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EMC Radar Consulting

atlas geophysical

Ground Penetrating Radar Survey

of

an area to the South East of the Abbey Church of

Dunfermline Abbey

For

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University of Stirling

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SURVEY OBJECTIVE

The royal Abbey of Dunfermline served as the primary burial place of Scotland's monarchs from the early 12th century until the demolition of the East end of the building began in 1560 as part of the religious reformation. In 1821 a new church was erected to the East of the remaining Abbey Nave in place of the demolished building. As part of the construction process, the site of the East end of the Abbey was levelled and pitch poured into the former building remains. The Abbey is now in the joint care of the Dunfermline Abbey Church, Historic Environment Scotland, and Fife Council.

Although historical records indicate that six Scottish kings, their spouses and close relations were buried beneath the floor of the Abbey, the location of most of these graves is currently unknown. The exception to this is the large grave uncovered in the choir of the current church, currently situated below the pulpit. This grave is currently designated as that of Robert I.

While it would not be reasonable to suggest that the historical role played by the Abbey has been neglected, it is true that the extant buildings which include several phases of church buildings, the remains of a royal palace and the shrine dedicated to St Margaret, do not currently demonstrate their full cultural and historical importance to the interested visitor. It is intended that this should be remedied by a programme of research including the use of non-destructive surveys in order to confirm the relationship of the current church to that of its predecessor and to locate, if possible, the site of as many large tombs as possible.

A first Ground Penetrating Radar (GPR) survey of part of the North Transept and the Vestry was completed in 2016. Although this did provide grave locations, there was no clear evidence, on the basis of size and relative location, for royal tombs. This survey also confirmed that it was useful to deploy antennas of 400MHz and 250MHz as part of the strategy. The 400MHz has the better image definition capability, useful for resolving closely spaced targets but the 250MHz antenna has the advantage of greater depth penetration and better detection capability where moisture is present.

In 2017 a second stage survey covering three areas towards the east end of the current parish church, namely the central area of the church from the door of the Vestry to the Altar and two external areas thought to lie above the Lady Chapel of the former Abbey Church. The area lying between the Vestry and the Altar was chosen because it links the two surveys carried out in 2016. The external areas were chosen in order to complete coverage of the remaining areas of the Lady Chapel not surveyed in 2016. The Lady Chapel is known to have contained royal graves.

The objective of this survey was to test the possible existence of a second chapel lying in an area to the South of the existing church, possibly dedicated to St John the Baptist, and located in a mirror image position to that of the former Lady Chapel to the North.

SURVEY STRATEGY

Use of Ground Penetrating Radar

GPR operates on the same principles as conventional radar except that it uses a wide

frequency range, a shorter pulse, and a much shorter range of detection. The radar generates a short pulse which is transmitted into the ground via an antenna. The return signals are received by another antenna. The amplitude of the returning signals provides information about changing ground characteristics with depth. The use of the radar does not affect underlying deposits: it is non-destructive.

GPR cannot identify the nature of the material through which the electromagnetic pulses pass. The signals returned to the radar are the result of changes in the electromagnetic properties between two or more adjacent materials. The amplitude (strength) of the returned signals is a measure of the magnitude of the difference between these materials rather than being a characteristic of any one material.

It is a feature of GPR that the same signal patterning may be produced by different combinations of features &/or materials. It is also not possible to date remains except relatively where one set of remains overlies another.

It is important to appreciate that the radar can only detect the final state of any extant remains and not the process which has brought about this result. The separate identification of two or more objects requires these to be sited a distance of one wavelength apart from each other. If this separation is not present, they may be detected as a single object. For these reasons, where a site has been used and re-used over centuries it can be difficult to understand the structures represented in the data.

Features such as wall foundations may be identifiable within 2-dimensional data provided that sufficient vertical remains exist. In a site such as this one where extensive reuse has taken place over the centuries, identification of a specific built structure such as a chapel is normally made on the basis of patterning in the horizontal data. This could be the remains of wall foundations, the outlines of floors subsequently built over or potentially the distribution of a mixture of partially destroyed material used as the foundation either for another later structure or simply to level the ground. The 2017 survey to the North of the parish church revealed the outlines of the former Lady Chapel walls and, adjacent to them, areas which might have contained tombs. In this instance, the area to the South of the present church includes the access path around the church and a post medieval graveyard. The ground slopes downwards towards the South and there are steps to the South of the South transept door. The slight elevation, taken together with known concerns about the level of groundwater in this area, make it likely that any building materials remaining on site may have been used not only for levelling the site but also possibly for constructing the slope to the South.

In the previous surveys two frequencies of antenna were deployed, 400MHz for optimal definition and 250MHz for its greater depth capability. There is no benefit to be gained from using higher frequency antennas than these due to the depth of the medieval burials relative to the floor of the current parish church and the relatively lossy soils within a site for which retention of groundwater was sufficiently a concern of the church architect, William Burn, that he used pitch beneath the church floors as protection. Unfortunately, there was considerable rainfall in the Dunfermline area in the months before the survey took place. As a result, it was not possible to use the 400MHz antenna due to the increased signal losses caused by wet ground although a brief trial was made. The 250MHz antenna was therefore used for this survey.

To be consistent with the 2017 survey of the area of the former Lady Chapel to the North, the survey was carried out along a North/South axis. This optimises the potential detection of any walls parallel to the parish church and also any graves existing within the survey area.

Equipment

The equipment used for these surveys was a GroundVue 3_1 with a 250MHz antenna. The uneven terrain prevented the use of a manually towed short skid as used in the 2017 survey. A trolley with large wheels was used instead.

The antenna used contains a dual array for narrowed signal beam and is screened in order to comply with European legislation to control the level of stray legislation. This also reduces the effects of external interference from objects above ground. It is not possible however to fully eliminate transmissions such as those emanating from the Abbey's fire alarm system since these are also reflected from the subsurface. The transmission frequency differs sufficiently from that of the radar that, although this makes the data relatively unsightly, it has not prevented target detection.

Site Conditions

This was a challenging site on which to use GPR. Not only does the site slope gently towards the South but there are a considerable number of above ground obstacles ranging from grave markers and commemorative stones to external lights and stone steps all of which prevent direct survey in their vicinity. There was also variation in the surfaces which could be surveyed. These included asphalt, gravel, grass, gravestones and grave markers. Some of the latter were slightly raised above ground level, potentially creating artificial data from the resulting air gaps.

This did not prevent the survey from being carried out in a systematic and accurate manner but has resulted in blank areas within the horizontal data where above ground obstacles prevented the radar from having contact with the ground.

Site Coverage

In order to maximise the information obtained by the GPR, survey lines were completed at a transect spacing of 0.25m. This is half the spacing required by the widely accepted guidelines published by Historic England (English Heritage, 2008). These were originally set as a compromise between the investment required to optimise the imaging capability of the radar and an acceptable level of information with a lesser use of resources. For this investigation, it is more appropriate to achieve the optimum level of data for imaging purposes because of the limited area access and the potential difficulty of interpretation given the history of the site. Also, the areas being limited in extent means that there is a negligible incremental impact on resources. The 0.25m spacing complies with current European guidance (Schmidt et al, 2015).

Survey Parameters

A sampling interval of 27.14mm along the line of travel of the radar was set. The data were collected to a probing depth of 100ns (approximately equivalent to 5m in dry conditions, c. 3.9m in the site conditions). As will be seen from the data, the actual depth of penetration of each antenna is less than theoretical. The actual probing depth is determined by the electromagnetic properties of the subsurface, including both the soil and any water content.

Calibration

GPR depths are measured in nanoseconds time because electromagnetic waves do not travel at a constant velocity. To translate this into depths measured in metres, it is necessary either to know the speed of transmission through the ground or to calibrate using either borehole information or curve fitting to hyperbolas (targets) in the data.

In the previous survey of parts of the North Transept and the Vestry it was not possible to determine a single transmission velocity in the subsurface as the values within each area varied significantly, presumably due to the presence of moisture. For the 2017 survey, the central area between the Vestry and the altar steps appeared to be uniformly dry and curve fitting provided a transmission velocity of 0.1m/ns. The two external areas covering the ground above the former Lady Chapel proved to be damp and curve fitting produced the slightly lower speed of 0.08m/ns.

For this survey, a range of transmission velocities were derived as shown in the table below. These show that there is a gradient of waterlogging, as evidenced by the slower transmission velocities, with the near surface being wetter than the soils below. The pattern is slightly more complicated than this since the shallow levels beneath hard manmade materials have been protected by this cover from the worst of the waterlogging. The average transmission velocity, 0.0775m/ns has been used for translation of depths. This corresponds to the velocities measured in the survey of the area of the former Lady Chapel by both the 400MHz and 250MHz antennas.

Survey Line	Distance	Depth	Velocity
1	-6.67m	29ns	0.08m/ns
19	1.7m	43.84ns	0.08m/ns
47	4.76m	38.3ns	0.085m/ns
88	1.01m	36.3ns	0.065m/ns
106	-4.5m	32.88ns	0.08m/ns
114	3.4m	33ns	0.08m/ns
114	-0.81m	24.18ns	0.065m/ns
122	7.64m	13.7ns	0.085m/ns

Fieldwork

The survey was carried out on 21st August 2019. The ground was wet from previous rainfall and weather conditions ranged from cloudy and windy to wet.

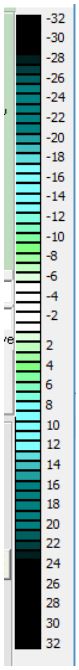
SURVEY RESULTS

Data Display

All 2-dimensional data is presented from North (on the left) to South (on the right). All horizontal time slices extracted from 3-dimensional data are presented with East at the top of the page and North to the left-hand side.

The Use of Colour in GPR Data

It is important to realise that GPR uses electromagnetic pulses (radio waves) and is not an optical technique. The signal amplitude indicates a change of materials, but it is a relative and not an absolute measure. As such, it does not and cannot usually be used as an indicator of the actual materials present. The stronger the signal, the more contrast is visible in the data. Similar colours (signal amplitudes) can originate from different combinations of materials. It is only legitimate to postulate continuity of a feature if that continuity is evident directly from the data and not solely on the basis of similarity of signal amplitude. For that reason, greyscale images have been used for analysis of the 2-dimensional data. The 2-dimensional data is displayed in greyscale of black (strong positive) to white (strong negative). On this colour scheme, grey represents continuity rather than an absence of material. Black and white indicate anomalous material.



Colour has been used to illustrate the 3-dimensional data from which horizontal time slices have been extracted (Figure 1). On this colour scale black indicates a high signal amplitude (positive or negative) and therefore the greatest difference in material composition from the immediate environment. For the remainder of the colour range the darker the colour, the greater the difference between the feature and its surrounding environment. White denotes continuity with or similarity to the adjacent subsurface environment.

Figure 1: Amplitude Colour Scale.

The Survey Area to the South East of the Parish Church

Two parallel survey reference lines were laid out in along an East/West orientation. Line 1, to the North, was placed to align with the south front of the south transept (Figure 2). Line 0 was placed 8m to the south of Line 1 (Appendix A). This line lies along the path (Figure 3). Where a marker 1 has been placed on the 2-dimensional data, this indicates the position at which the radar crossed this survey reference line. Line 0 was used as the start point for the majority of the survey lines (see also Figure

3). The West end of the survey aligns with the second buttress to the West of the South Transept door (Figure 4). The position of the survey lines were defined by GPS as shown in Appendix A. ALEX – GPS Please

The survey was completed by surveying from south to north beginning at the east end and working westwards with each line 0.25m distant from the previous one. In the area of the steps (see Figures 2 and 3), two sets of survey lines were completed. The first of these lay between line zero and the foot of the steps and the second between the steps and the south transept door.

Figure 2: The position of survey line 1 relative to the south transept door.

Figure 3: The position of survey line 0, parallel to and 8m South of line 1.

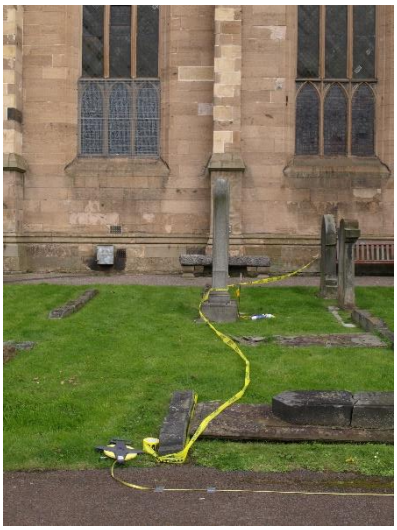


Figure 4: West End position of survey lines.

2-Dimensional Data: 250MHz

The 2-dimensional data has been processed by:

- Correction for Tzero;
- Constant background removal;

- Addition of gain to compensate for diminishing signal strength with depth;
- Application of Bandpass Butterworth to remove any spurious signals.

The alignment of each radargram is to survey reference line 1 so that the x = 0 (distance travelled by the radar) position lies along this line. Negative distances are to the North & therefore closer to the church wall, positive distances lie to the South of the parish church, towards the path shown in Figure 3.

The uneven nature of the ground surface particularly with respect to both gravestones and the grave markers lying just above the surface, has given rise to discontinuities in the 2-dimensional data. Figure 5 shows a particularly bad example. The effect is greatest within the first 5m distance.

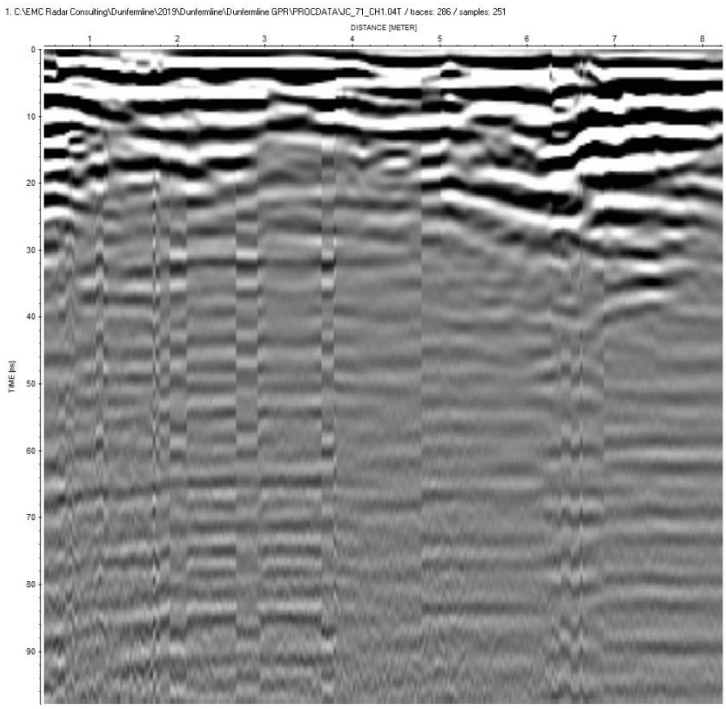


Figure 5: Survey line 71 (along y = 17.75m).

The 2-dimensional data are characterised by a high density of signals within the first 20ns to 30ns (c. 75cm to 1.12m) of depth (Figures 5 and 6). It is probable that this depth equates to post medieval activity rather than the target archaeology. Below this there are relatively few signals and the prevalence of ringing (echo effects) suggests heavy signal losses, probably due to the relatively high water content of the soil. These effects are visible throughout the lower levels of Figure 5. The 2017 surveys demonstrated that the soil in the immediate vicinity of the Abbey contained an ionised component such as clay. In combination with water, this results in signal loss in the form of a weak electric current transmitted into the soil. If it is possible to survey this area in drier conditions, it may be possible to obtain better results beyond 30ns.

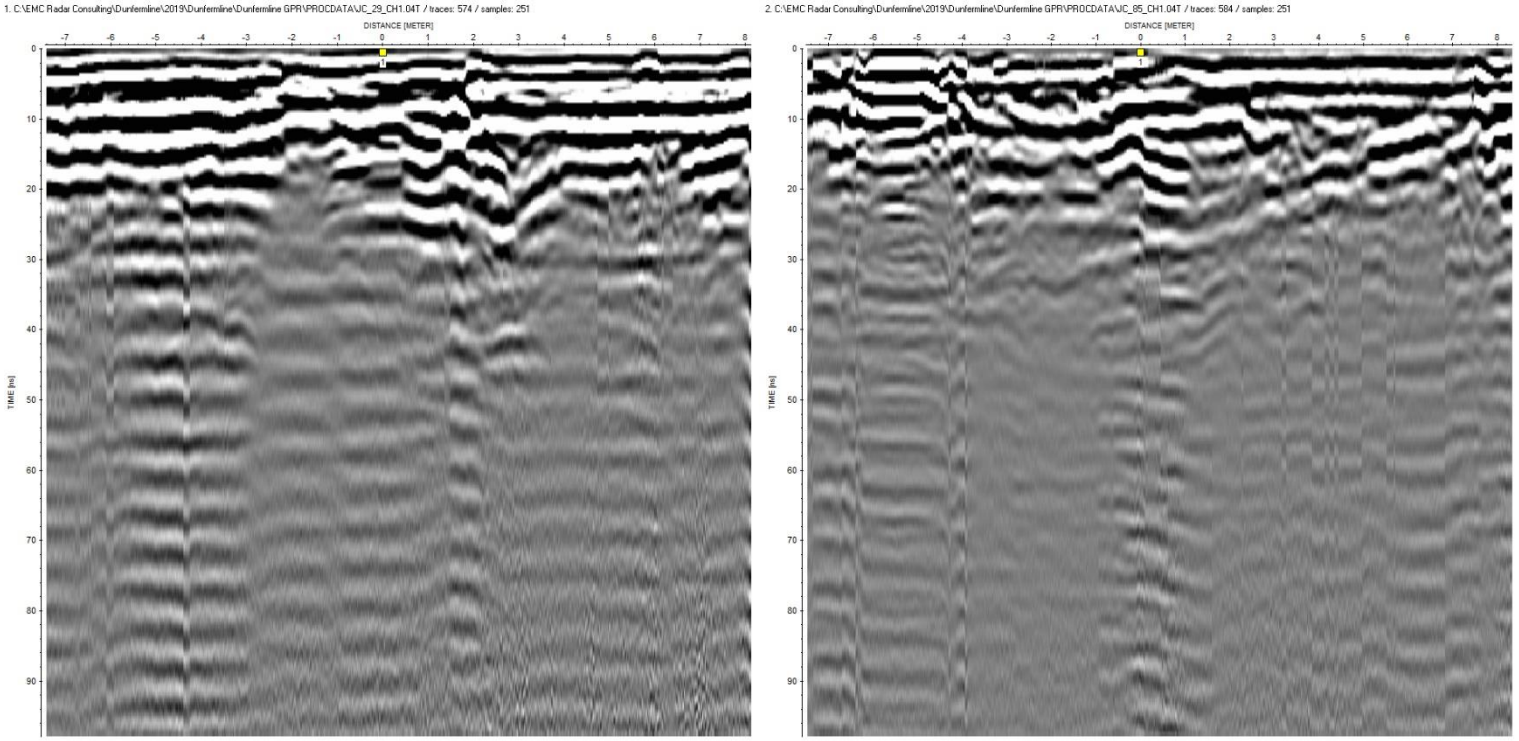


Figure 6: Survey lines 29 and 85 (along y = 7.25m and 21m respectively).

Figure 6 illustrates echo effects from the near surface but also shows a different type of ringing. Below line 1 (x=0) in survey line 85, the ringing originates from an object lying directly above the floor of a layer which appears to slope downwards from right to left (south to north). It is possible that, if this were corrected for the slope of the ground (north to south) that the floor of this feature is horizontal or at least flatter than indicated. It is likely that the cause of the ringing is a void. The strength of the ringing is insufficient to suggest metal, but an air gap within a

utility is likely. In spite of the shallow depth one possibility is that this is a drainage channel. The other implication of this data is that the ground, at least at this location, has been cleared of older structural remains.

The entrance to the Elgin vault is visible in line 85 between x = -6m and -4m. The ringing from this feature also originates from the air gap within the entrance.

3-Dimensional Data: 250MHz

The 2-dimensional survey lines have been incorporated into a 3-dimensional data block based on their relative positions along survey line 1. Time slices, horizontal plans, have been extracted from this data block based on the change in signal patterns visible in the data. East is at the top of the page for all the time slices.

Although the data is shown as a flat surface, in reality this represents a slope. There are known air gaps included within the data, for example, the entrance to the Elgin vault and some of the stronger signal returns may also represent other subsurface air gaps. Analysis of the 2-dimensional data implies different degrees of water content within the subsurface. Along the line of the slope, where air gaps exist, or moisture is present the view will be quasi-horizontal i.e. apparently horizontal but not physically so due to the differing transmission velocities in different parts of the survey area. This does not, however, appear to have significantly distorted the results of the survey but should be borne in mind should there ever be a trial excavation in the area.

Survey line 1 is located along x = 0. White areas within the time slices are where surface obstacles (steps, upright gravestones, lights) prevented direct survey.

The 2-d data selected for illustration can be located on the time slices as follows.

Survey Line	Y position on Time Slices
1	0.25m
2	0.5m
14	3.5m
16	4m
18	4.5m
25	6.25m
29	7.25m
71	17.75m
82	20.25m
85	21m
87	21.5m
88	21.75
110	27m
117	12m
127	14.5m

Surface Time Slice

In Figure 7, the surface time slice, ‘1’ marks the position of the entrance to the Elgin

vault, ‘2’ marks the location of the steps in front of the south transept door and ‘3’ marks an area where it was not possible to survey due to the dense distribution of surface obstacles. The symmetrically spaced blank areas on either side of the steps mark the position of external lights.

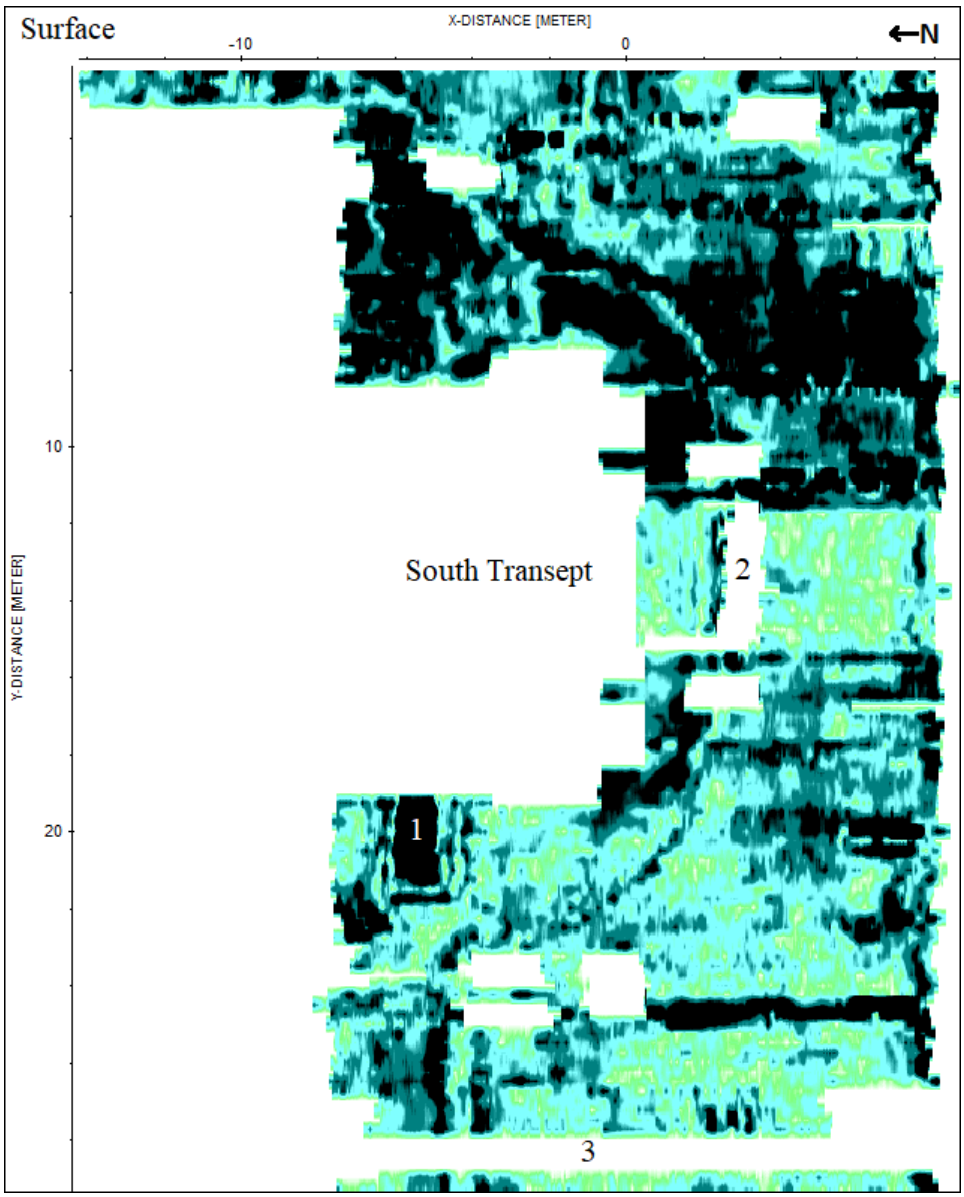


Figure 7: Surface time slice

Black lines running along a North/South orientation show the position of grave markers slightly raised above ground level, but which were close enough to the surface to allow survey. These signals arise from the air gaps created by the radar passing over each obstacle in turn.

The light areas directly in front of the door leading to the south transept (on either side of ‘2’) reflect the position of the path and steps leading to the door. The manmade surfaces protect the underlying soils from rainfall and generally dry out faster than the adjacent grass.

It is not immediately obvious what forms the semi-circular feature around the outline

of the south transept and along the north edge of the steps ('2') but the likelihood is a utility. Since the location (0.69, 21) coincides with the probable utility in survey line 85 (Figure 6), it is likely that this corresponds to the top of a utility trench, probably a drainage feature.

The more extensive black areas to the East of the survey area indicate either higher moisture levels at ground level or construction materials. The constructed path immediately adjacent to the outline of the parish church (cf Figure 2) forms part of this area but so also does the combination of grass and gravestones immediately to the south (rhs of time slice).

Time Slice at c. 9cm Depth (c. 2.3ns)

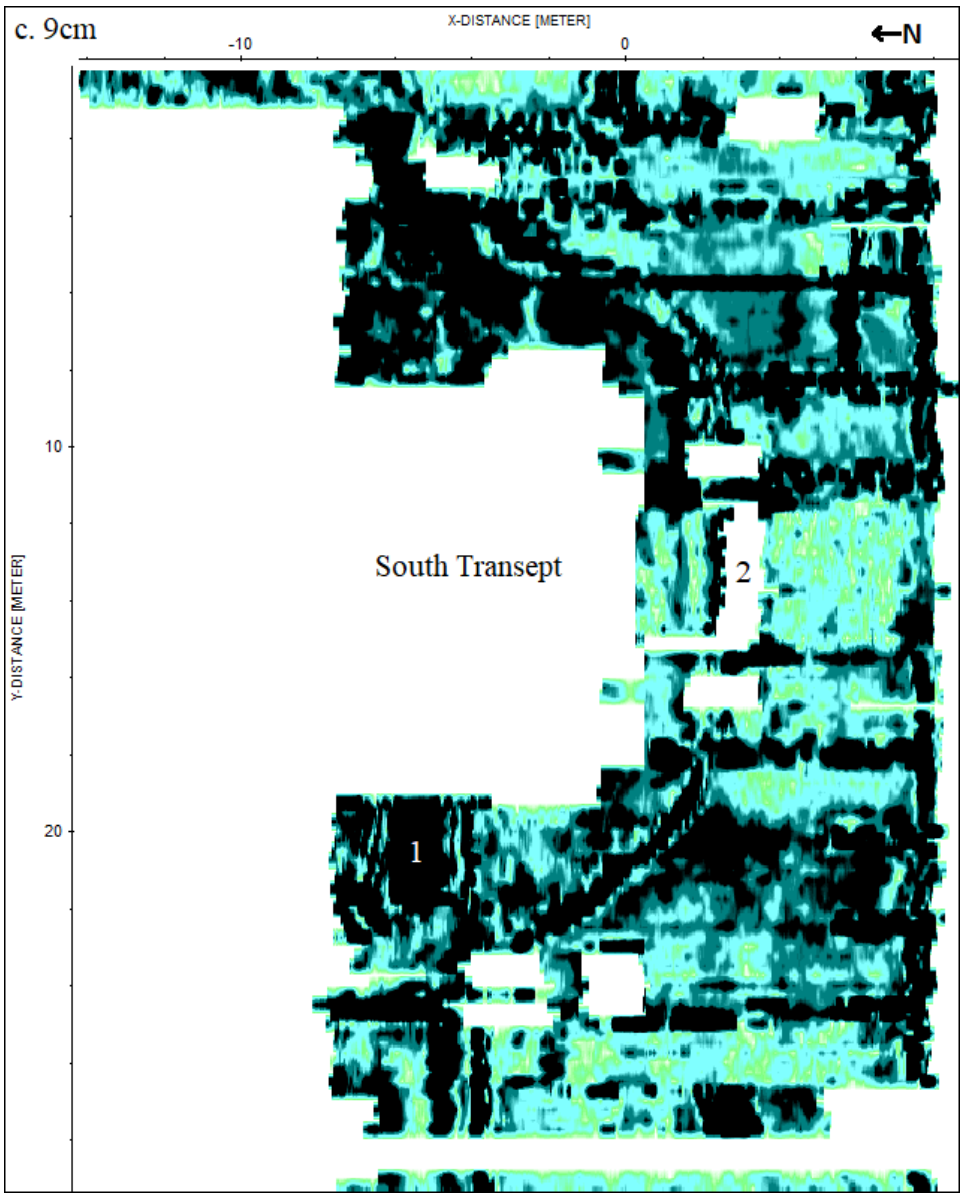


Figure 8: Time Slice at c. 9cm depth.

The patterning of the 9cm time slice is similar to that of the surface (Figure 7). The

divisions of the burial ground are clearly discernible with the East/West divisions becoming visible along the south side and also in the NW corner of the survey area. The entrance to the Elgin vault is clearly visible ('1') and the possible drainage feature is also.

In the NE corner by the east wall of the south transept, there are a number of strong signal returns. The area around the transept lies under a path. The 2-dimensional evidence from this NE corner suggests layering of construction. In some cases, this overlies other features some of which could potentially be burials and all of which contain echo effects from features buried in the subsurface.

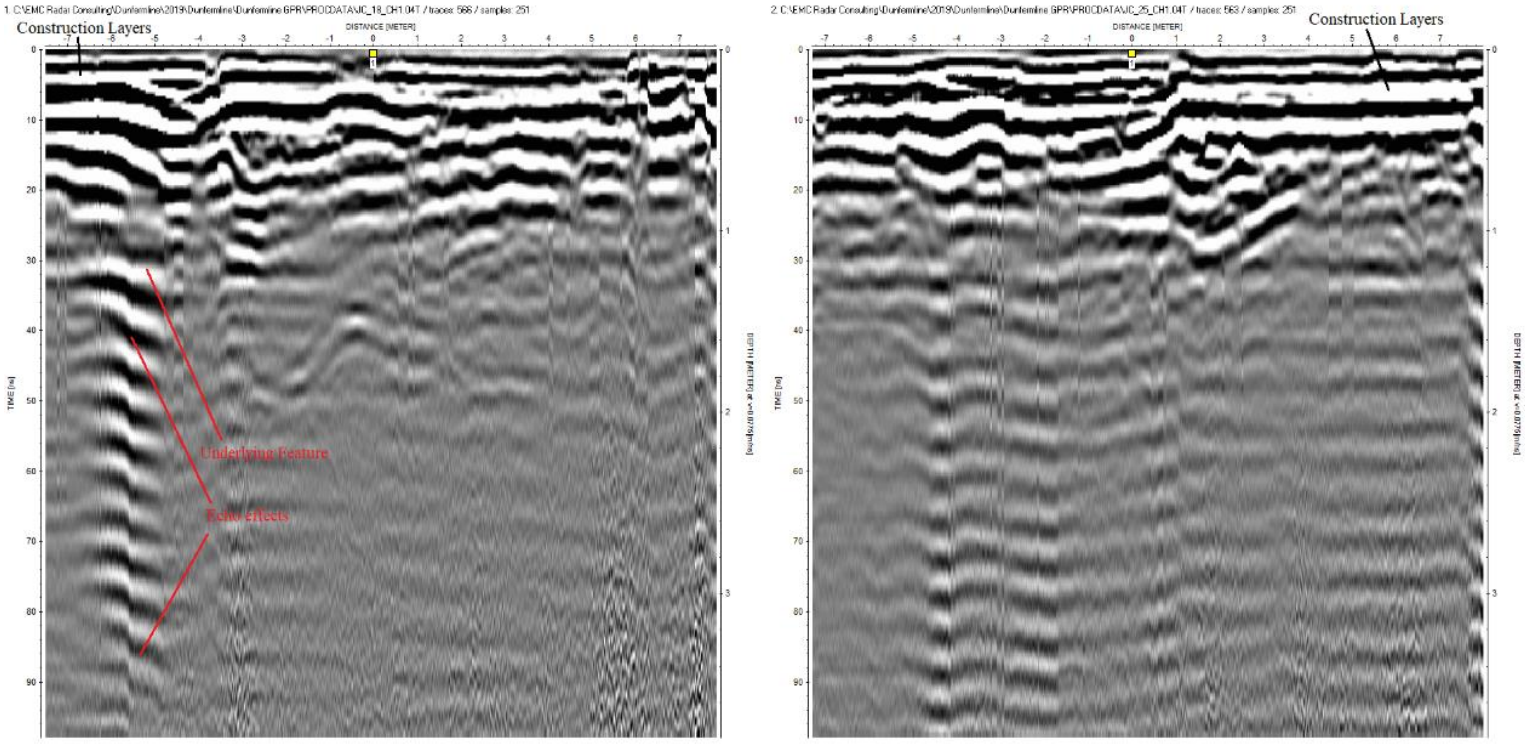


Figure 9: Survey Lines 18 and 25 (along y = 4.5m & 6.25m respectively).

In the western section of the site, the evidence is not dissimilar (Figure 10). At this level, post medieval construction is the reason for the

darkened areas in the time slice. There is no direct evidence of burials as such. The Elgin vault is visible between -6m and -5m in line 82. Line 110 has 3 distinct sets of narrow hyperbolas visible in the near surface which could potentially indicate voids (air-filled containers). If so, these would have to be made of a more durable material than wood.

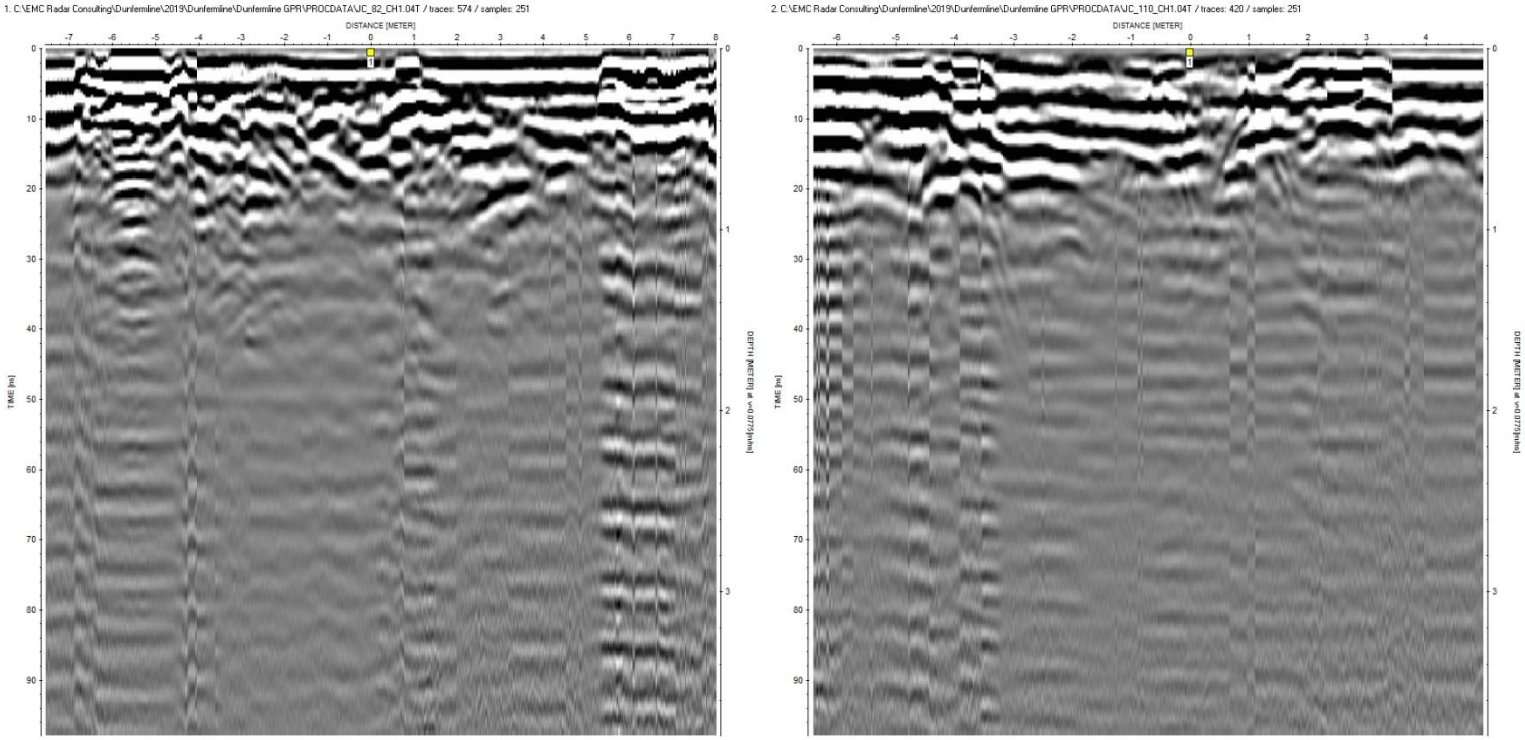


Figure 10: Survey Lines 82 and 110 (along y = 20.25m & 27m respectively)

Time Slice at c.35cm Depth (c. 9ns)

There are three main changes in patterning at this depth. The wide curve of construction material which crosses the NE corner adjacent to the eastern edge of the transept has broadened. The similar material directly to the south of this area

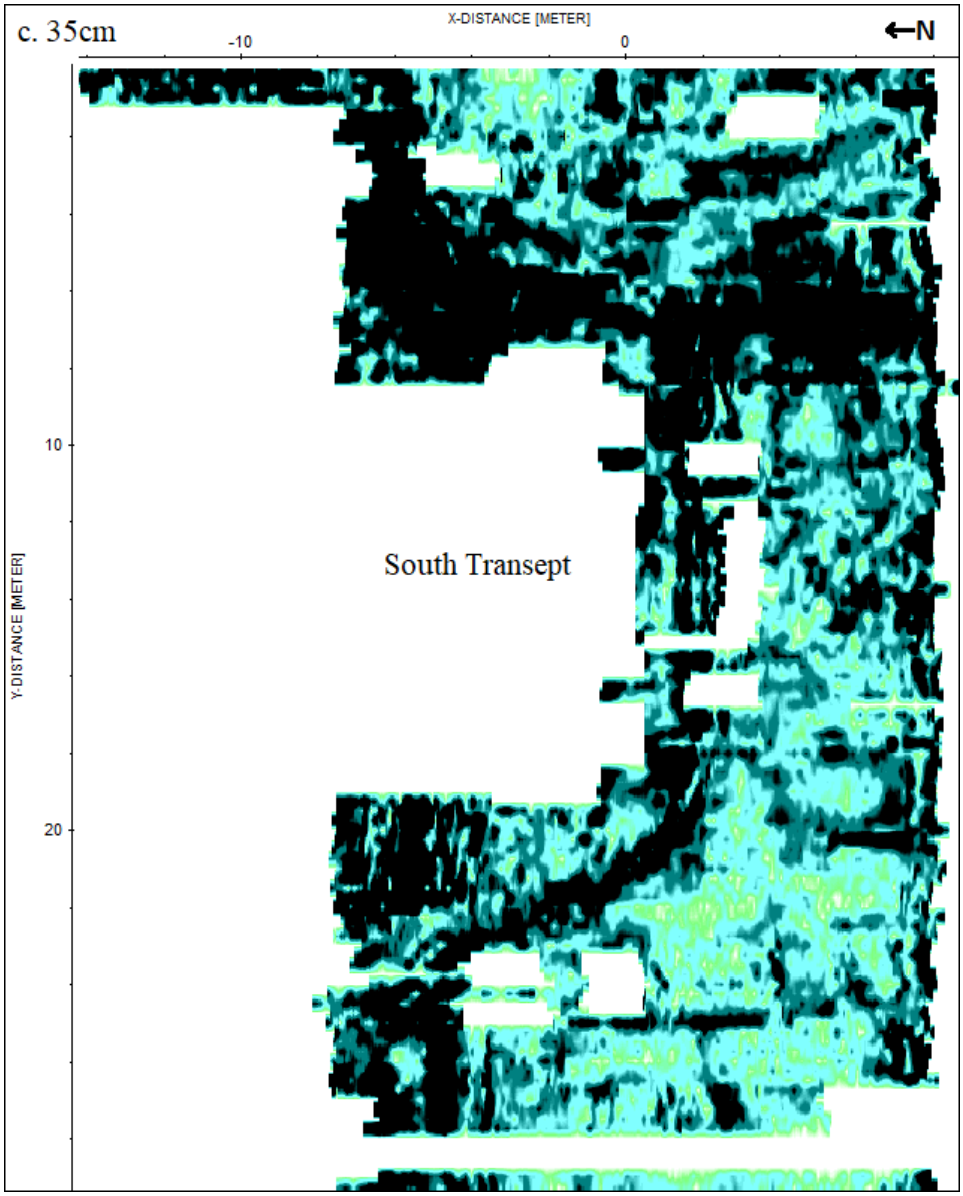


Figure 11: Time Slice at c 35cm depth

now forms a rectilinear feature. The utility, possibly a drainage feature, has also broadened. Comparison with Figure 9 confirms that the broad curvilinear feature appears to be construction layers at this depth. Comparing the outline of the utility with that of the object at the base of a trench in line 85 suggests this is the principal element of this feature (Figure 6).

The rectilinear feature is made up of a series of smaller rectangles whose main axis aligns East/West. It therefore appears to be evidence of post medieval graves. This is consistent both with the outlines seen at the surface and also the positions of the

various grave markers. The 2-dimensional evidence suggests that this level still lies in the horizontal layers directly above the graves themselves (cf Line 25, Figure 9).

Time Slice at c.79cm Depth (c. 20.3ns)

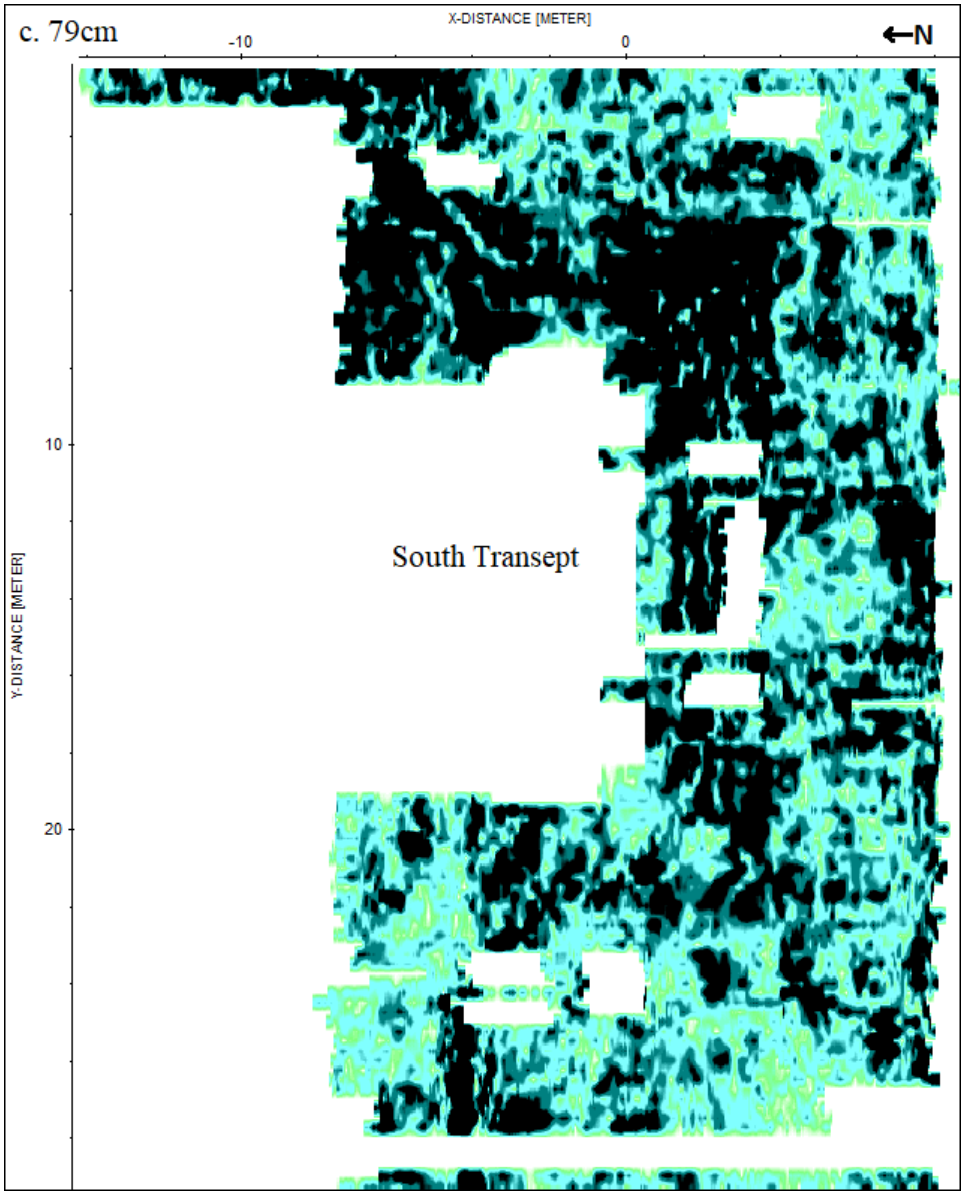


Figure 12: Time Slice at c.79cm depth.

This level is of interest because it is close (10cm) to the depth at which possible medieval remains began to appear on the North side of the present parish church in the area of the former Lady Chapel (2018 report). To the East of the south transept, the dark area now forms a rectangular shape which may be related to the rectangular scatter of dark signals to the West and a group of similar signals along the front of the transept (eg between the door and the steps).

Since the northern edge of this feature lies along the line x = 4.3m in both the East and West sections and the southern edge lies between x = 3.6m and 3.8m to the East and at 3.65m in the West, this does not appear to be a random pattern. It is strongly suggestive of the outline of a former building which, having been destroyed, has then

been either backfilled or its remains spread over an area in order to provide a level surface for later construction.

Survey lines 18 and 25 cross the East end of the rectangle (Figure 9). Survey line 18 shows a division between the dark outline to the North and the beginnings of this rectangle at c. 4.2m which confirms the northern edge of this feature as essentially separate, at this depth. There is evidence in both data sets of a mixture of materials. However, lines 17 to 20 inclusive also demonstrate an area of linear continuity e.g. from x = -1 to 4 in each section (cf Figure 9). This suggests a solid feature of c. 1.5m width which could indicate a possible section of the remains of a thick outer wall or of a floor although if the latter, the depth is shallower than expected for medieval material.

In the central area outside the transept door, the dark stripes lying between the door and the lower steps appear to be formed by discrete objects directly beneath the modern construction levels. To the south of the steps, the signals are weaker but there are signs of previous use of the ground (Figure 13 at 20.3ns). Although it is not possible to draw definite conclusions from this, the pattern is consistent with the possibility of the dark rectangle being the remains of a former building's outline.

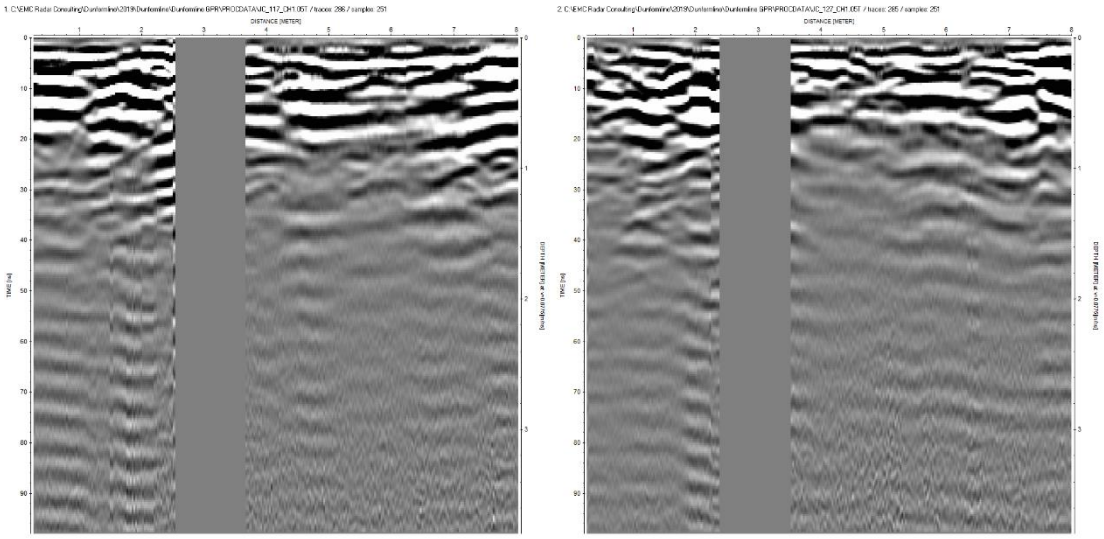


Figure 13: Survey Lines 117 and 127 from the area in front of the South Transept door.

At the western end, survey lines 87 and 88 define the edge of the feature (Figure 14). These both show a continuous layer at approximately this level, allowing for the distortion caused by the downward slope to the south (rhs) which shows as a rising slope in the data. A similar linear feature is visible in survey line 85 (y = 21m, Figure 6) and this can also be traced eastwards as far as y = 20m, at least in part. This suggests either the remains of a wall, over 1m thick, or the remains of a partial floor (from the North/South continuity of each line) or the construction of an artificial hard standing prior to more modern construction. As noted above, the apparent upward slope is the reflection of the current ground profile (distance below ground decreases to the South) which indicates that the feature does not follow the contours of the current surface slope, it is horizontal. This matches the patterning at the East end of the feature, confirming that the overall pattern visible in the time slice is a real reflection of a former construction. It is not possible to date this feature based on

GPR data alone other than saying that it pre-dates the construction of the parish church transept.

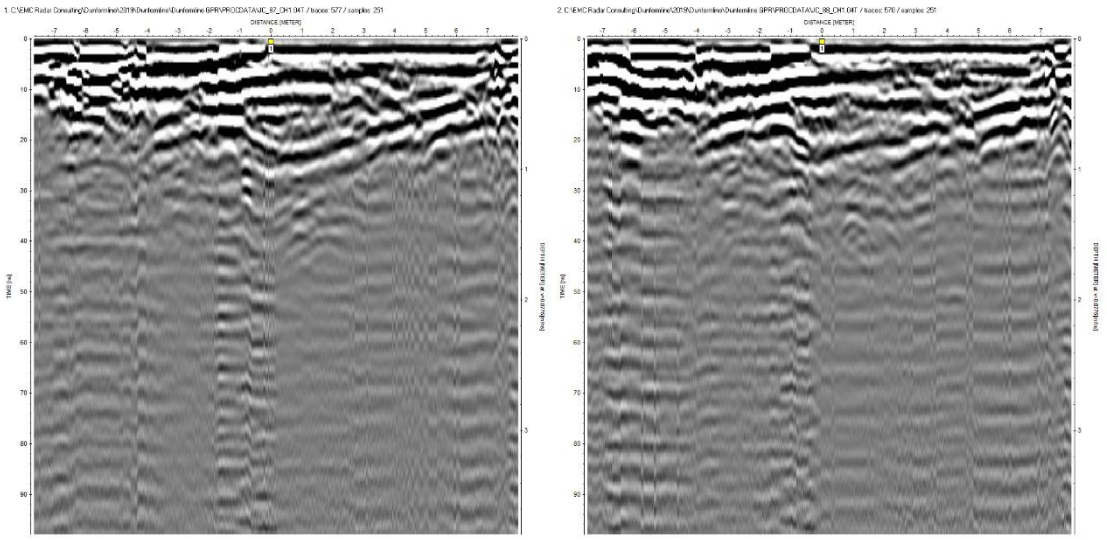


Figure 14: Survey lines 87 and 88 at y = 21.5m and 21.75m respectively.

The ringing (echo effects) visible in survey line 87 (Figure 14) appear to originate from a combination of a slightly raised object at ground level just before the zero x position and the large subsurface feature centred on x = 0.5m which lies above the possible wall/floor level (layer change). This second feature corresponds with the position of the possible drain identified earlier and the ringing is likely to derive from an air gap within the utility. There is also ringing visible in survey line 88 but this appears to originate from an object immediately adjacent to and at the level of the possible wall/floor feature.

In the NW sector of the survey area, the Elgin vault is no longer visible. This does not mean that the entrance to the vault lies no deeper than 79cm. It is the air content of the entrance which produces the strong signals visible in earlier time slices. As radio waves travel at 0/3m/ns, the potential depth is of the order of 3m.

Time Slice at 91cm Depth (c. 23.4ns)

The outline of the rectangular feature discussed above is clearly visible at this level. In the eastern end of this feature there appears to be a distinct break between the northern edge and the x = -1m edge of the southern section. This reflects the data visible in survey lines 18 and 25 (Figure 9). Taken together with the more broken pattern in the western sector, this suggests the destruction of a former building rather than the construction of a hard standing prior to the building of the current church.

The short North/South lines follow those visible either at the ground surface (Figure 7) or at 9cm depth (Figure 8) and are therefore echo effects from the grave markers above.

There is a sufficiently dense pattern of signals in the NE corner to question whether this also contains the remains of a former building. Survey lines 14 and 16 show

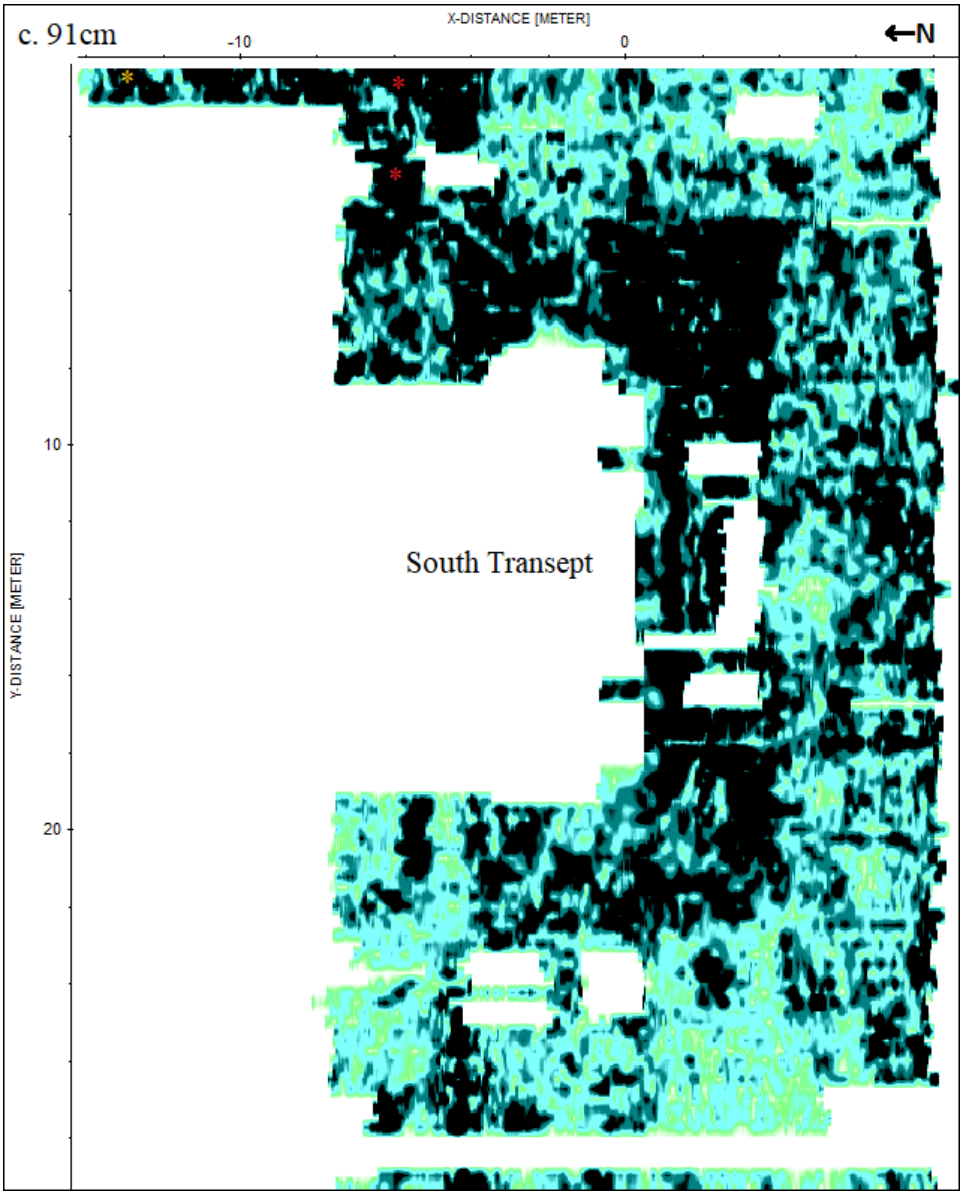


Figure 15: Time Slice at c. 91cm depth.

large blocks of signal immediately to the south of the transept (Figure 16). The upper layers are probably related to the site preparation prior to building the parish church. The lower layers are similar except that the increased vertical spacing of the banding around x = -6m may indicate a slower transmission velocity. This would indicate an increase in water content within the underlying layers but may also indicate a change of materials. Interestingly, these blocks of signal align with small columns of signal within the first two survey lines (Figure 17). Two red stars in Figure 15 show the relative horizontal positions. The yellow star in Figure 15 indicates the position of small anomalies centred on x = -13.1m on the first two survey lines (Figure 17). The position of the current church transept means that there is simply not enough area coverage to conclude whether these positions mark the remains of part of a building or not. It is a possibility which would require excavation to prove or disprove. If it is, the destruction has been greater than that of the main rectangular feature.

The thick black line, oriented East/West and centred on x = c. -5.5m to the west of the

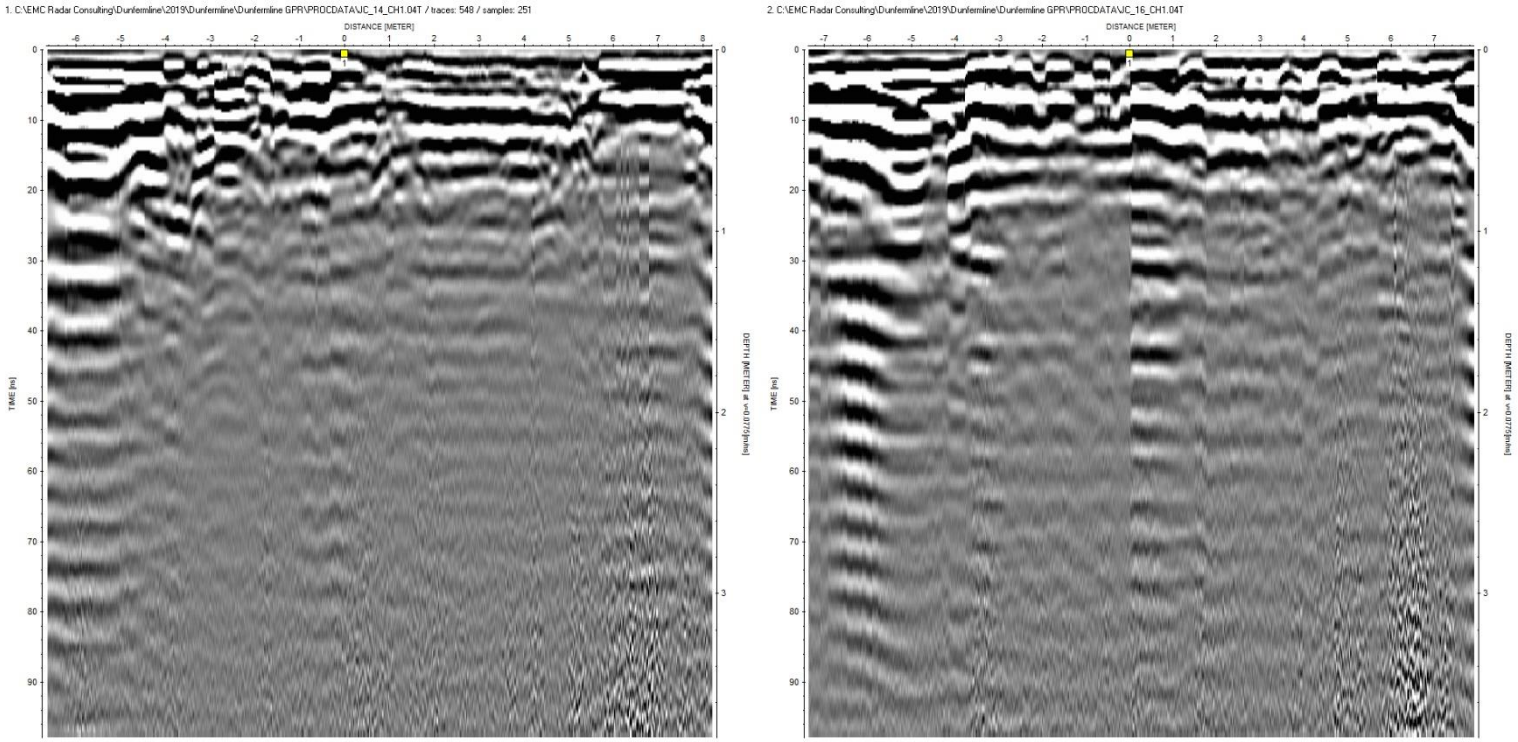


Figure 16: Survey lines 14 and 16 along y = 3.5m and 4m respectively.

transept lies directly beneath the entrance to the Elgin vault. This appears to be an echo effect from the air gap of the entrance above (cf line 85 in Figure 6).

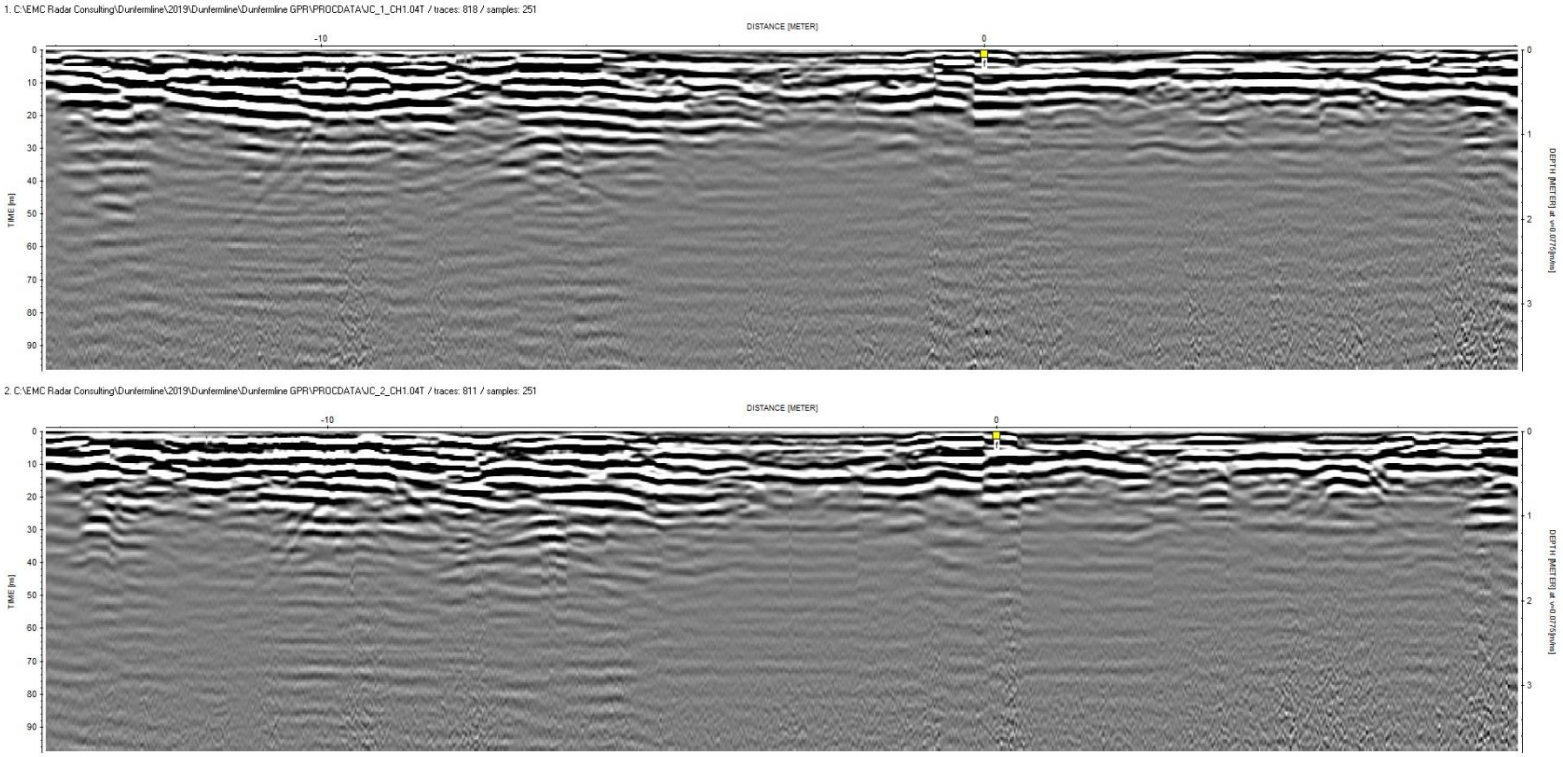


Figure 17: Survey lines 1 and 2 along y = 0.25m and 0.5m respectively.

Time Slice at c.1.1m Depth (c. 28.5ns)

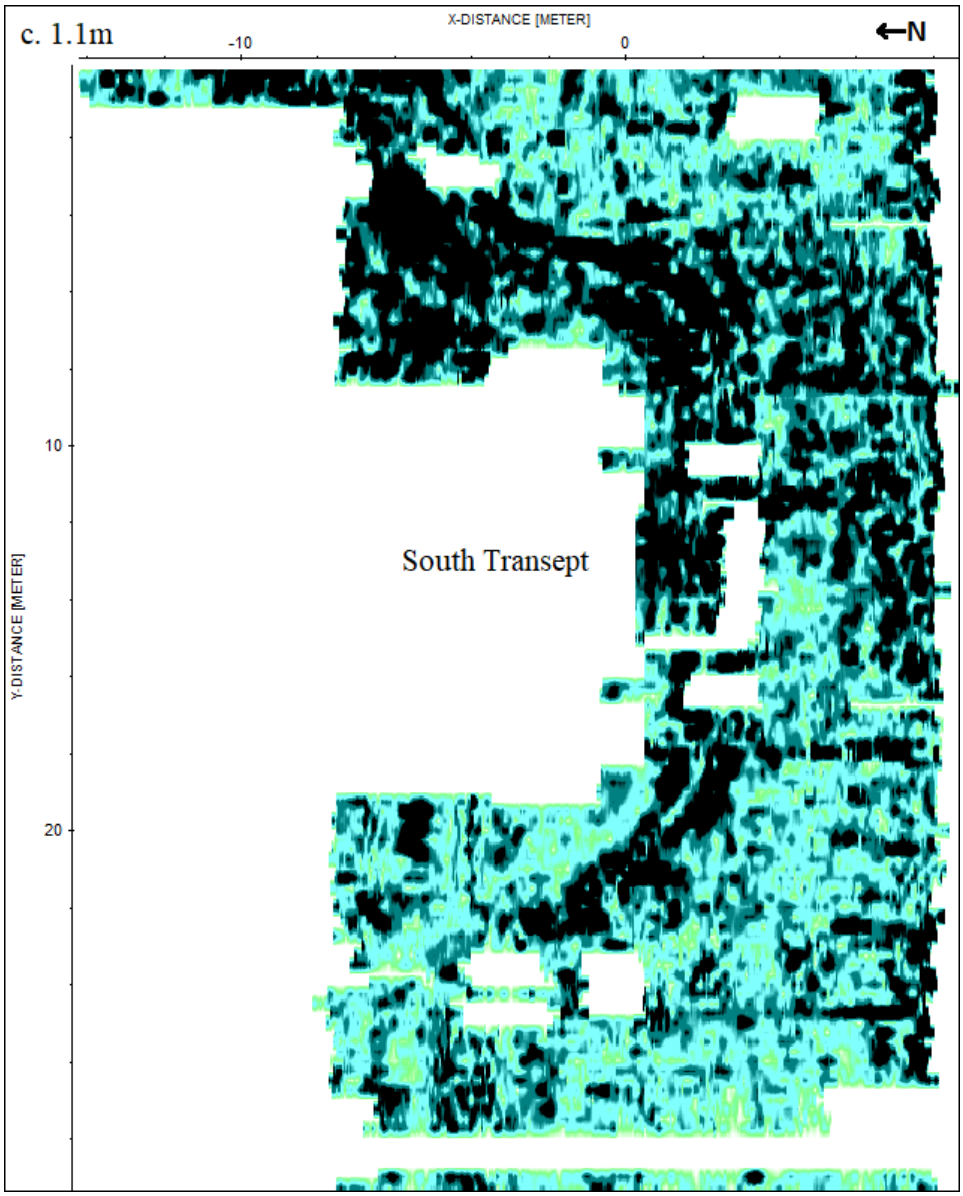


Figure 18: Time Slice at c. 1.1m depth.

Most of the signals in this time slice are echo effects from above. The outline of the possible rectangular feature has mostly disappeared, giving way to ringing from the path adjacent to the parish church and from the possible drainage pipe. A similar effect is visible from the entrance to the Elgin vault and from the many north/south lines indicating the position of grave markers.

The area outside the NE corner of the transept is mostly no exception. The strong banding of signals, increasingly stretched in the vertical direction, suggests slowing down of the transmission velocity which indicates that this area is holding water in the subsurface. An example is the first 2m of line 14 (Figure 16). However, there are a few signals which suggest the presence of anomalous material at this depth. Examples can be seen in line 16 below x - -5m (Figure 16) and line 18 below x = -5m and -3.2m (Figure 9). Unfortunately, they do not form a coherent pattern which makes them difficult to interpret. It is possible that a better result might be obtained if

this part of the survey could be repeated in drier conditions. Water does not just slow down the transmission velocity, it also increases the attenuation (loss) of the signals, especially in a soil like this which is not wholly favourable to GPR survey.

Time Slice at c.1.24m Depth (c. 32ns)

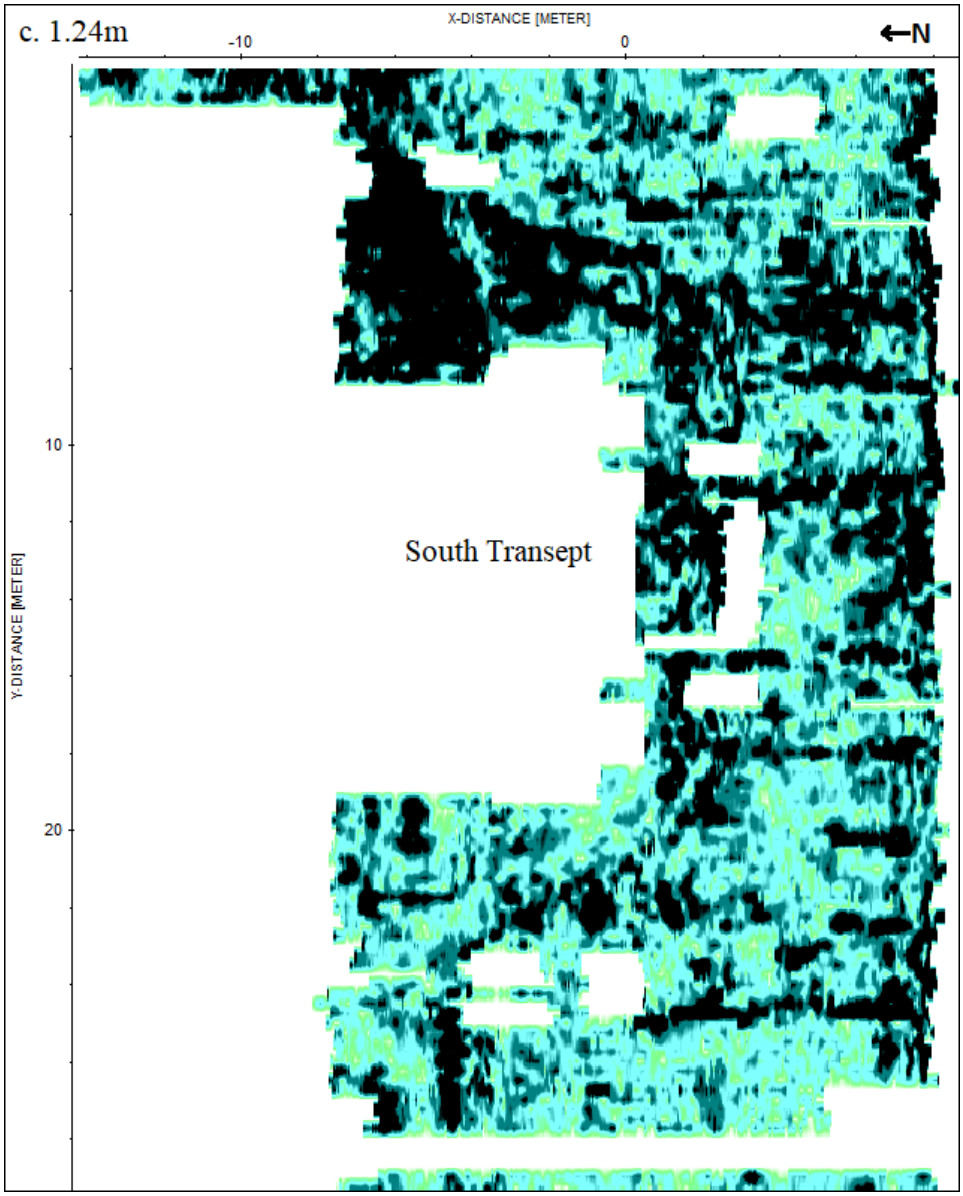


Figure 19: Time Slice at c. 1.24m depth.

By this depth, although there are a few real signal returns, these are obscured by the greater number of echo effects. Survey line 18 shows a short section of real data between x =-2m to 1.2m (Figure 9). This line is part of the area adjacent to the East wall of the parish church transept, at y = 6.25m. As with the previous time slice, it is possible that a better depth of penetration and better distinction of archaeological remains within their context might be possible if the water content of this environment were less.

Time Slice at c.1.73m Depth (c. 44.5ns)

The same problem arises with the time slice at 1.73m depth (Figure 20). Survey lines 16, 18 and 29 in the east; 117 and 127 in the central area; and 82, 87 and 88 in the west all suggest that there are real remains at this level, but the pattern of real remains is indecipherable due to the widespread presence of ringing and losses associated with water content. See Figures 6, 9, 10, 13, 14, and 16.

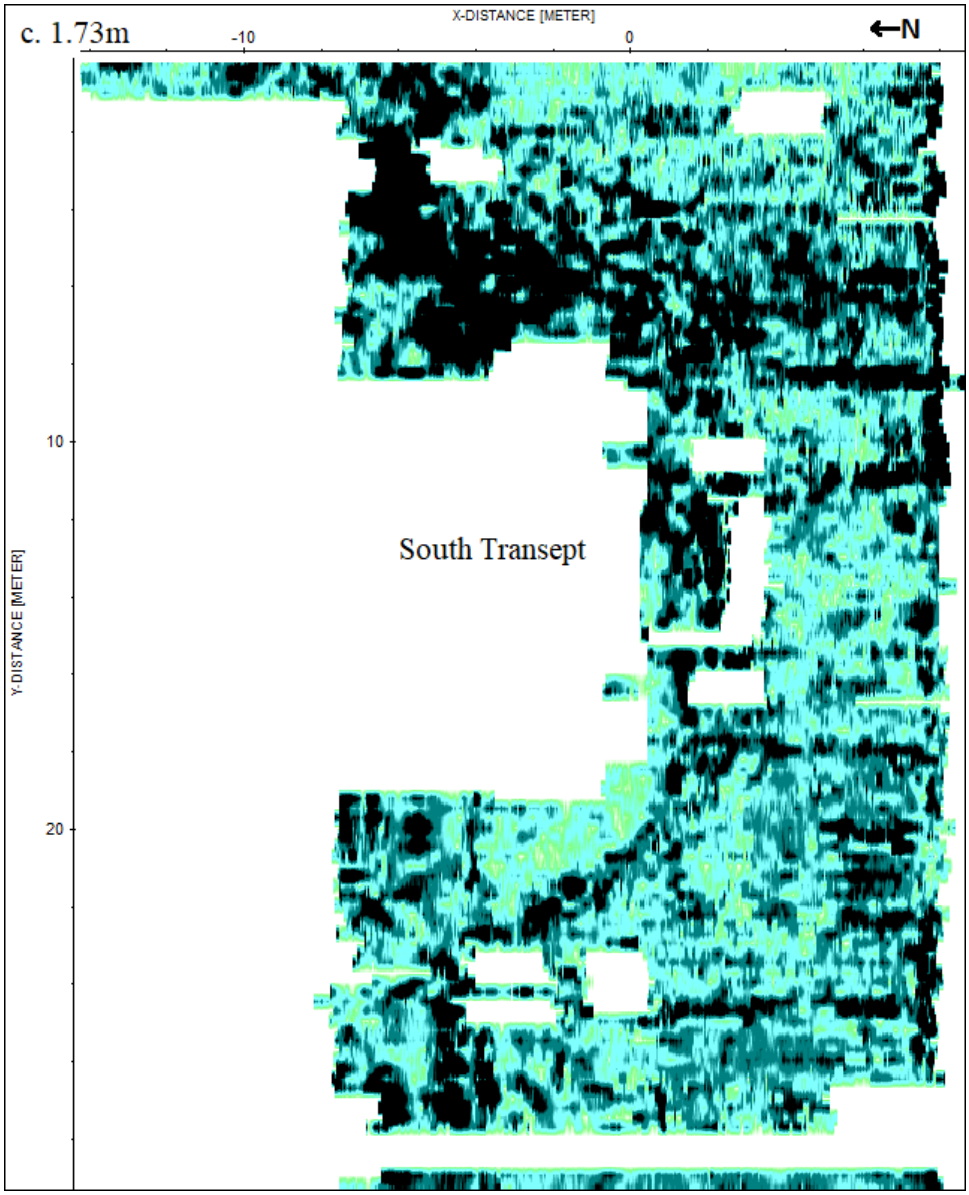


Figure 20: Time Slice at c. 1.73m Depth.

Time Slice at c. 2.44m Depth (c. 62.9ns)

Echo effects can sometimes be useful in identifying the outline of certain features (Figure 21). This time slice is composed entirely of ringing, but it confirms that somewhere in the upper levels, there is a diagonal linear feature running from the first buttress on the south side of the parish church towards the NE corner of the transept. It is probable that, as for all the other strong signal returns depicted, this is a modern feature.

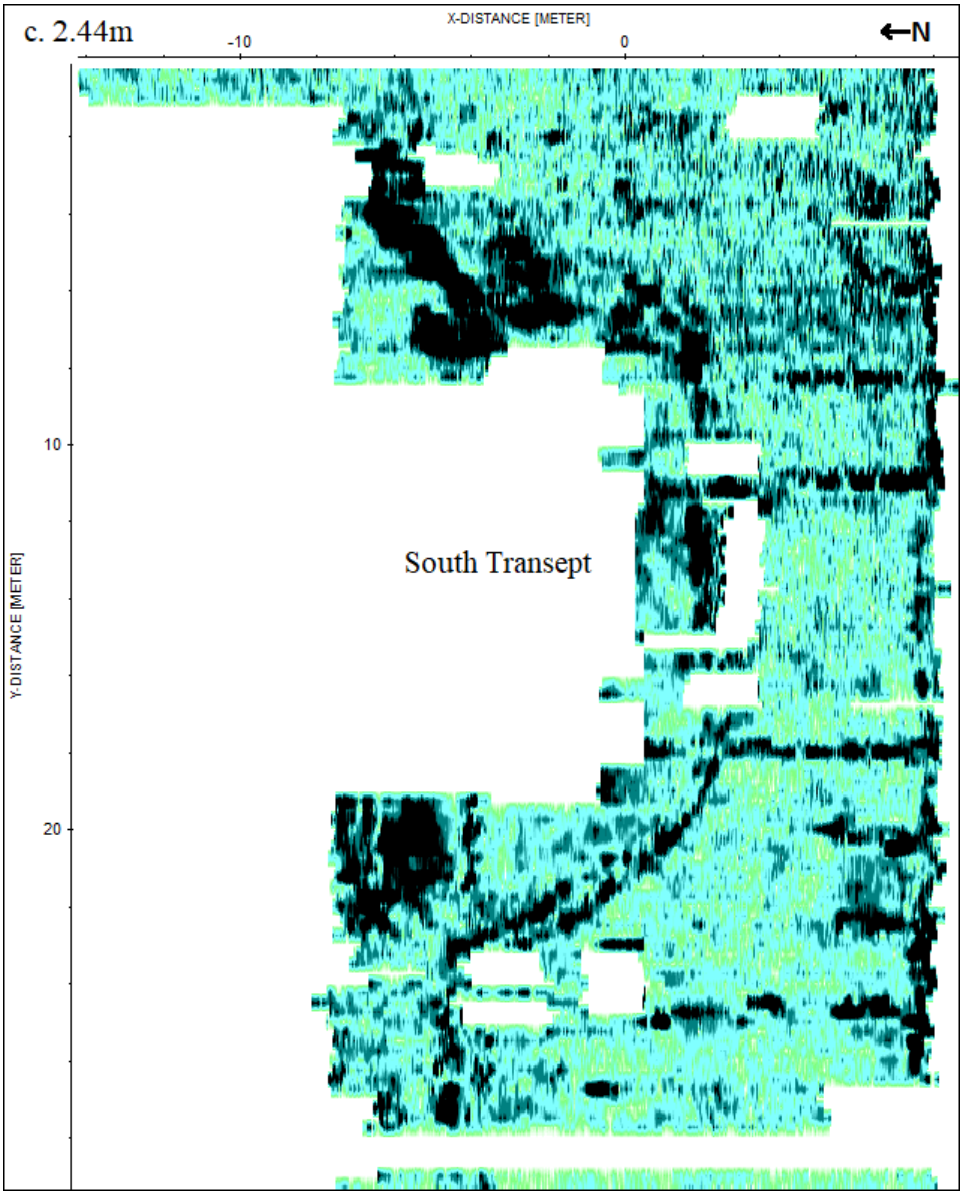


Figure 21: Time Slice at c. 2.44m Depth

2-Dimensional Data: 400MHz

The two previous surveys have made use of both a 250MHz and a 400MHz antenna, the former being used for its greater depth capability and lower attenuation and the latter for improved target definition. Although this strategy has been successful in the past, the increased moisture content of the ground following a period of prolonged wet weather in this year reduced the likelihood of the 400MHz antenna being able to penetrate enough depth to detect any medieval remains. A trial of two survey lines was made at the eastern end of the survey area using the same survey reference lines as for the 250MHz antenna. This confirmed that, although it was possible to survey down to c. 20ns (c. 75cm depth), no further depth was achievable as attenuation was virtually 100% thereafter. Since this meant that it would not be possible to reach a realistic depth for the medieval archaeological remains, the 400MHz survey was not continued. This survey could and should be attempted when the site is drier.

Conclusions & Recommendations

In theory August should be one of the best months in which to carry out a GPR survey in the vicinity of Dunfermline Abbey. As noted in the previous two reports, the soil is not entirely favourable, due to its clay content. In dry conditions, it is possible to survey successfully on clay soils or, as in this case, soils with a major clay component. Water provides mobility to the ionised components in the soil, resulting in the loss of signals into the ground as a weak electric current. The site was wetter than in previous years. This impacted significantly on the survey. The resulting attenuation restricted the depth penetration of both antennas, making it impractical to use the 400MHz antenna and weakening the strength of the returned signals originating with the 250MHz antenna below 1m depth. It was still possible to detect at least one major feature which predates the construction of the present parish church and which does not appear to relate to the use of the ground as a graveyard.

It was also possible to observe, within the 2-dimensional data, that other features existed at greater depth although the associated signal returns were relatively faint. However, it was not possible to distinguish the pattern of these features in the horizontal (or quasi-horizontal) plane due to extensive ringing (echo effects) caused by the nature of some near surface features (possibly exaggerated in some instances by water content) and the uneven surface of the site. These strong echo effects obscured the fainter signals from the deeper anomalies, making analysis of the signal patterning impossible.

The first two time slices, Figures 7, 8 and 11, contain patterns of post medieval use of the site. Previous reports ignored shallow layers less than c. 20ns in depth. These time slices were reproduced and analysed because of the existence of extensive ringing. They allow the echo effects to be discounted in the time slices with real data of interest, particularly Figures 12 and 15.

The first appearance of possible earlier building remains is seen at c. 79cm depth (Figure 12). Although the scattered pattern of the remains make it clear that this structure has been demolished, the outline of a building is clearly defined across the site with outer sections that appear extremely solid. The depth measurement is not great. The feature is visible for the next 20cm in depth but no more (Figures 15 and 18). This leaves open the question of whether the extant remains are those of a floor or an outer wall surrounding a floor. If the remains of walls define the outer edges, the implied width of a single wall may be as much as 1m to 1.5m from the continuity of the signal patterning, viewed in 2-dimensional data.

There are a few similar anomalies in the NE area of the site, close to the current building. It is not clear if these form part of the same structure, attached at right angles, or a separate one since the current church transept has been built over the greater part of this area.

It is not possible to date either structure beyond noting that it underlies the current parish church, lies above the limited evidence for deeper features (cf Figure 9) and is very slightly closer to the modern surface (by c. 10cm) than the topmost level of potential medieval remains found in the area of the eastern section of the former Lady

Chapel (2018 report). This places the feature above the level of the remains of the possible tombs within the area of the former Lady Chapel.

Recommendations

The outline of the possible building or buildings defined in Figures 12 and 15 should be compared with historical evidence in order to determine its nature, whether it formed part of the east end of the former abbey church and the time period in which it was used. It would also be interesting to understand why there appears to be the slight difference in depth levels between the GPR evidence to the North and that in the South of the present parish church, unless this represents different time periods.

It would be advisable to repeat at least parts of the survey using a 400MHz antenna at a time when the site was less saturated with water. Ideally, it would be useful to cover the full area. However, the surface obstacles will have a greater impact on the output from this antenna due to the size of any air gaps generated at surface level relative to the wavelength (25cm in dry soil) and there is a risk of increased ringing. If a restricted area were to be attempted, the most suitable parts of the area to investigate are the east end and the area in front of the steps to the south of the south transept door.

If it is possible to schedule a further survey in drier conditions, it would also be worth using the 250MHz antenna to sample the areas where this survey has identified deeper anomalies which could not be interpreted within the context of this survey. The target area, as defined by the 2-dimensional data from this survey, coincides with the area of the rectangular structure(s) identified in this survey.

Acknowledgements

This report was written, on the basis of the GPR survey, by Erica Carrick Utsi of EMC Radar Consulting working in conjunction with Alexander Birtwisle of Atlas Geophysical Ltd. The authors were also responsible for carrying out the GPR survey.

EMC Radar Consulting and Atlas Geophysical Ltd would like to thank Dr Michael Penman for his assistance with the practical aspects of the survey and for dealing with visitors to the Abbey during the survey.

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For the results of the 2016 Survey:
EMC Radar Consulting & OJT Heritage (2016) “Ground Penetrating Radar Survey of Part of the North Transept and the Vestry of Dunfermline Abbey for Dr Michael Penman University of Stirling”, 12th September 2016.

For the results of the 2017 Survey:
EMC Radar Consulting & OJT Heritage (2018) “Ground Penetrating Radar Survey of the Central area between the Vestry and the Altar and 2 External Areas overlying the former Lady Chapel of Dunfermline Abbey for Dr Michael Penman University of Stirling”, 9th January 2018.

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Schmidt, A, Linford, P, Linford, N, David, A, Gaffney, C, Sarris, A and Fassbinder, J (2015). "EAC Guidelines for the use of Geophysics in Archaeology. Questions to Ask and Points to Consider" EAC Guidelines 2, Europae Archaeologia Consilium (EAC), Belgium. ISBN 978-963-9911-73-4.

Further Information

Any queries arising from the content of this report or the GPR survey to which it refers should be addressed in the first instance to Mrs Erica Carrick Utsi, EMC Radar Consulting.

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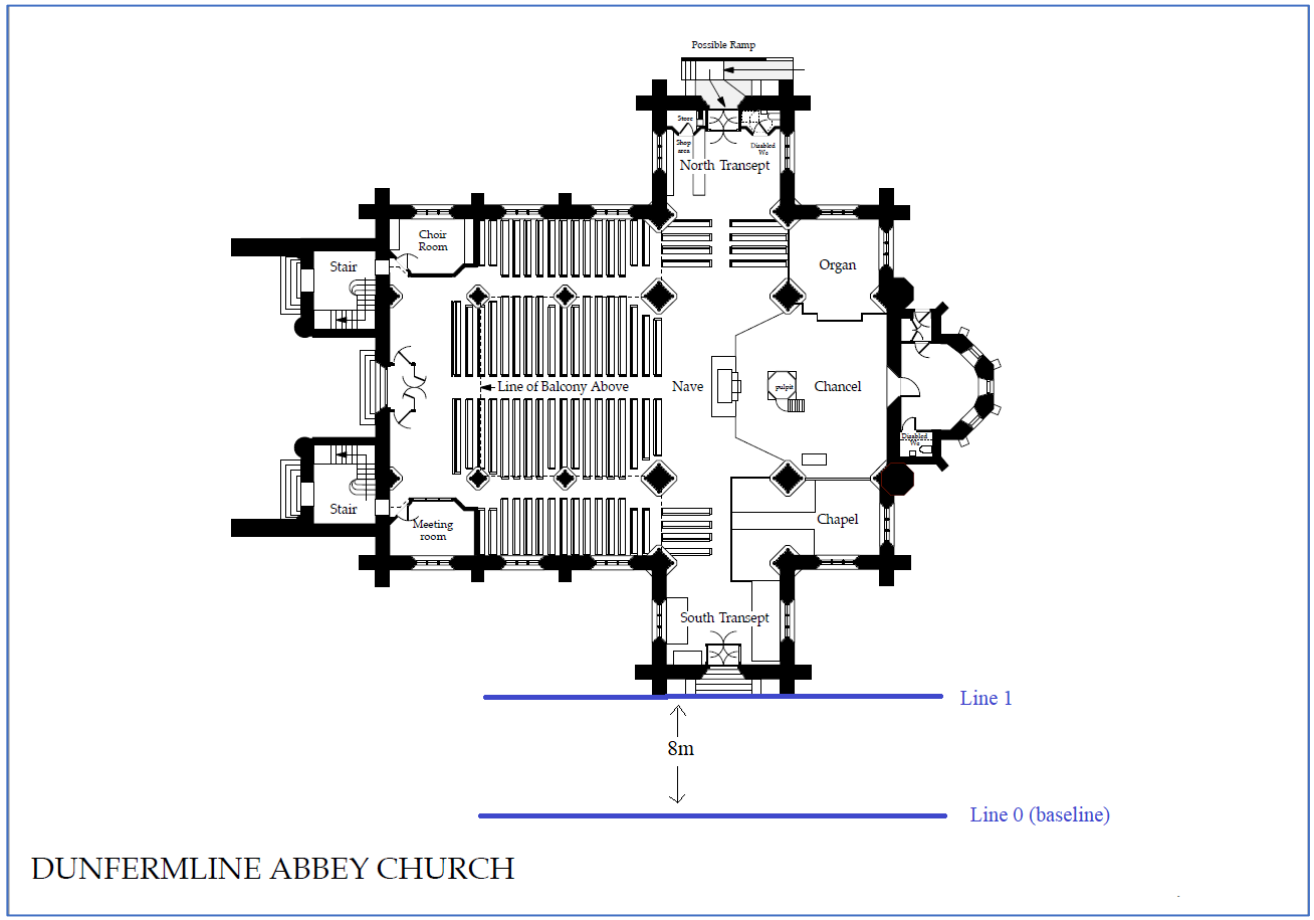
Appendix A: GPR Survey Reference Lines

GPS Refs o/s



Plan based on that drawn up by Tod and Taylor, Architects, Edinburgh in January 2005.