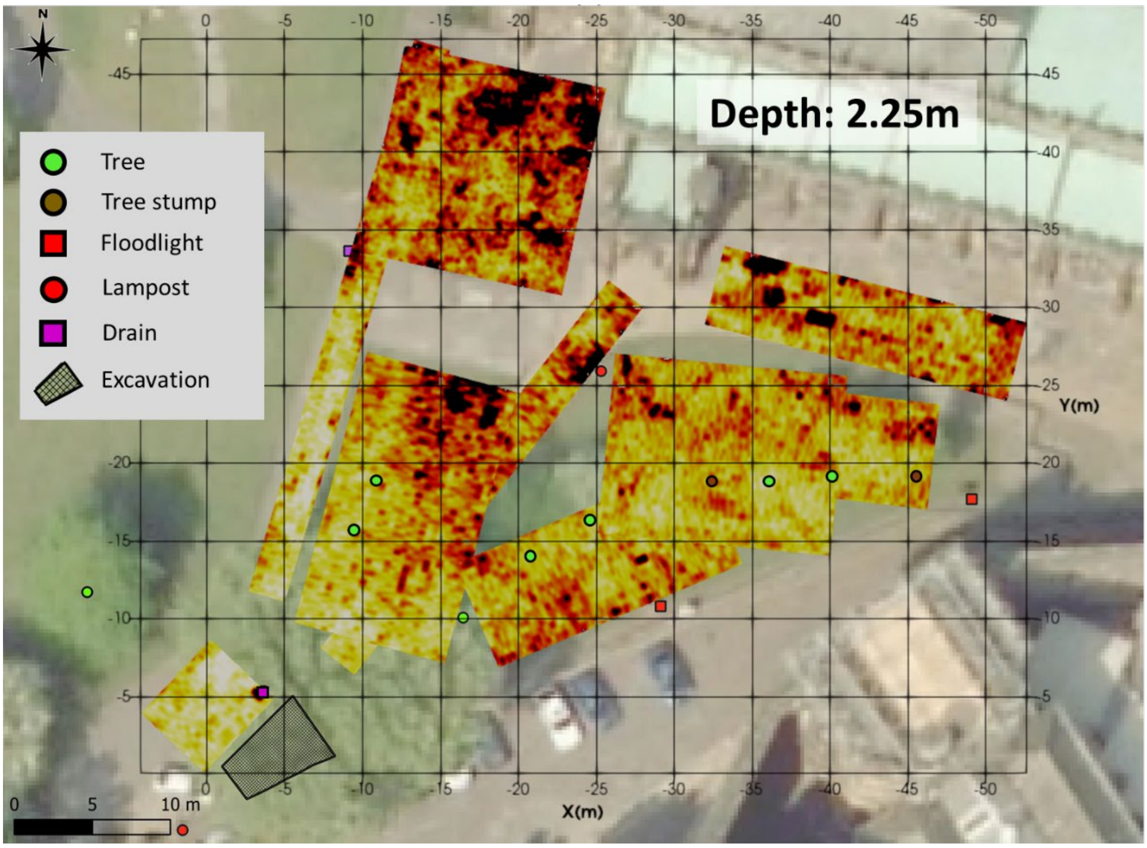


Figure 25: Southern churchyard 250MHz results, depth: 2.25m.

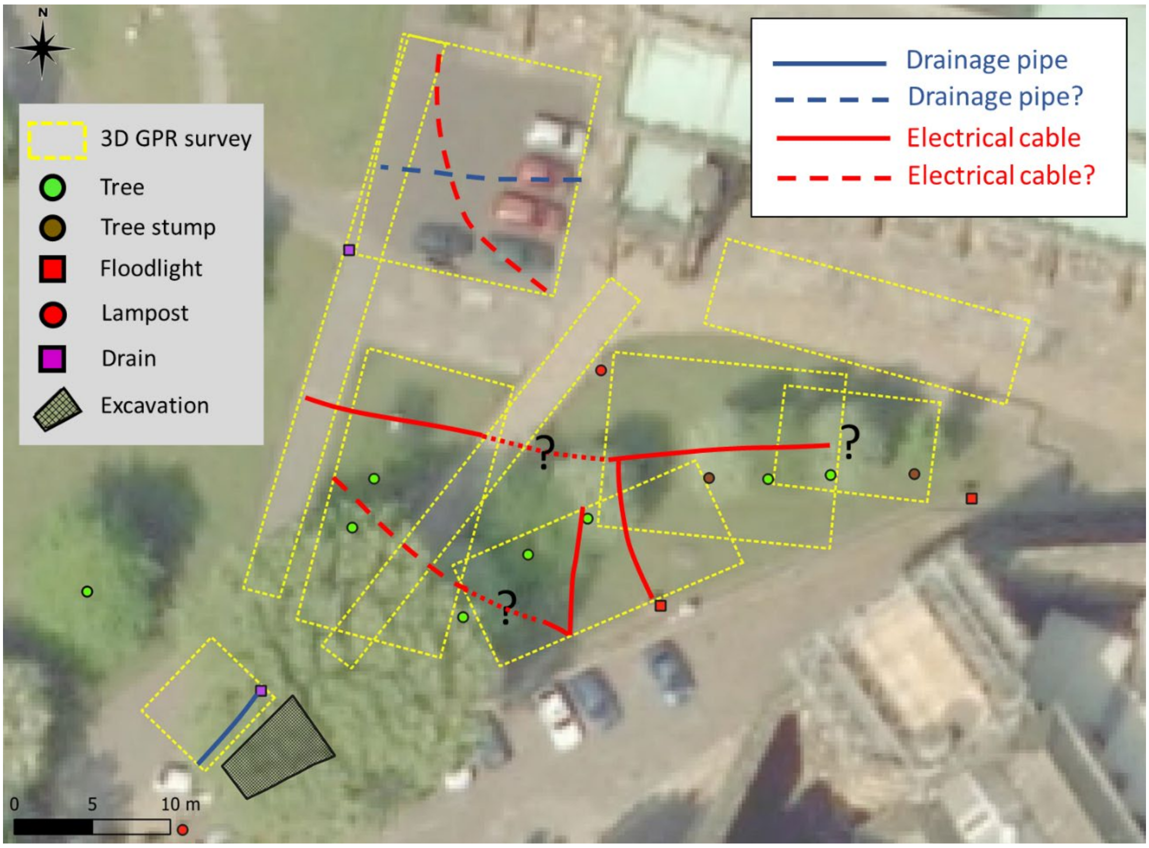


Figure 26: Interpreted possible underground services in the southern churchyard. A “?” marks areas where no shallow anomaly was detected but some continuation of the service is likely to be present.

Figure 27: Location of Plot Q.

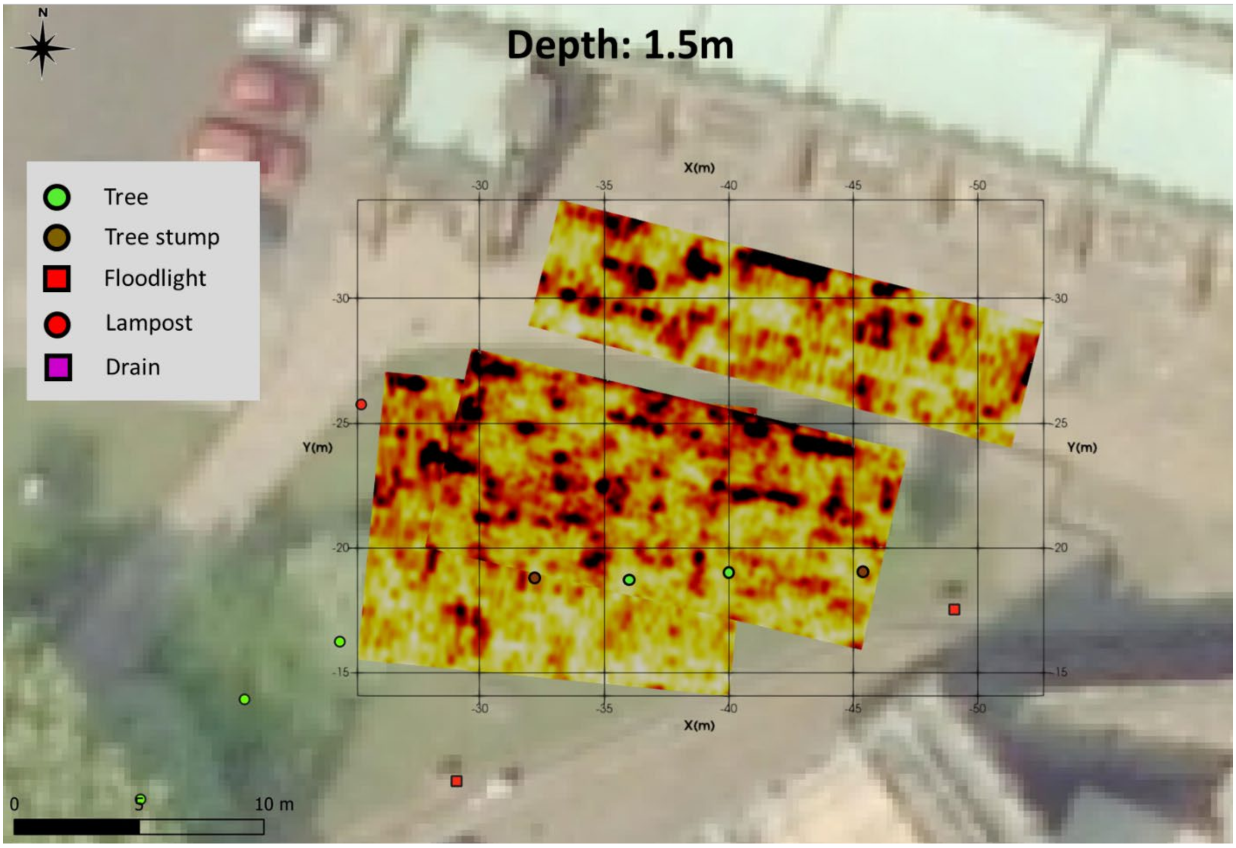


Figure 28: Horizonal slice of 250MHz data from Plots I, Q and R (depth: 1.5m).

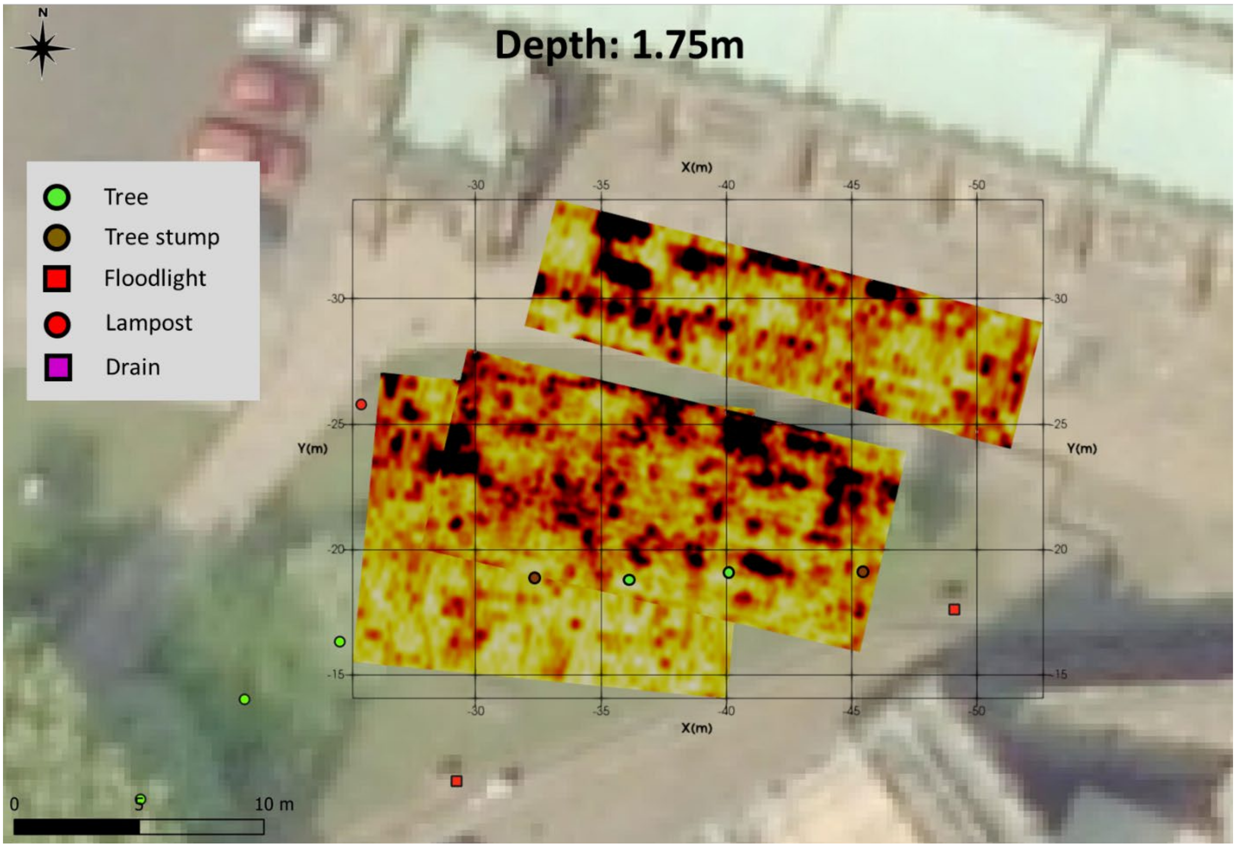


Figure 29: Horizonal slice of 250MHz data from Plots I, Q and R (depth: 1.75m).

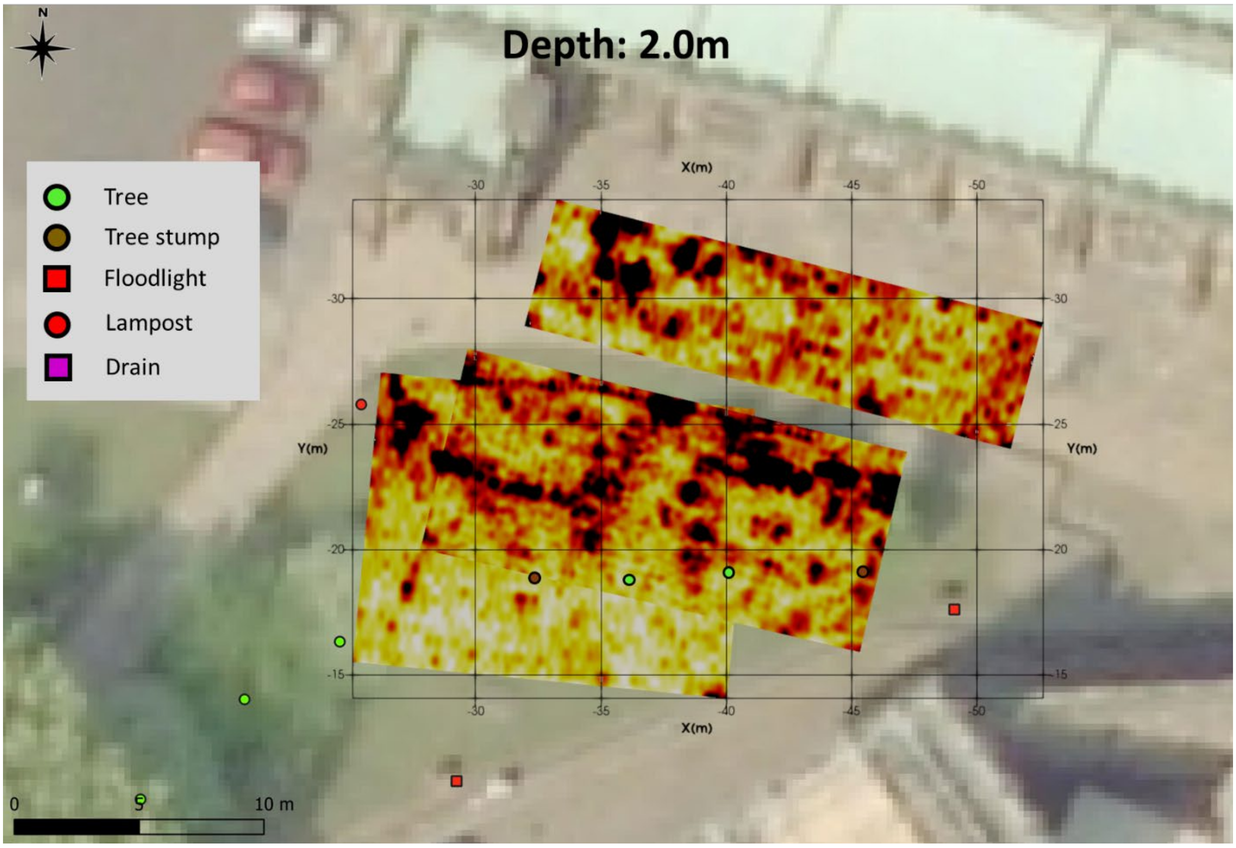


Figure 30: Horizonal slice of 250MHz data from Plots I, Q and R (depth: 2.0m).

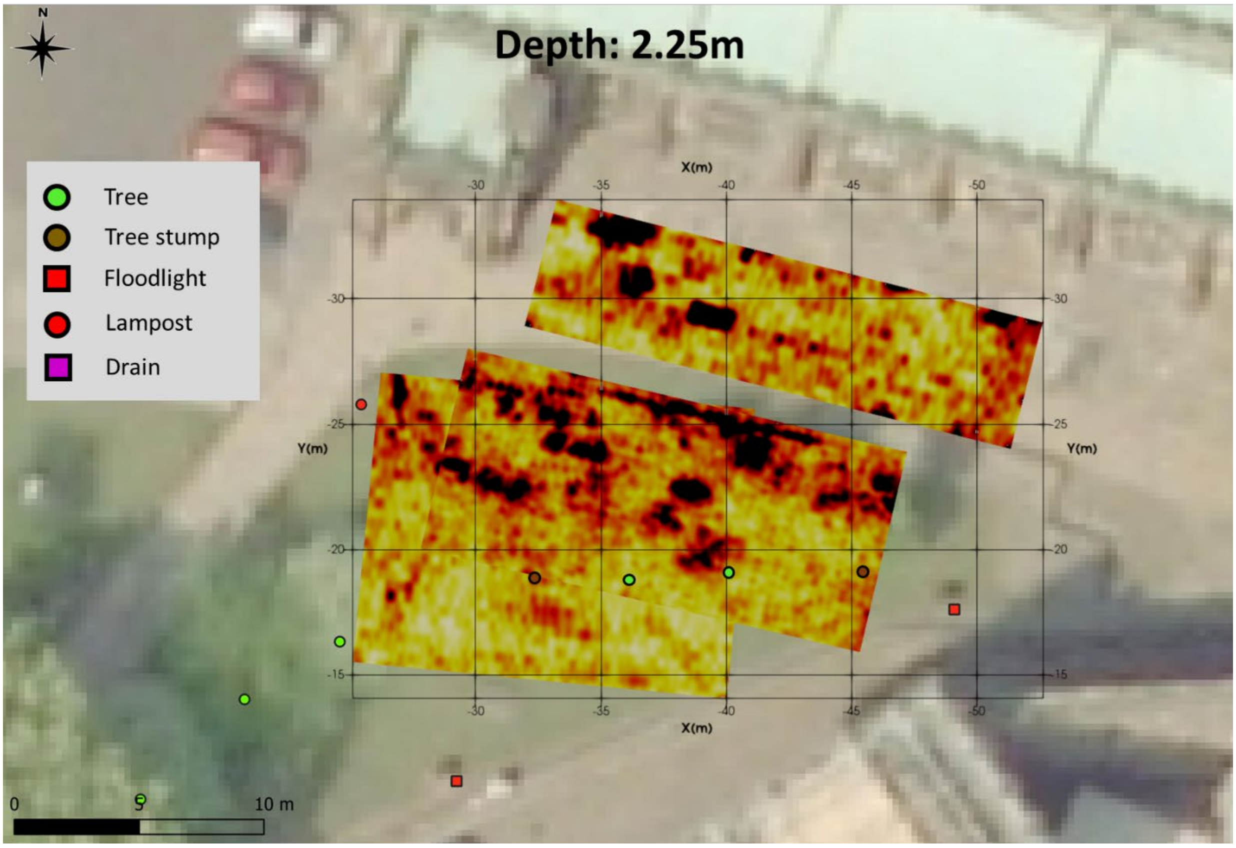


Figure 31: Horizonal slice of 250MHz data from Plots I, Q and R (depth: 2.25m).

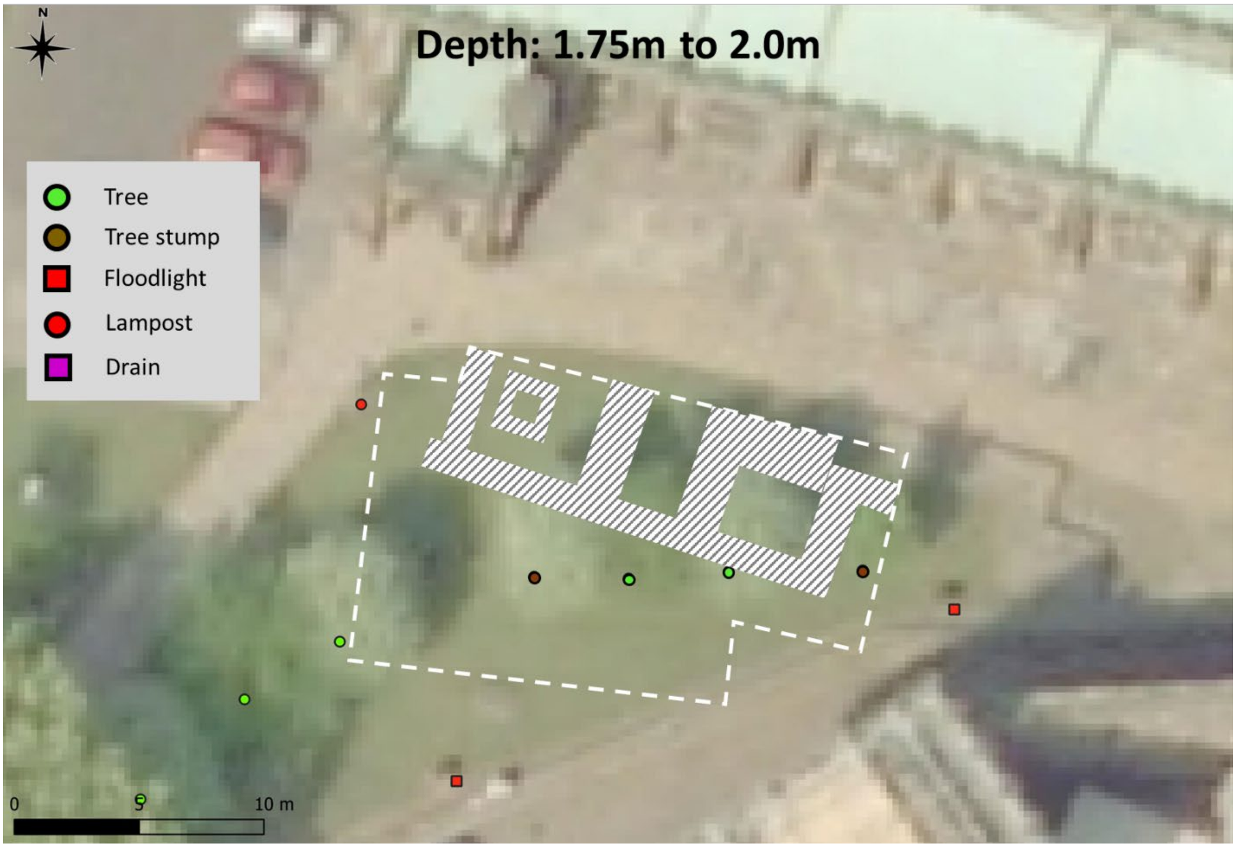


Figure 32: Interpretation of 250MHz surveys (Plots I and Q).

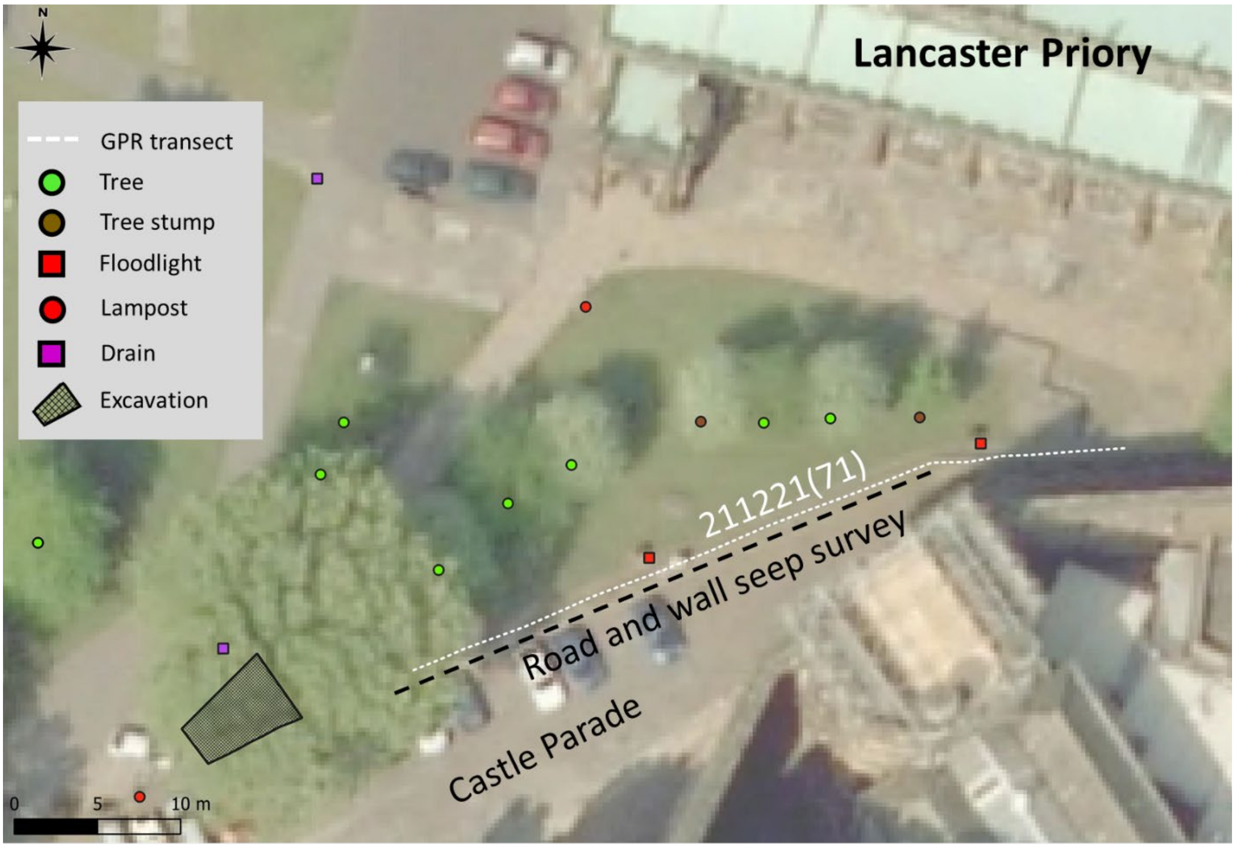


Figure 33: Southern wall survey location.

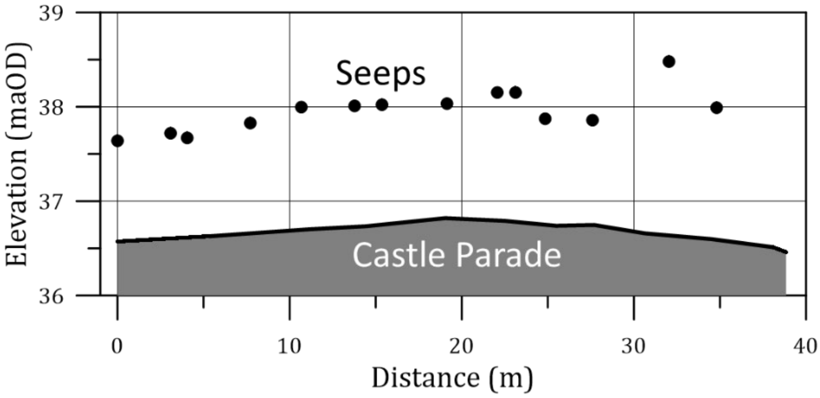


Figure 34: Water seep survey. Photograph taken 5 January 2022 and location of seeps surveyed 12 January 2022.

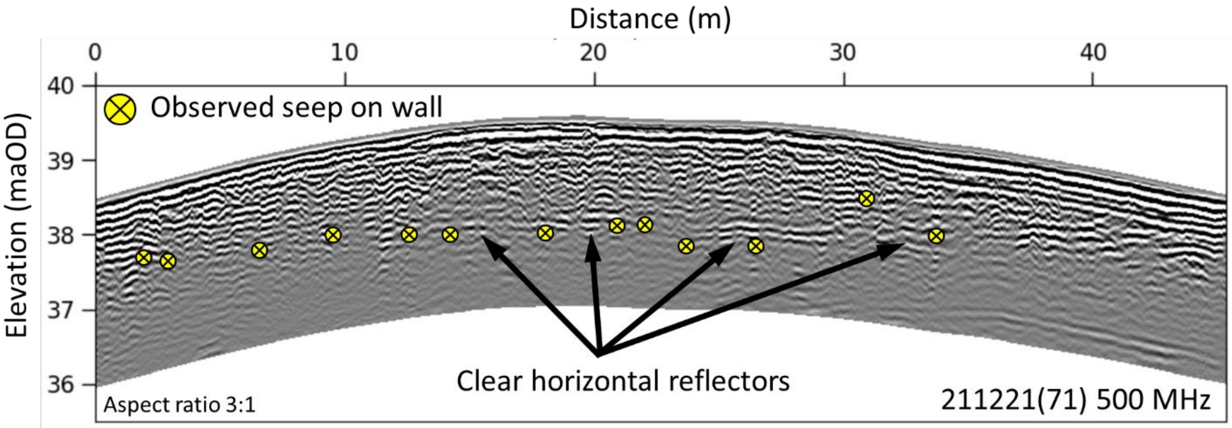


Figure 35: 500MHz GPR survey adjacent to the Castle Parade wall (within the churchyard).

Figure 36: Location of Plots N, O and P in southwest churchyard.

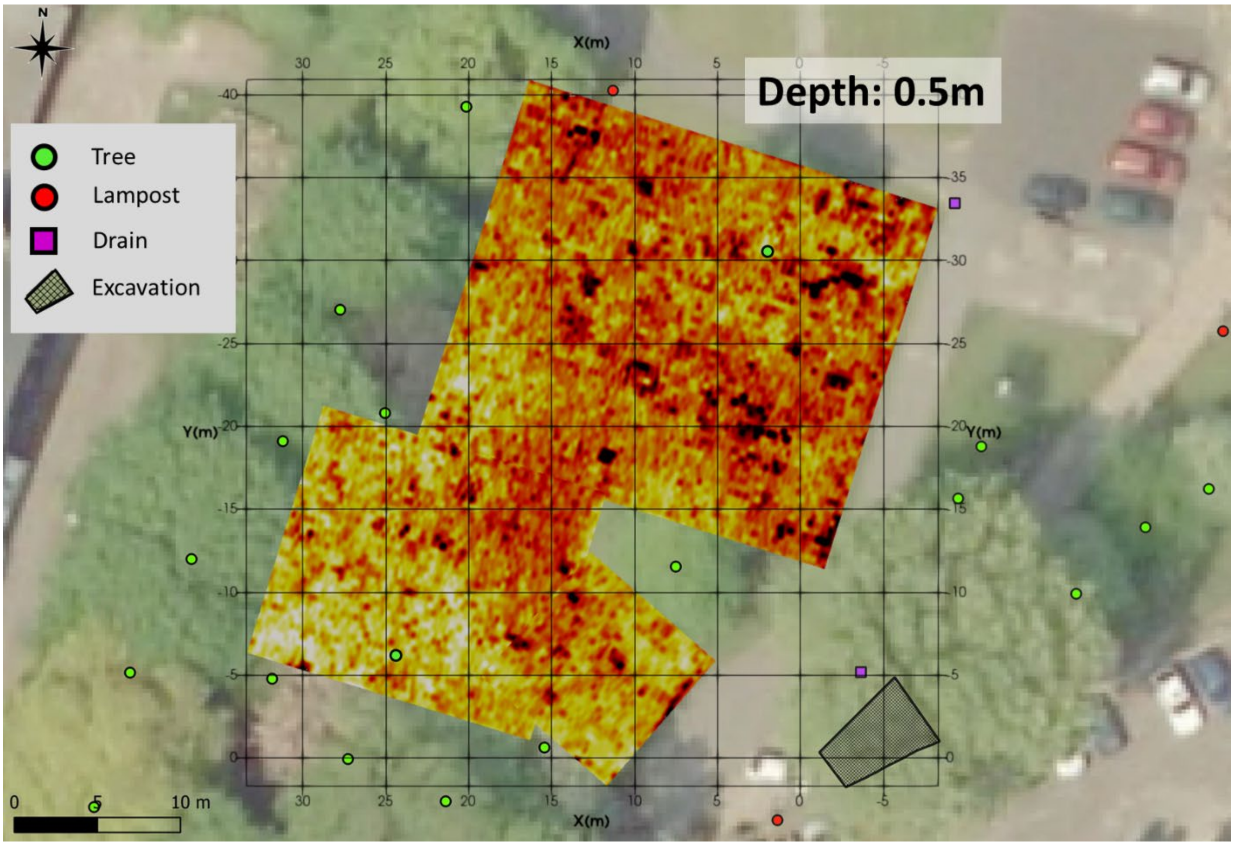


Figure 37: Horizontal slice at 0.5m from 250MHz data.

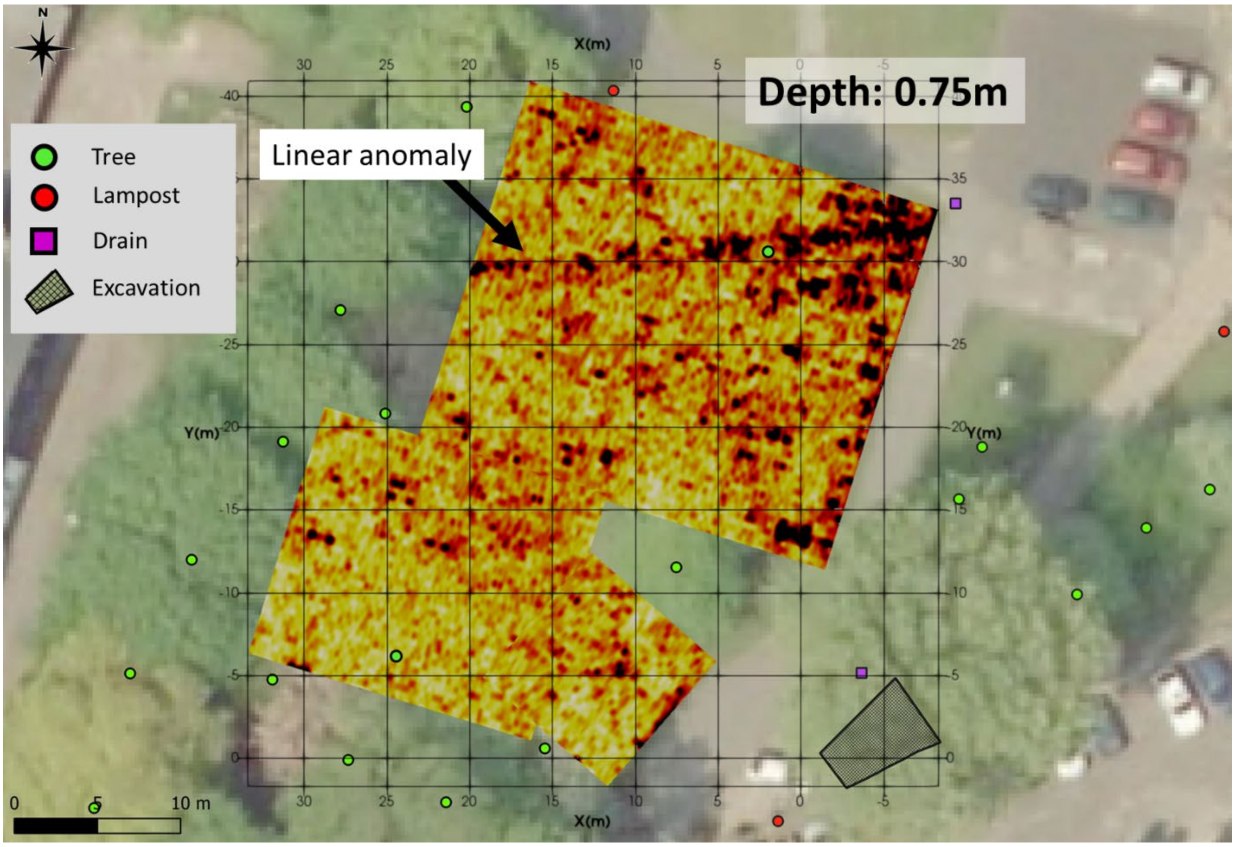


Figure 38: Horizontal slice at 0.75m from 250MHz data.

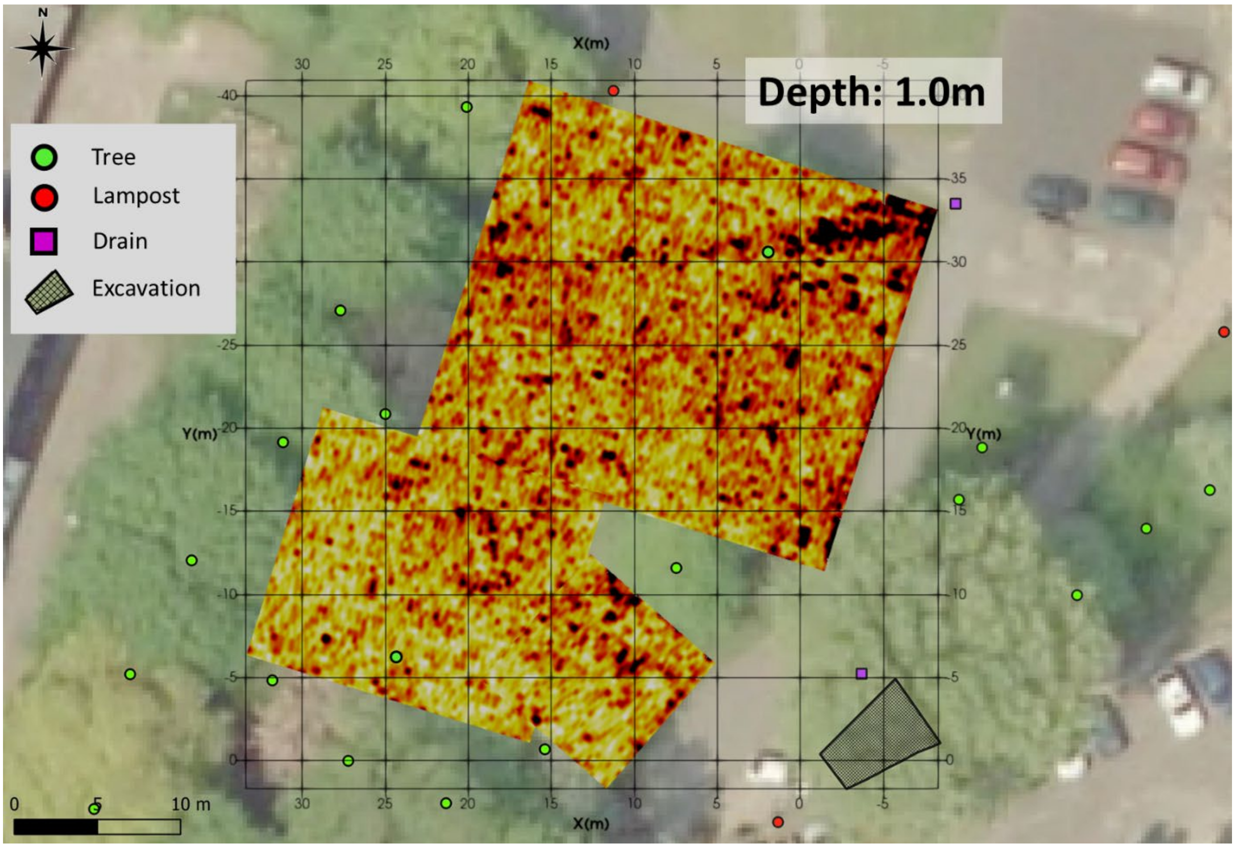


Figure 39: Horizontal slice at 1.0m from 250MHz data.

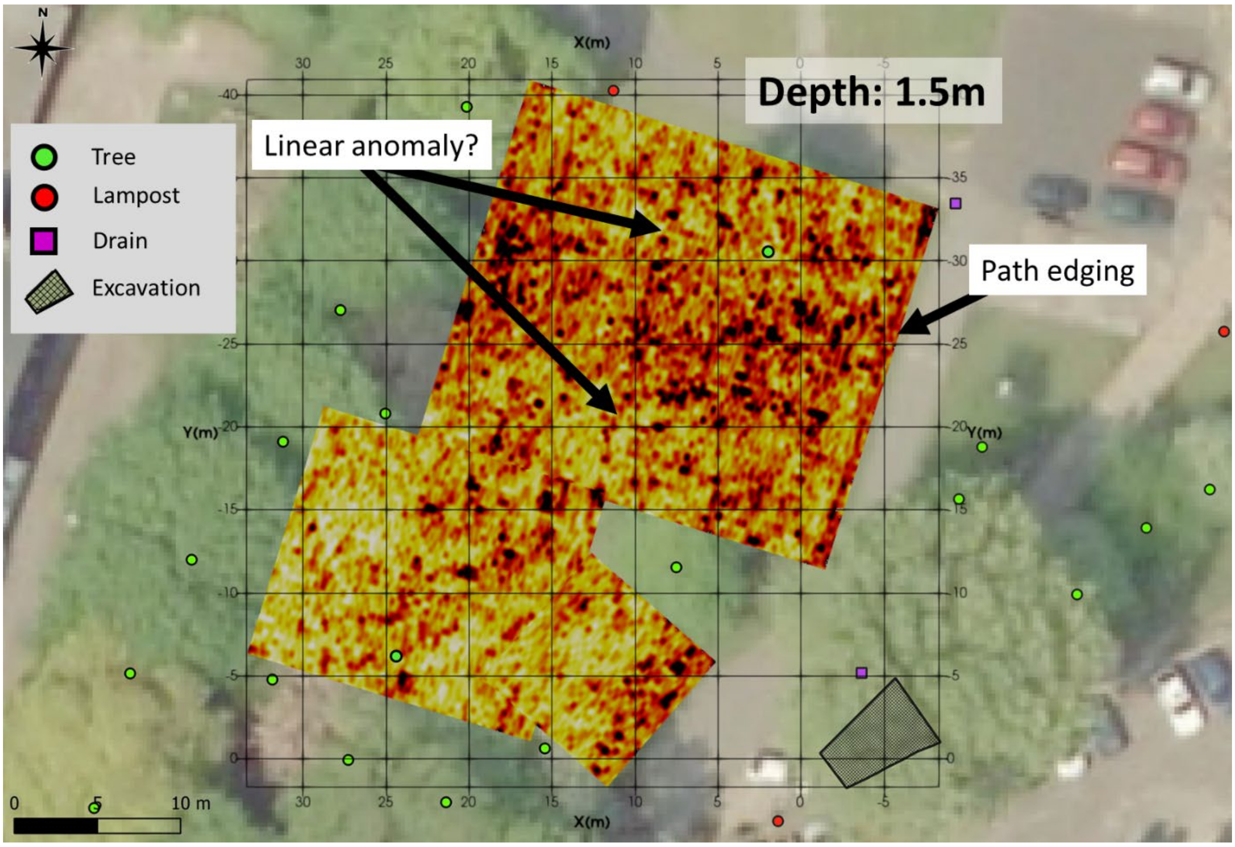


Figure 40: Horizontal slice at 1.5m from 250MHz data.

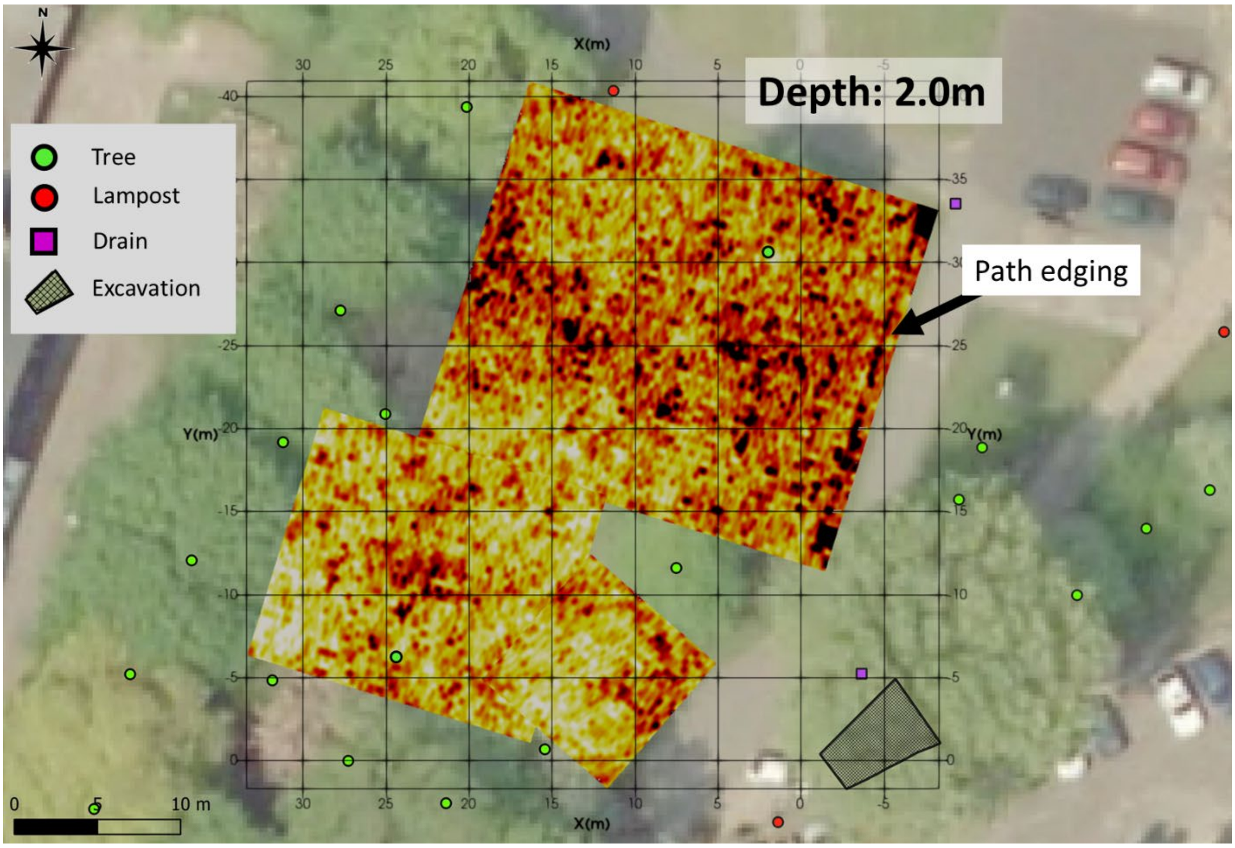


Figure 41: Horizontal slice at 2.0m from 250MHz data.

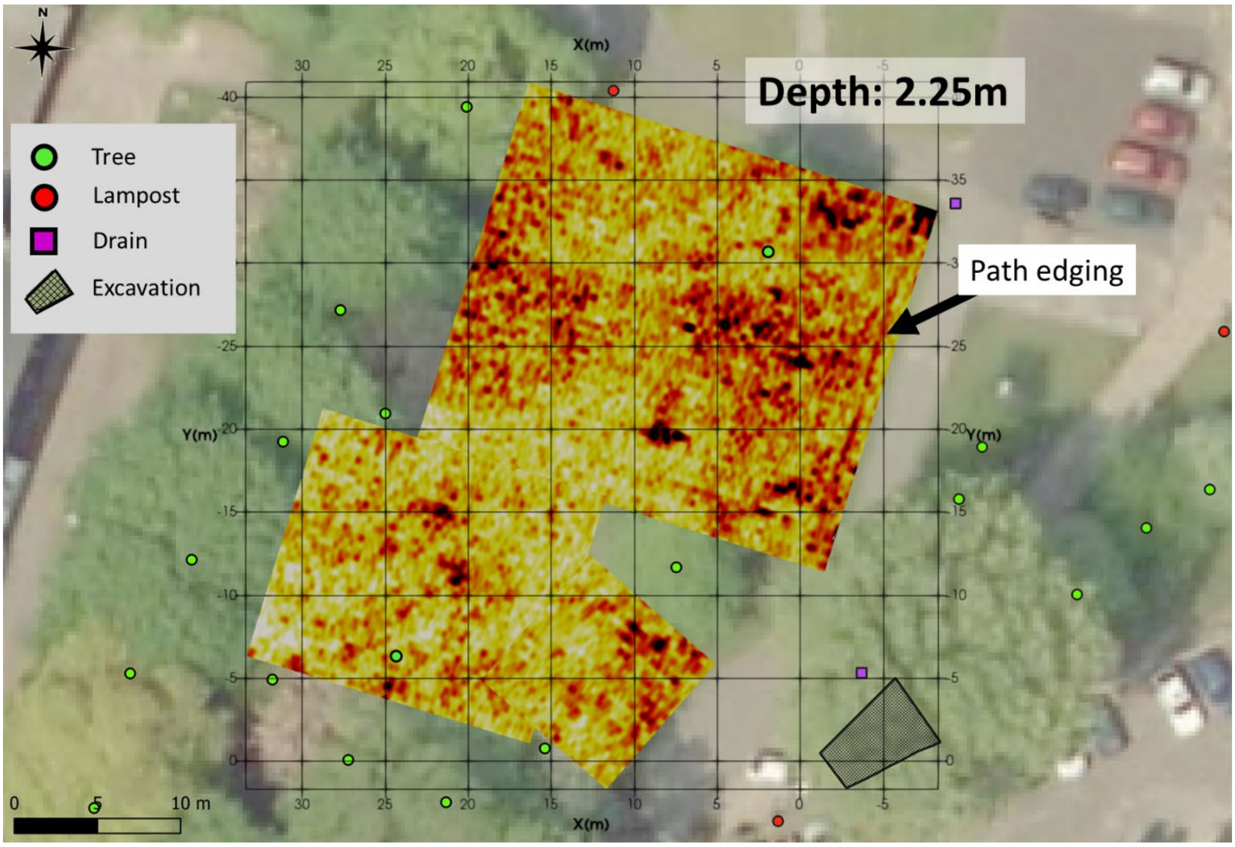


Figure 42: Horizontal slice at 2.25m from 250MHz data.

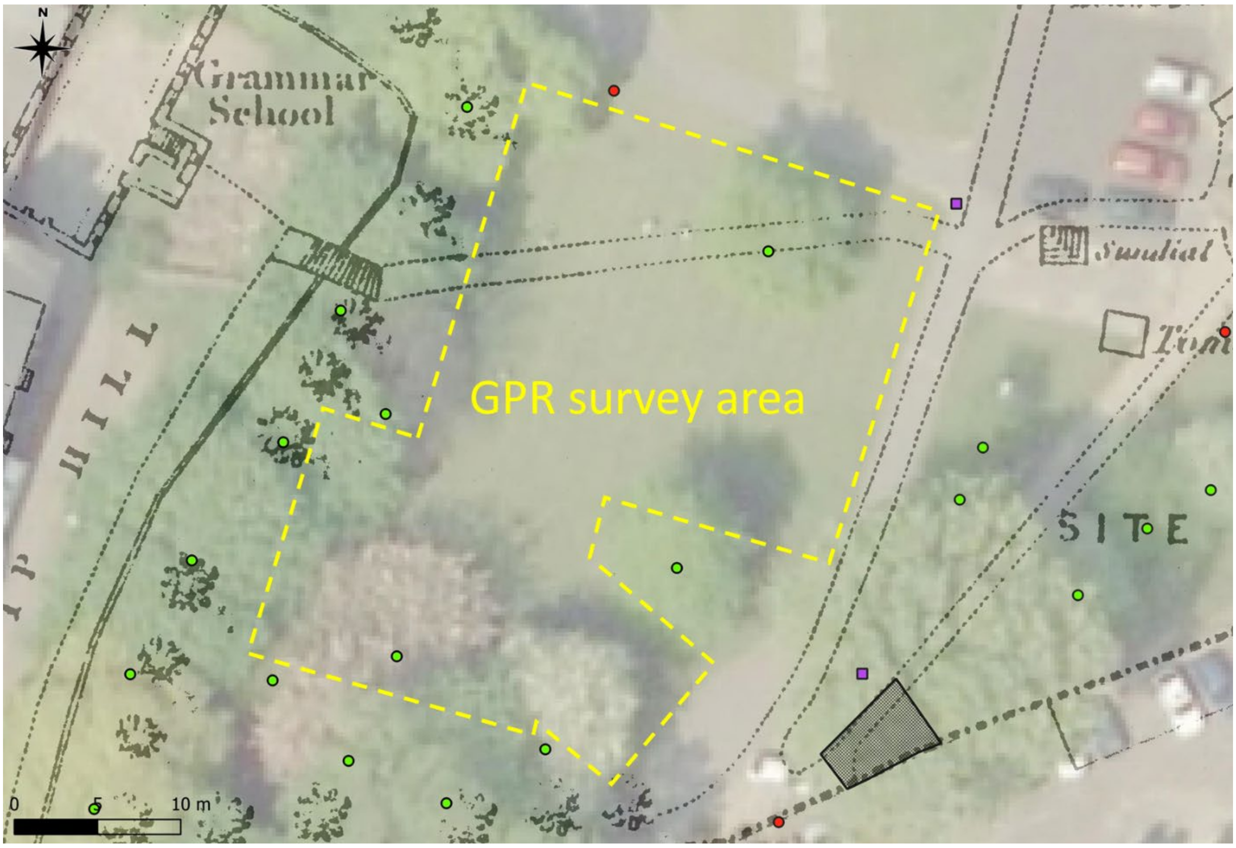


Figure 43: Southwest churchyard survey area with overlaid 1846 map showing location of former grammar school and path connecting to the Priory.

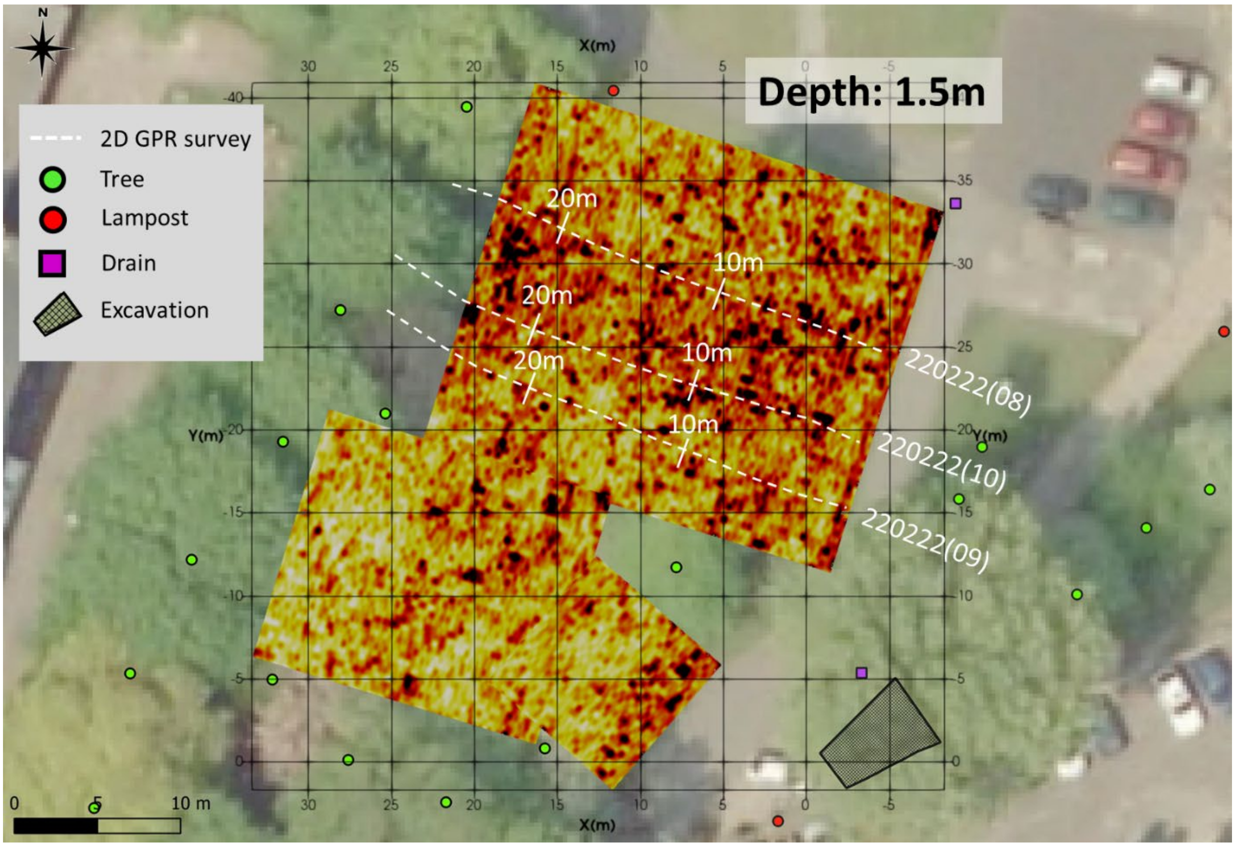


Figure 44: Horizontal slice at 1.5m from 250MHz data and position of three selected 100MHz transects.

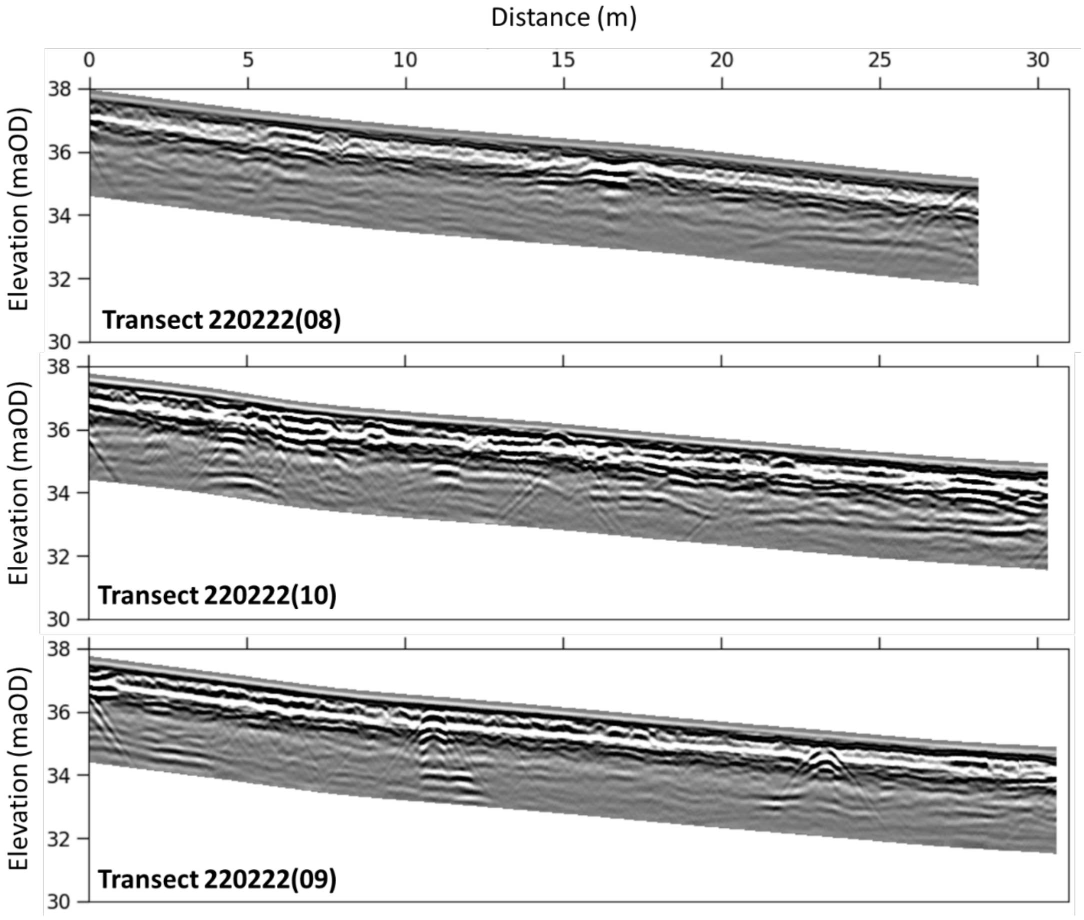


Figure 45: Selected southwest churchyard 100MHz transects. For position see Figure 44.

Figure 46: West churchyard 250MHz surveys in relation to Roman fort boundaries.

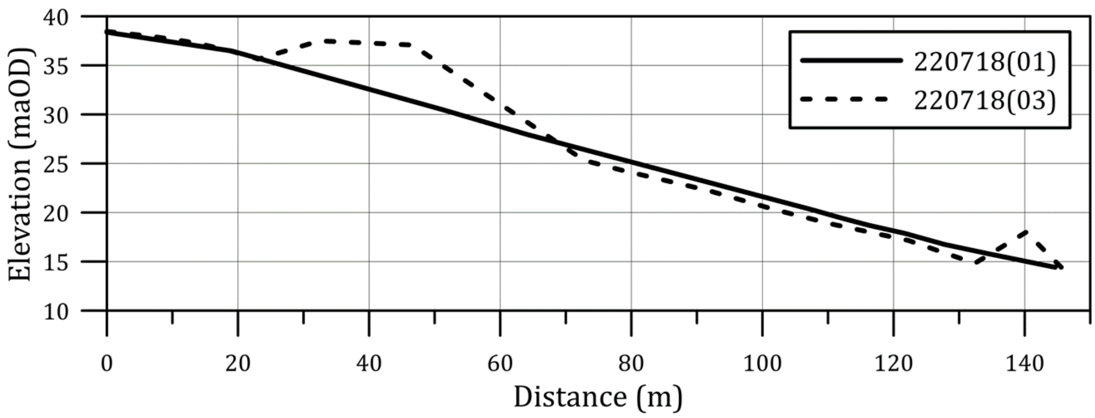


Figure 47: Topography along selected 250MHz transects.

Figure 48: Marked sections of selected 250MHz survey lines (see Figure 45 for entire survey position).

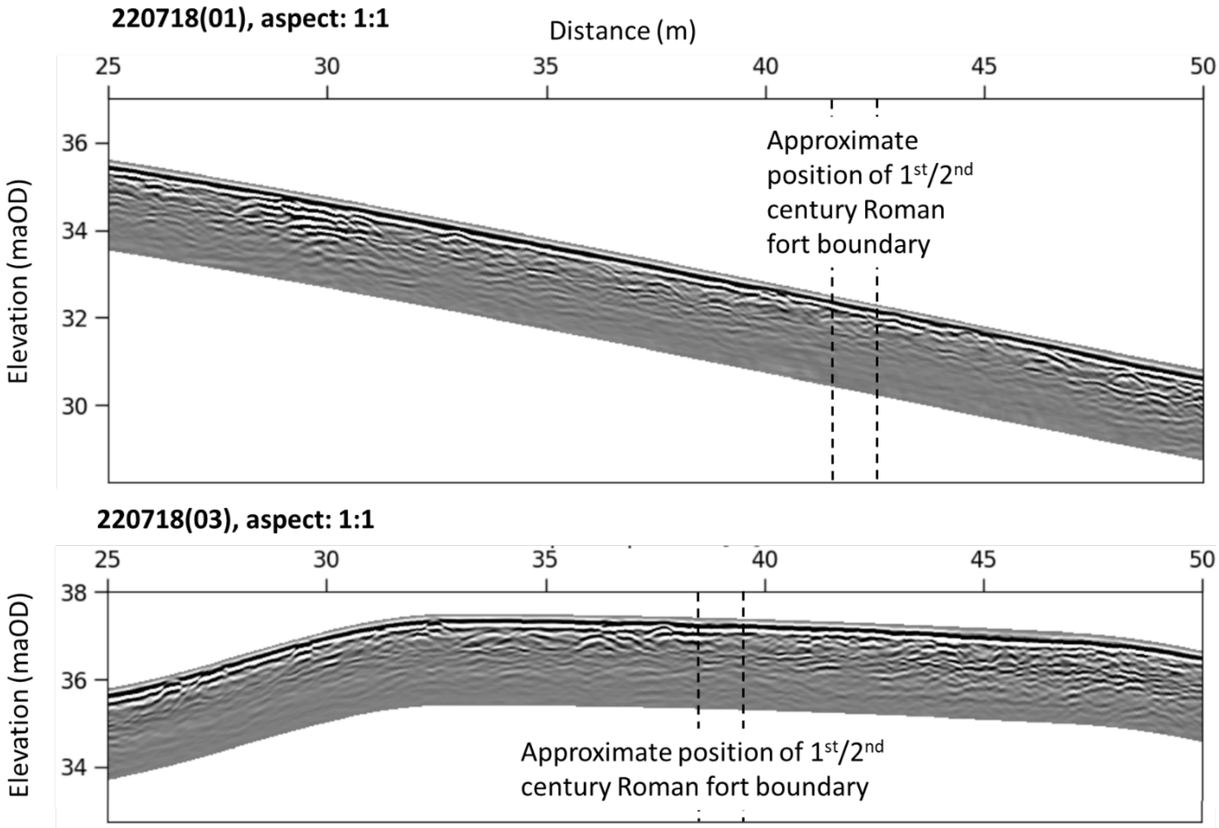
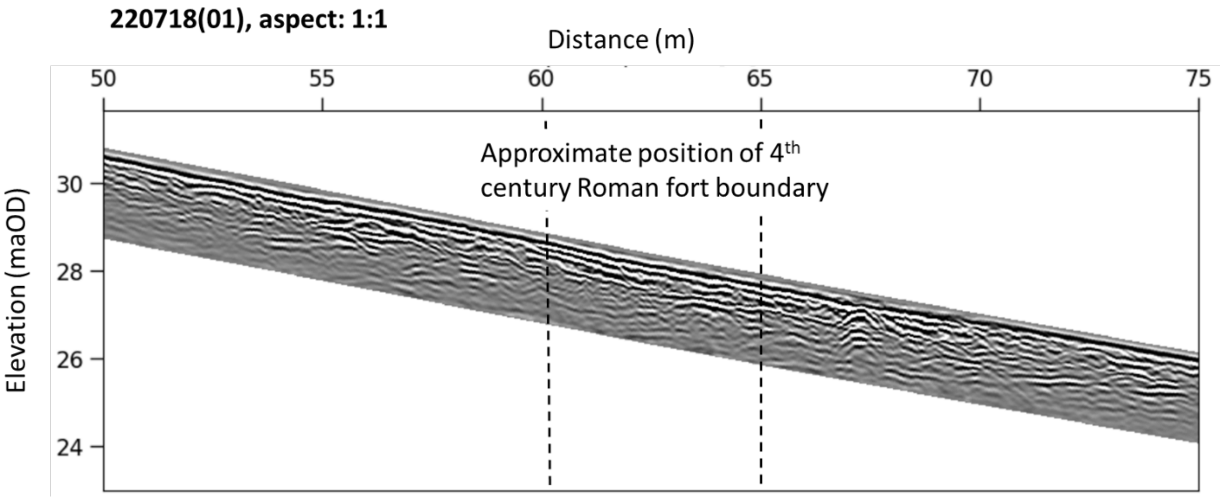


Figure 49: Sub-section of selected 250MHz surveys in the west churchyard. Refer to Figure 46 for position.



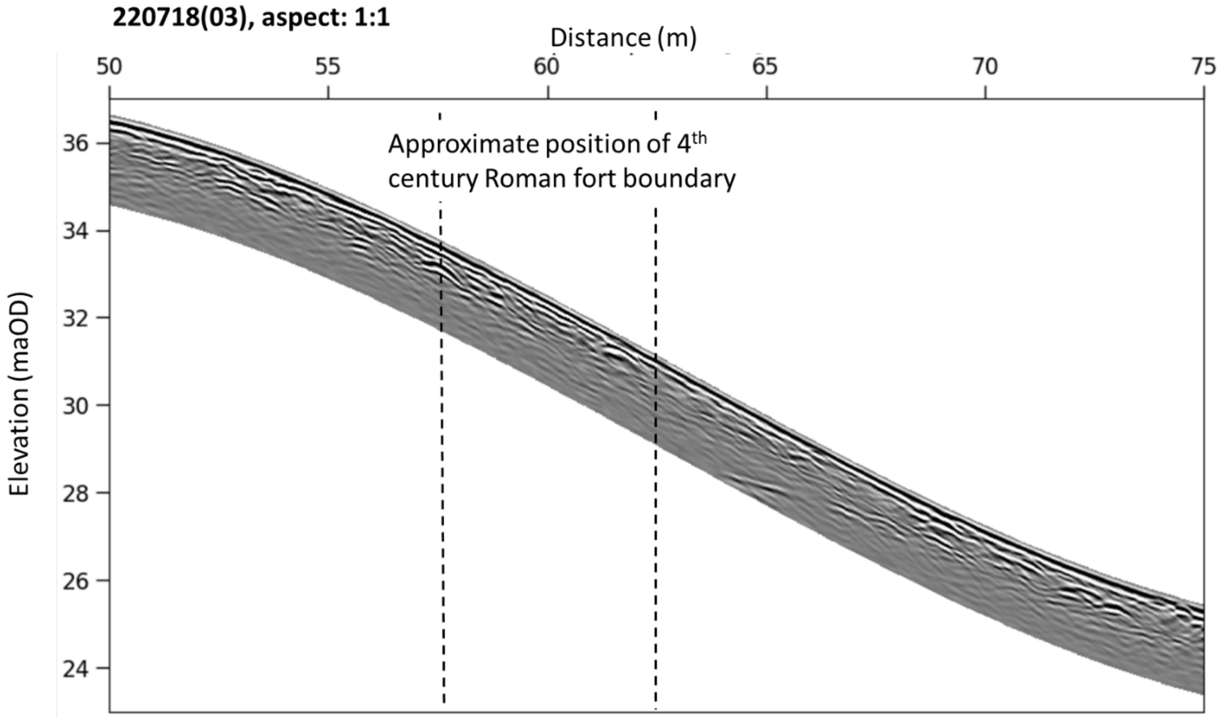


Figure 50: Sub-section of selected 250MHz surveys in the west churchyard. Refer to Figure 46 for position.

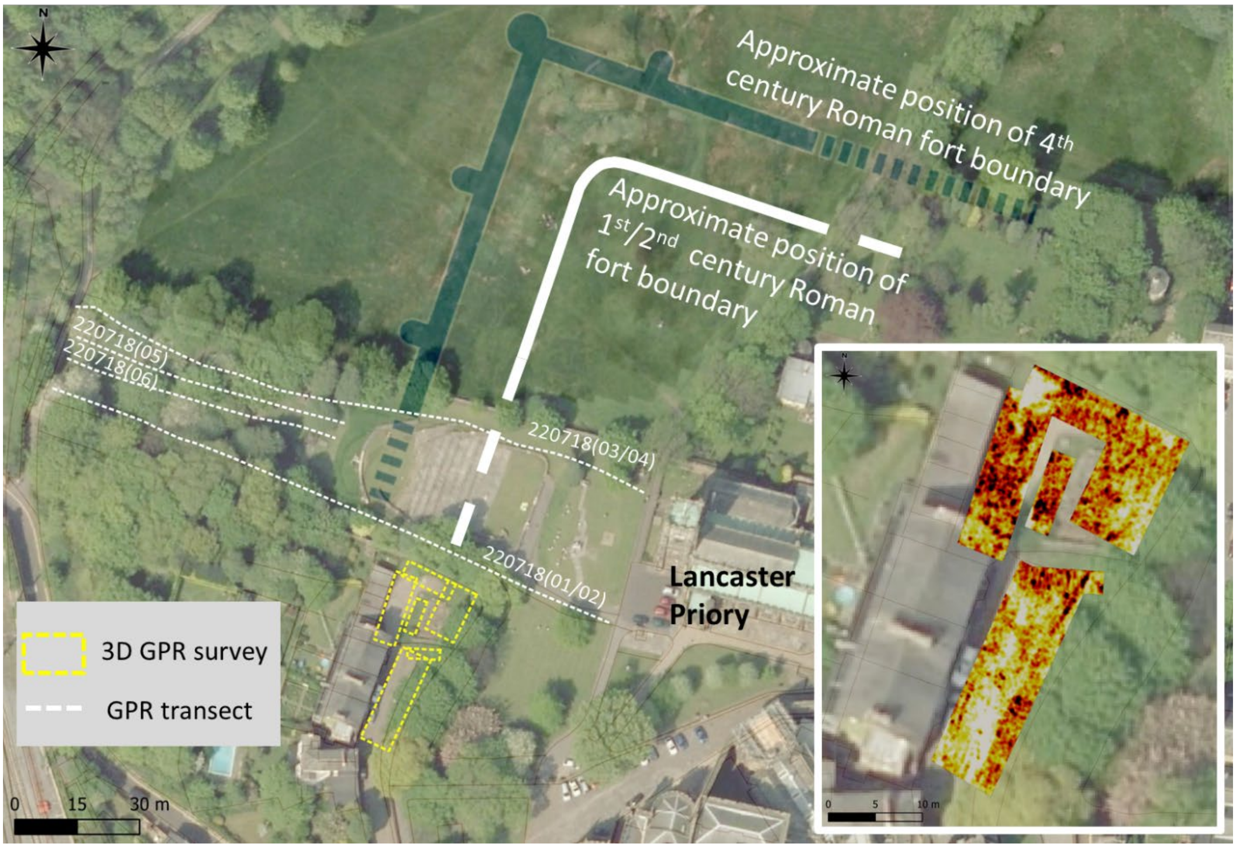


Figure 51: Map showing location of Hillside 500MHz GPR surveys by Binley (2023) in relation to approximate position of Roman Fort boundaries. 250MHz transects shown in Figure 46 are included for reference. The insert image shows Hillside GPR results at a depth of 0.7m below ground level.