DRAFT

EMC Radar Consulting

OJT heritage

Ground Penetrating Radar Survey

of

Part of the North Transept and the Vestry of

Dunfermline Abbey

For

Dr Michael Penman

University of Stirling

25th August 2016

DRAFT

CONTENTS

DRAFT

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 a number of monarchs, their spouses and close relations were buried beneath the floor of the Abbey, the location of most of these graves, including those of six Scottish kings, is currently unknown. The exception to this is the large grave uncovered in the choir of the mediaeval choir, currently situated below the pulpit stair. This grave is thought to be 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 at least its predecessor and to locate, if possible, the site of as many large tombs as possible.

Accordingly this survey is a first trial to test:

- Whether it is possible to use Ground Penetrating (or Probing) Radar (GPR) successfully to investigate the subsurface of the present church;
- Which frequencies of radar antenna are suitable, if any, for this investigation;
- Whether it is possible to detect any large graves in the area below the parts of the North Transept currently free of church furniture; and
- Whether it is possible to detect any graves located in the subsurface below the Vestry which comprises the eastern end of the church and lies immediately to the West of St Margaret's shrine.

The areas selected for survey were chosen because they were potentially of interest since it is thought that the North Transept may lie above the former Lady Chapel and the Vestry is adjacent to St Margaret's shrine. Both areas are free of immovable surface obstacles which is not the case elsewhere, the majority of the church floor being covered by fixed pews.

SURVEY STRATEGY

Use of Ground Penetrating Radar

GPR operates on the same principles as conventional radar except that it uses a wider 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 signal is received by another antenna. The amplitude of the returning signal

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.

Identification of graves is normally made on the basis of patterning in the horizontal data. It may be possible to detect potential graves on the basis of 2-dimensional, vertical data but it can be difficult to determine the full extent of the feature unless an area survey is completed. Identifying the extent of a potential grave is often the easiest way to distinguish between a grave and any other subsurface feature.

The type of patterning depends upon the style of burial, the surviving contents of the grave and the frequency of radar antenna used for the survey. Human remains, of themselves, are not usually identifiable except in the early stages of decomposition where associated liquids and gases may be detectable. Bones buried in soil interact with their environment and rapidly become electromagnetically indistinguishable. Large tombs which incorporate air gaps are easily detected by GPR. Typically, the interface between stone and air (or soil and air) results in a strong signal response since the two materials have very different electromagnetic properties. Where either metallic grave goods have been interred with the deceased or a metallic coffin or coffin lining has been used for burial, detection by GPR is a good prospect. The electromagnetic response of metal is typically very strong because of its conductive properties. It is also not possible for radar to penetrate metal so, providing that the artefacts under examination are large enough for the conical radar beam not to penetrate past them, the only signals below metal objects should be echo effects, known as ringing.

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 or 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. Inter-cutting of graves is a good example of where this may be a difficulty. It is to be expected that royal graves will not intercut with one another although the possibility exists of ground clearance prior to a royal burial.

As far as built structures such as the footings of walls are concerned, identification may be possible in the vertical plane if sufficient vertical extent exists. It is usually easier to identify wall foundations from their patterning in the horizontal plane by recognising the remains of a linear, rectangular or other non-randomly shaped feature.

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.

Christian graves in the UK are invariably oriented East/West and the trial survey therefore was carried out along a North/South axis in both areas of investigation, namely part of the North Transept and the Vestry. This was in order to optimise detection of any extant identifiable graves since optimal detection by GPR occurs when the radar crosses the target. Although other subsurface material may be differently orientated, this is not a primary aim of this survey.

Survey depth was a major concern for this survey due to the demolition of the mediaeval Abbey and the construction above of the present building. Although it was not possible to determine the full depth extent of any former Abbey Church foundations, historical records researched by Dr Michael Penman of Stirling University suggested that a gap of 2m to 3m between the floor of the current Abbey church and the remains of the previous church was to be expected. Part of this gap is air. With this in mind, low frequency antennas were selected for the initial trial so as to maximise depth penetration. Unfortunately this also means that the degree of target definition is limited since both probing depth and target definition are the direct product of the wavelength(s) emitted by the radar. Longer wavelengths increase probing depth at the expense of a reduced degree of target definition. In dry soil the wavelength of a 400MHz antenna is approximately 25cm making objects of less than 2.5cm undetectable. Under the same conditions the wavelength of a 250MHz antenna is approximately 40cm making objects of less than 4cm undetectable. In practice, the target definition may be considerably less than these calculations suggest. In terms of distinguishing one target from another, the separation required, as noted above, is 1 wavelength and therefore 25cm in the case of the 400MHz antenna, 40cm for the 250MHz antenna.

Equipment

The equipment used for these surveys was a GroundVue 3_1 with two different frequencies of antenna, 400MHz and 250MHz. GroundVue3_1 is a single channel radar and the two antenna frequencies were therefore used sequentially rather than simultaneously.

In order to ensure that the maximum data were obtained from relatively small survey areas, the antennas were deployed on manually towed skids rather than using a more traditional trolley for which there would have been an offset between the front of the trolley and boundary walls, pews etc. All antennas contain arrays for narrowed signal beam and are heavily screened in order to avoid interference from objects above ground. It is not possible however to fully eliminate transmissions such as those in the Vestry 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

Although both floor areas were uneven, this was consistent with the expected variation found in the floor levels of most historic churches and did not prevent the survey from being carried out in a regular and accurate manner. In the case of the North Transept, the floor covering was wood, for the Vestry there was a carpet above the wooden panelling.

Both surface types had an effect on the encoder wheel distance measurement. The data has been adjusted to correct this by reference to the known distance between the two survey reference lines in each area.

Site Coverage

In order to maximise the information obtained by the GPR, survey lines for all four surveys were completed at a transect spacing of 0.25m. This is half the spacing required by the widely accepted guidelines published by English Heritage (Jones, 2008) These were originally set as a compromise between the investment required to achieve the Nyquist requirement for full information and an acceptable level of information with a lesser use of resources. For this investigation, it is more appropriate to achieve the Nyquist requirement because of the limited area access and the potential difficulty of interpretation given the history of the site. Also, the areas being limited 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 along the line of travel of the radar was set for 23mm in all four surveys. The 400MHz data was collected to a probing depth of 80ns (approximately equivalent to 4m in dry conditions). The 250MHz data was collected to a probing depth of 100ns (approximately equivalent to 5m in dry conditions). As will be seen from the data in the appendices, the actual depth of penetration of each antenna is a little less than the theoretical. This is determined by the electromagnetic properties of the subsurface.

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.

There are potentially at least three variations in velocity for the Abbey. Firstly there are known air gaps directly below the current church floor. Electromagnetic waves travel at a velocity of 0.3m/ns through air. The velocity of these waves through soil, even dry soil, will be much less. Historical information indicates that the Abbey was prone to flooding in the past. The presence of moisture reduces the velocity at which electromagnetic pulses can travel. Unfortunately it is not possible to produce radargrams (2-dimensional GPR data) with adjustments for varied velocity. The data are therefore presented at the calibrated velocity. This means that the depth in nanoseconds time is accurate but that the absolute depth in metres is not since adjustment needs to be made for the size of any air gap. As explained later in this report, it is not possible to distinguish the areas of void from those where no air gap exists because of the limitations of measurement imposed by using a low frequency radar.

Curve fitting has been used to calibrate the transmission velocity of 0.1m/ns, indicating dry conditions in most of the subsurface of the Abbey church at the time of the survey.

During processing of the 400MHz data, it was noticed that there were areas where signal was being lost. Calibration by curve fitting in these areas confirmed that transmission velocity was lower in these areas, consistent with the presence of moisture.

Depths have therefore been expressed in nanoseconds time rather than metres/centimetres since these are an accurate measure. To obtain an accurate depth reading in metres/centimetres at any given point, the proportions of dry depth, moist depth and the dimension of air gaps, if any, would have to be known.

Fieldwork

The fieldwork was carried out on Monday 13th June and Tuesday 14th June 2016.

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 and no colour scale is therefore provided.

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. On this colour scale pink indicates a high signal amplitude (positive or negative). The darker the colour, the greater the difference between the feature and its surrounding environment. White or light grey denotes continuity with or similarity to the subsurface environment.

The North Transept

Two parallel survey reference lines were placed in the free area of the North Transept in a North/South orientation from the area of the Organ in order to ensure that each radargram could be re-aligned accurately relative to the full data set. Markers 1 and 2 on the data indicate the positions at which the radar crossed the survey reference 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 2-dimensional data (radargrams) from the area of the North Transept are characterised by dense signals from the immediate subsurface of the current church floor. In the immediate vicinity of the organ, there is relatively little material lower down. Within 1m to the West, however, a relatively high density of signals becomes visible for virtually the full depth of 100ns. The radargrams show a clear break between the modern subsurface and the historical remains at around 30ns to 40ns with the historical remains appearing at a depth of approximately 50ns to 60ns (Figure 2). Line 3 (left hand image) in Figure 2 illustrates the relative paucity of signals below 40ns. The signal returns visible mimic signals higher up which indicates that these are echo effects from the modern subsurface since echoes invariably follow a similar path to the original signal from which they emanate. If there were signal returns from historical material these could potential mask the ringing, provided that the signal strength was sufficiently strong. Line 6 (right hand image) shows signal returns from both the near surface material and the historically buried material. Line 3 was recorded at 1m and line 6 1.75m to the West of the organ step.

Although this data is relatively difficult to interpret there does appear to be a stratigraphic interface around 35ns in both plots as indicated by an unbroken black/white/black line across the full length of the plot at this depth. For line 6, this line curves with its maximum height being between -0.8m and -0.2m along the x-axis (direction of travel of the radar).

The apparent density of material will be a reflection of a number of factors including the use of a low frequency radar (low target resolution), the pitch backfill and any site levelling carried out before construction of the present church as well as the density of remains. Line 6 indicates strong echo effects below 60ns, to the right of x = 1m. This might indicate the presence of metal directly above the ringing.

Further to the West, there is continuing evidence of a similar pattern. There are closely packed signal returns within the first 30ns to 40ns of the current church floor. The signals below this are fewer in number but appear to be reflections of larger objects. Lines 24 and 26 cross not only the North Transept but also most of the Nave. Signals which could potentially be consistent with formal graves are visible in both areas.

The most obvious of these is a large block of signal lying approximately at the centre of the Nave, between 8m and 9m along the x-axis, in both radargrams (Figure 3). The top of the upper signal lies at c. 35ns along the y-axis. Directly beneath this is a similar block of signal whose upper edge lies at c. 50ns depth. It is difficult to be certain that there is a reversal of polarity in these signals but line 26 suggests that this may be the case. A reversal of polarity is indicated by a black/white signal being replaced by a white/black signal lower down (or vice versa). There is no significance in whether the signal passes from positive to negative or the reverse. It is the reversal from one to the other which is the indicator. This typically occurs when the radio waves enter a body of anomalous material and then leave the same body again lower down. Where such a reversal is clearly seen, it is possible to measure the height of the buried object from the entry and exit of the reversed signals. Although this is not possible in this instance, the patterning suggests that this feature has a substantial depth of c. 75cm, based on the calibrated transmission velocity (which could potentially vary within this material). The first survey line to cross the nave is line 21 and the last is line 26, the survey access having been determined by the position of the fixed pews. This represents a distance of 1.25m for which the feature is detectable. Within the area of the North transept there is a similar but smaller feature, visible below marker 1 in line 26 and in a similar position in line 24. This does not have the same physical breadth of the substantial feature in the Nave and may therefore be a different type of feature. It is also possible from the number of adjacent signals that this is an area that has been disturbed which might therefore have originally been a larger feature.

Finally there is a large feature within the near subsurface of the current church just beyond the 14m mark along the x-axis. Although is unlikely to relate to the former Abbey church, it is worth noting because it suggests that there may be moisture present within this area. Water slows down the transmission of the electromagnetic pulses. The width of the black and white banding in this area can be seen to increase with depth in line 26 compared to line 24 suggesting a slowing down of transmission velocity and therefore the likelihood of a wet subsurface.

Continuing further to the West, lines 38 and 42 show similar patterning with at least one significant feature immediately to the East of survey reference line 2 (indicated by the marker 2 in Figure 4). In line 38 (lhs), there is a substantial column of strong signal return which could potentially be associated with ringing from metal at the top of the column, originating at c. 69ns. Since radio waves cannot penetrate metal, this type of echo effect would be typical. The patterning in line 42 is more dispersed but still indicates anomalous material within the same area. This is considerably deeper than the large feature in the Nave. The difference in depth of 34ns would be approximately 1.7m, assuming no air is present. An air gap would increase the depth difference. There is other material directly above this feature but still apparently lying within the subsurface of the former Abbey church i.e. below 30ns in depth.

3-Dimensional Data: 250MHz

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

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.

The area surveyed is primarily comprised of the part of the North Transept free from fixed pews. The extension to the North is the centre of the shop and the extension to the South crosses the Nave towards the South Transept.

As there is a known air gap between the current church floor and the historic land surface (measured to 55cm below survey lines 39 and 40), it is extremely likely that transmission velocity does vary across the site. Depths have therefore been given in nanoseconds time and not translated into metres and centimetres. This can be done where the position and size of the air gap is known. For example, an air gap of 55cm would measure 3.7ns in depth. A depth of 40ns along lines 39 and 40 would therefore represent 55cm of air and a further 1.8m of subsurface making a total depth of 2.35m. The general rule of thumb for depths where the transmission velocity is 0.1m/ns is that each 20ns represents 1m. If this air gap did not exist, the full probing depth would therefore be 2m. The depth is greater where the air gap exists because the radio waves travel three times faster in air.
In the light of the 2-dimensional data which show a division between the current church subsurface and that of the previous Abbey church between 30ns and 40ns, time slices are considered from 30ns downwards.

Time Slice at 30ns (Figure 5)

This time slice shows 4 discrete rectangular or near rectangular areas of very strong signal return which could potentially represent formal graves. All are located in either the western or eastern ends of the North Transept and are marked 1 to 4 in Figure. The area beneath the centre of the Nave, although large in extent, does not appear to form a coherent pattern that might represent a grave.

There is a wide spread of other anomalous material across the remainder of the survey area, particularly in the centre of the North Transept.

Time Slice at 38ns (Figure 6)

The patterning towards the western edge of the North Transept strongly suggests a series of graves, potentially at least two more than seen in the earlier time slice, both marked with "?" in Figure 6. The additional feature to the North could potentially be consistent with a single burial in a lead lined coffin, the outline would be unlikely to be more clearly shaped due to using such a low frequency antenna. There is a suggestion that more material might be found beneath the pews further to the North. It is not possible to be dogmatic about the potential grave to the South of those marked "3" and "4" since only an edge is visible but the signal strength and such coherent patterning as can be seen suggests a potential double grave.

The lack of coherent patterning in the area of potential graves "1" and "2" does not rule out this interpretation. It might merely indicate a mixture of contents as opposed to the top and bottom of the features. The extra 8ns of depth would measure 0.4m through soil or building materials but potentially 1.2m for any area containing a void.

The area beneath the Nave, while appearing to be significant, does not appear to contain an outline that could reasonably be interpreted as one or more graves.

There is a linear feature running eastwards from the area of potential graves which may be significant. This could be an air gap remaining between two halves of a built structure, either still containing air or potentially backfilled with pitch. There is a possibility that it is an echo effect from a linear feature above, for example, connected with the church heating or lighting.

Time Slice at 44ns (Figure 7)

By this depth, another surface interface is visible in the area of potential graves "1" and "2". It is not an echo effect since it covers a different area from the signals directly above. Whether this is the base of the same grave or another lower down depends on the material from which the strong reflection emanates.

The western edge of the survey area again strongly suggests the presence of at least three graves with potentially more adjacent. This suggests the presence of either air or metal or both. The previous time slice is unlikely to contain reflections from metal in the area of "3" and "5" since these are not repeat reflections. Possible grave "4" however, could be an echo effect since it essentially covers an identical area.

There is an increase in anomalous material in the centre of the survey area. The linear feature observed in Figure 6 is still present (marked "L" in Figure 7) but seems to cover a slightly wider, less regular area.

There is a major change in the signal patterning in the area below the Nave where the strong signals appear to follow the edge of a large, potentially rectangular feature.

Time Slice at 63ns (Figure 8)

The positions of the potential graves marked 1 to 4 in the earlier time slices are still visible. With the exception of possible grave "4", the areas are reduced in size. There is also less material visible in the central section of the North Transept although the outline of the linear feature is still visible.

The large feature outlined below the Nave has all but disappeared although it would seem that the remaining smaller feature must be connected in some way.

The potential grave towards the South of the western edge of the North Transept is no longer visible.

Time Slice at 70ns (Figure 9)

The same three basic areas of interest are again highlighted at this depth. The eastern end of the North Transept appears to be covered by a greater number of potential graves than previously. This may indicate another level of graves although it is not

clear from the 2-dimensional data whether this represents echo effects from above or not. The column of signal visible in the right hand radargram (line 6) of Figure 2 at 70ns corresponds with the patterning in this time slice. Line 6 lies along y = 1.7rm.

A similar dilemma affects the western end of the survey area. However, the evidence of line 38 (Figure 3) suggests that there could be a combination of ringing from above combined with a potential new feature, possibly with metal content. Line 38 lies along y = 9.5m.

In the centre of the Nave subsurface there appears to be an extension of the feature previously identified. It seems likely that the visible edge is ringing from components above but there does also appear to be a possible channel leading downwards towards the West.

The central area of the North Transept is essentially unchanged although the linear feature running East/West previously referred to is clearer than might be expected. There are also traces of more anomalous material at this depth across the central area.

The one new area where strong signal reflections have not previously been seen is within the South end of the shop. It is not clear what this represents although it is unlikely to be a reflection from graves since, from the colour, the signal strength is less, indicating a lesser difference in material. However, several of the 2-dimensional radargrams from this area suggest that the signals are of a similar type to those thought to represent burials so it may be that these are simply less grand in nature.

Time Slice at 87ns (Figure 10)

The same patterning is visible in this time slice as in the previous one with the exception of the feature underlying the shop. This suggests that, rather than representing another level of graves, it is primarily composed of ringing (echo effects) from the features lying directly above.

Assuming that this does mostly represent ringing, then it is possible that some attention should be paid to the layout of the central area of the North Transept where the scatter of anomalous material follows a right angle corner into the shop entrance. This should be compared with known plans of the historic Abbey Church since it may be a reflection of a partial building outline although the signals themselves are likely to be either from scattered material or pitch infill.

Time Slice at 90ns (Figure 11)

This time slice is quite similar to the previous one. At the eastern end, comparison with the 2-dimensional data suggests that these may be echo effects from overlying features. However, at the western end, the 2-dimensional data suggests that these strong reflections are a mixture of ringing (e.g. as in line 38, Figure 4) and real features (cf line 42, Figure 4). If line 38 contains metal, as seems likely, then it does not cover the full length of the grave although it may cover the full width.

The material in the centre of the North Transept and below the centre of the Nave does appear to contain mostly echo effects.

2-Dimensional Data: 400MHz

The same survey reference lines were used for the 400MHz survey of the North Transept as for the 250MHz investigation. 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.

There is some speckling visible in the 2-dimensional data which corresponds to an unknown external transmission source. Although the frequency is sufficiently different not to prejudice the survey results, this can unfortunately not be removed from the data.

The 2-dimensional data from the 400MHz survey are unsurprisingly similar to that from the 250MHz survey. As with the former survey, there is an indication of a break between the relatively modern subsurface and the subsurface of the historic Abbey church at around 30ns. It is very noticeable that the higher frequency antenna is not achieving the same depth of penetration, as would be expected for the shorter wavelength. There is an improvement also in target definition where sufficient signal has penetrated.

As with the former survey, the survey lines to the West of the area, those closest to the organ, show details of the immediate subsurface but do not indicate any remains below c. 30ns. Survey lines 8 and 12, at 2m and 3m respectively from the organ step, lie in the area where some evidence of archaeological material below the c. 30ns level begins to be seen (Figure 12). In the case of line 12, the signal returns are not particularly strong which suggests that the underlying material is not significantly different from its surrounding environment. Line 8 is very different. There is some ringing originating just above the 30ns dividing line but considerably more below, including a column centred on the zero point of survey line 1. Ringing most commonly occurs either with metal because the radio waves cannot penetrate this or with air gaps because of echo effects set up by the relative sizes of the void and the wavelength. Either is potentially an indicator of a historic grave. In addition to the echo effects, there are two surfaces visible at c. 40ns and c. 50ns which suggest a buried structure.

Survey lines 15 and 19, recorded at 3.75m and 4.75m respectively, contain comparatively less evidence of archaeological material (Figure 13). There are faint traces of a possible structure in line 15 immediately to the South of survey line 1 (marker 1 in Figure 13) and some ringing immediately to the North of survey line 2. The indications of a possible structure below survey line 1 are very much stronger in line 19. A similar echo effect is visible below survey line 2. From marker 2 towards the South, there is a major change in the nature of the subsurface. The entire area of the radargram contains far less contrast and the few signals visible look like reflections of the surfaces above. This indicates attenuation or lost signal. Coupled

with the increase in the width of the black and white banding, it suggests that this area contains another material which is effectively slowing down the transmission of the electromagnetic pulses. The usual reason for this is the inclusion of moisture in a soil with ionised content, typically clay. Although it is not possible to test transmission velocity on this survey line due to the lack of hyperbolas, line 16 does contain a hyperbola which curve fits to 0.06m/ns, confirming the presence of moisture. Note that attenuation does not affect all frequencies of antenna equally. The general rule is the higher the frequency, the greater the losses (electrical and magnetic).

Lines 22 and 26, at 5.5m and 6.5m respectively to the South of the organ step, cover not only the North Transept but also cross the Nave (Figure 14). Both lines demonstrate that the bulk of strong signal returns occur within the current church subsurface. However, among other potential indicators of archaeological remains, there is an indication of a surface at c. 30ns depth at x = 6m and a little lower down at x = c. 10.5m in line 22. The markers b and a show where data were collected around church furniture which is why there is an absence of data in this section of the line. In line 26, there is a possible structure visible between x = 8m and x = 9m with the signal returns visible from 30ns down to c. 45ns.

The possible archaeology is not confined to the area of the Nave. Both lines contain short lengths of flat signals which could indicate the top and bottom of earlier features between the two markers indicating the possibility of areas of interest within the North Transept.

Moving further towards the East, lines 36 and 41 were recorded at 9m and 10.25m respectively from the organ step. Line 36 contains two substantial blocks of signal return, centred on x = 0 and x = 0.8 at c. 30ns depth which could potentially be graves (Figure 15). It may be significant that they lie at approximately the same depth and very close together. To the South, below marker 2, is a column of ringing which may relate to metal work in the subsurface of the current church. Beyond this, further to the South, there is more evidence of attenuation (or loss of signal) within the historic subsurface. Lower down than the two possible graves, at around 60ns, a short layer signal is visible.

Line 41 has a strong interface around 50ns depth and a fainter change from 60ns sloping upwards towards the South. Apart from these two possible layer changes, the main signals visible are a series of signals from 33ns onwards, directly to the North of marker 2 which may be ringing (echo effects) from features lying in the near subsurface from the regular spacing in the vertical direction.

3-Dimensional Data: 400MHz

As was done for the 250MHz data, the 400MHz data were combined into a 3-dimensional data block from which horizontal or quasi-horizontal time slices (where velocity changes occur) were extracted on the basis of changes in the plan view patterning.

Time Slice at 19ns (Figure 16)

This time slice has been extracted at a depth consistent with the near subsurface

associated with the current Abbey church because it shows a linear feature running West/East which is also visible at greater depths in both the 400MHz and 250MHz data. This corresponds to the ringing which can be observed in many of the radargrams immediately before marker 2 cf for example Figures 13 to 15 and the commentary on Line 41 above. It is therefore unlikely that this represents an archaeological features and it is more likely to be associated with the current building.

Time Slice at 28ns (Figure 17)

This time slice represents the first view of potential archaeological remains. Although it is much shallower than the 250MHz data this represents the only indication of the apparently major feature in the centre of the Nave where the apparent depth was 44ns (Figure 7). As in Figure 7, the overall outline appears to form the edge of a structure lying to the East of the survey area. However, it appears to contain a mixture of materials, unlike the depiction in Figure 7. It is not surprising that the outline is less solid since the target imaging capability of the 400MHz antenna is much greater than that of the 250MHz. Where the lower frequency antenna cannot image individual elements because they are too close together (less than 1 wavelength), it will combine adjacent features into one. The 400MHz data are therefore the more accurate. This does not necessarily mean that the feature is less substantial than originally thought. It may indicate a mixture of materials used for the construction of the feature.

The discrepancy in depth is more surprising. Some difference is to be expected since the two antennas are measuring in different basic units (their wavelengths). One possible reason is that the electromagnetic pulses transmitted by the higher frequency are being attenuated more strongly than those of the lower frequency so that the ability to detect the feature lower down is being lost. From the 2-dimensional data, the signals from the 250MHz antenna are not being attenuated significantly.

Since the discrepancy in strength of signal was noticed during survey, a 1.5GHz antenna was used to survey across the centre of the Nave in an attempt to improve the definition of the central feature. The maximum depth capability of this antenna is c. 30ns but this can only be achieved in good conditions where the soil is suited to GPR survey. Maximum depth is the depth at which real signal returns can be detected by the antenna. The maximum depth achieved with this antenna was c.19ns so that this feature lies below its range. This confirms that, although it is possible to use GPR on this site, the soil conditions are not optimal. It also confirms the necessity of using a low frequency antenna in order to reduce signal losses as much as possible.

Although the outline is not as clearly defined as in the 250MHz data set, there are two, possibly three groups of strong signal returns in the East of the area which might correspond to the possible graves observed in Figure 5. There is also a partial rectangular outline of strong signal to the South of these features which may or may not be a similar structure although, in this case, there is no anomalous material in the centre (and hence no air gap). If these are graves, then it seems likely that they have been disturbed, on the basis of the irregularity of their outline which indicates the addition of material similar to the surrounding environment. This would also imply potential removal of at least some of the contents.

The linear feature identified in Figure 16 is clearly visible but it is likely that this is an echo effect from above. Close to this feature, in the centre of the survey area a smaller rectangle of strong signal is visible, centred on (0.9, 5). Although this appears to be relatively short, c. 0.8m in length, it is also associated with a square area of strong signal which would potentially extend it by a further 0.6m. It should also be borne in mind that these strong areas of signal may represent the air gaps in the interior rather than any external stone construction. Although it is often possible to distinguish stone from soil, the difference in electromagnetic properties between air and soil are very much larger than those between stone and soil. Where air gaps exist, these signals will dominate the patterning. This is not to say that all strong signals visible in the time slices are air gaps as it is likely that there are both building remains and possibly also pitch added at a later date.

Time Slice at 31ns (Figure 18)

This time slice clearly shows two of the same graves as the previous 250MHz data set at the western end of the survey area. This confirms that these are substantial features and therefore potentially royal graves. On the basis of this time slice, these do not appear to be of similar construction. The more northerly appears to be shaped at the head end and possibly also at the foot. This may indicate shaping on the inside of a stone coffin. The shaping is consistent with but clearer than in the 250MHz data set (cf Figure 5). Grave 4 appears square in shape with extensions towards the East, outlining the remainder of a rectangle. This would be consistent with air gaps at the western end and partial air gaps (at this level) at the eastern end of the grave. There does not appear to be any internal shaping other than this.

These features lie in the area covered by Lines 36 and 41 (Figure 15). This confirms that the large signal returns visible in these radargrams are graves. It appears unlikely that, in this case, there is any metal present since no echo effects are visible in the 2-dimensional data below this level. Radio waves cannot penetrate metal and an effect such as that visible in Line 8 (Figure 12) or Line 38 (Figure 4) would be expected if metal were present. It seems therefore very likely that the radar is detecting air gaps only at these locations.

The patterning is very much less distinctive in the East of the survey area although there is a good candidate for an internally shaped grave in the centre of this section, with other possible similar material immediately adjacent. The irregularity of the signal shapes might also be the result of one or more graves having been opened post deposition. This area is covered by line 8, line 12 lies just on the western end (Figure 12). Line 8 shows clearly that this corresponds to ringing consistent with the presence of metal which strongly suggests that this also represents at least one grave. The metal is not present in the adjacent lines (7 and 9) but line 7 shows a faint slightly curved interface which could potentially be a reflection of a shallowly curved vault ceiling. The signal response is relatively low except at the top of the curve which would suggest that the area has been partially backfilled (Figure 19). If this interpretation is correct it could explain the disparate distribution of apparent air gaps. Line 8 confirms that the signal patterning represents more than one anomalous material since there is definitely some metal present.

The remaining area of strong signal returns lies in the approximate centre of the survey area, to the West of the shop entrance. There are no large features visible in this area at the depth of this time slice. The survey lines 22 and 26 were recorded in this area. The two largest areas of strong signal return cross lines 27 and 29. Both of these lines show short sections of clear layer signals and associated ringing in the case of line 27. This suggests that this may be remnants of burials either not as formal as the grave outlines detected in the East and West or potentially disturbed either by subsequent burials or post depositional investigations.

Time Slice at 34ns (Figure 20)

This time slice also contains clear indications of graves in a consistent manner with the previous one. There are at least two large graves in the western sector, fragmented evidence of something similar in the eastern section and the areas of strong signal return in the central section have increased. The evidence is also similar to the data generated with the 250MHz antenna, albeit with increased target definition (cf Figures 5 and 6).

Time Slice at 37ns (Figure 21)

Figure 21 shows the continuing development of the large graves in the West of the North Transept, at least one potential grave in the central section and some evidence for similar features in the eastern section. There is no evidence of any further features in the centre of the Nave.

The evidence is again quite similar to that from the 250MHz survey, allowing for the difference in wavelength and target definition.

Time Slice at 44ns (Figure 22)

The best grave definition from the 250MHz survey was obtained at this depth. In the 400MHz data, the same three areas continue to show evidence of possible graves with the most substantial remains being in the western section. The areas containing possible voiding appear to be smaller in the 400MHz data, potentially indicating that more of these areas have at least some contents, even if this is only soil. The implication is that the graves are probably slightly shallower than suggested by the 250MHz data.

As discussed above, the linear feature towards the southern edge of the North Transept appears, on the balance of probabilities, to be an echo effect from a feature higher up, closer to the present church floor.

There do not appear to be significant changes in patterning below this level in the 400MHz data.

Commentary: North Transept

Both surveys of the North Transept suggest the possibility of large sized graves within the western sector of this area. The identification of these features as graves rests upon the patterning visible in both the vertical and horizontal planes. It also relies on

a correct interpretation of the nature of the anomalous buried material. Even with a high frequency radar it is not possible to distinguish human remains from soil, clothing or wrappings as the electromagnetic difference between these materials is relatively slight and decreases with the length of time for which they have been buried. One common target which may indicate a grave are associated voids where the body has been placed in a large enough container whether this is a stone coffin or a vault. Included in the definition of a vault is any sort of simple stone structure, not necessarily a deep structure with an arched roof. Typically air gaps within coffins or small vaults diminish with depth assuming that some contents remain, whether this is soil, human remains or other associated material. Both data sets are consistent with this interpretation.

Another suitable target often associated with burials is metal and there is some evidence for a limited amount of metal present in this area (cf Figure 4).

Where the buried structure is large enough, it is common to find internal reflections from within the grave or vault. These show on radargrams as straight diagonal lines, visibly different in transmission speed from the surrounding environment. No such internal reflections are visible in any of the data which suggests that the graves are not as large as, for example, the burial cavities of the rich and famous in the 18th and 19th centuries.

In the central section of the North Transept the evidence in the vertical plane is potentially consistent with burials. However, in the horizontal plane, the patterning is much more confused and the areas of strong signal return are far less extensive than would be expected for an adult burial of a person with social status. There are at least two possible interpretations of this. Firstly, it is usual to find inter-cutting of graves beneath a church floor and unusual for this not to be the case (Rodwell, 2012). Given the use of low frequency antennas, it is unlikely to be possible for the GPR to distinguish between such graves and this patterning could reflect the situation where a higher status grave was surrounded by this type of material. The length of the one obvious potential candidate for a higher status grave (in the 400MHz data) is not consistent with the height of a mature adult but this could indicate the burial of a child or adolescent. Alternatively, the grave could be that of a full sized adult if it is assumed that the combination of a shorter full rectangle of signal to the East allied with a rectangular outline of strong signal to the West represents a particular type of grave construction. A second possible interpretation of the patterning is that the graves in this area could have been investigated at some point in time between the destruction of the East end of the Abbey and the construction of the present Abbey church.

Along the eastern edge of the North Transept the patterning is similar to that at the West end although the 400MHz survey also suggests that this patterning is more broken up than that to the West. There appears to be some evidence of vertical shaping although this only occurs for certain in one point. The likely explanations for the patterning are the same as those for the central area.

There appears to be an edge to an unknown large feature within the centre of the Nave. Although the 250MHz data show this as relatively solid, the 400MHz data

suggest that mixed materials may be involved. This implies that, rather than being an air gap, the signal returns may be from building materials.

There are two major discrepancies between the two data sets. The 400MHz data gave no indication of greater depth than 44ns whereas the 250MHz data indicates that the graves may extend below this level. The 250MHz data suggests that there are more large graves than does the 400MHz data.

It is not clear whether the depth evidence is due to the higher attenuation of the signals transmitted by the 400MHz antenna contrasting with the superior depth capability of the 250MHz antenna or whether the 250MHz data is primarily a reflection of echo effects generated within the 250MHz data. The general level of ringing in both data sets indicates that the soil in the subsurface is not entirely favourable to GPR survey although not so unsuited as to prevent the survey having useful results. From the 400MHz data there are also indications of areas with slower transmission speeds which almost certainly indicates the presence of subsurface moisture. It is probable that the results are a reflection of both processes. This would mean that the graves do extend at least some way lower than indicated by the 400MHz antenna but not necessarily to the full depth indicated by the 250MHz antenna due to the prevalence of ringing (echo effects) in both data sets. The echoes appear lower down in the data than the original features.

The question of the number of large graves is a matter of target definition. Both antennas measure within the parameters of their respective wavelengths. For either antenna to distinguish between similar features, there must be a wavelength between these features. In a dry soil, the wavelengths are 25cm for the 400MHz and 40cm for the 400MHz. If this spacing does not exist, the 250MHz will tend to show one larger object where two or more exist. The target definition of the 400MHz antenna is potentially the more accurate. The only possibility that the patterning of the 250MHz might be closer to the reality of the subsurface is if there has been intrusion into the graves in the central area or the eastern section. For this case, the 250MHz would effectively be reunited sections of the same feature. Currently there is no evidence to support this and it would require excavation to resolve.

The Vestry

Two parallel survey reference lines were laid out along an East/West orientation within the Vestry. At the western wall, line 1 was positioned 93cm from the South wall of the Vestry, ending in the North corner of the South bay window. Line 2was positioned 2.085m from Line 1, 0.8m from the large cupboard and ending towards the North end of the central window. Measurements given along these lines are the distance from the west wall of the Vestry.

The particular importance of the Vestry subsurface is that its proximity to the Shrine of St Margaret which lies directly to the East.

The transmission system for the Abbey's fire alarm is located within the Vestry. As this could not be turned off, there is some interference on both data sets. The frequencies transmitted are, however, significantly different from those transmitted by the radar and the overall effect is therefore the addition of some speckling to the data.

While this is not desirable, the effect is insignificant in comparison to the strong signal reflections from the archaeological layers below the Vestry.

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.

All 2-dimensional data is presented from North to South (left to right). The data from the Vestry shows a number of similarities with that from the North Transept, notably a division between the current church subsurface (down to c. 30ns) and the archaeological layers (from 40ns onwards), evidence of ringing in certain locations, a number of relatively strong signals from within the archaeological layers and some background ringing from the near subsurface associated with the soil conditions.

Survey lines 1 and 4 were recorded at 0.75m and 1.25m respectively from the West wall of the Vestry (Figure 23). Line 1 shows a crowded near subsurface and two distinctive columns of ringing of a type commonly associated with metal objects. The column centred on x = 0.9m appears to originate above the 30ns floor and therefore relates to a feature of the current church. It is not possible to tell whether the same is true of the other column of echo effects, centred on the end of the radargram but it seems likely, particularly since its location is directly beneath the floor of the Vestry toilet. The lesser strength of this column would be consistent with a pipe or duct not made of metal. Line 4 is more typical. The levelling off of the site prior to construction of the current church is evidenced by the flat stratigraphic layer visible around 40ns. Directly below this lie a number of features which are likely to relate to the former building remains, possibly with the addition of pitch. There are two signals lower down and therefore relating to the subsurface of the former Abbey church. The stronger of the two is visible at x = 0.77m and a depth of 78ns and the other at x = -1.5m and a depth of 76ns. It is very clear from this radargram that these low signals do not represent echo effects, confirming that the 250MHz data from the North Transept is not merely an echo of features higher up in the subsurface.

Survey lines 8 and 11, recorded at 2.25m and 3m respectively, show a similar pattern to line 4 although the old land surface visible at c. 40ns is neither as flat nor as uncluttered. Line 11 suggests that there is a considerable amount of material immediately below this surface. There are also signals from the relatively deep archaeology, around 80ns in line 11. Line 8 has a number of fainter layer signals.

Survey lines 14 and 17 were recorded at 3.75m and 4.25m from the West wall of the Vestry. The overall patterning is similar but the depth of the archaeological material varies from immediately below the subsurface (at c. 50ns) down to c. 80ns.

3-Dimensional Data: 250MHz

The full set of survey lines has been incorporated into a 3-dimensional data set on the

basis of their respective positions along survey reference line 2. Time slices have been extracted from the data set on the basis of changes in patterning.

Time Slice at 35ns (Figure 26)

This is the first level below the near subsurface where a potential for man-made features is apparent. It is not clear whether these are graves, the remnants of grave markers from the ground surface of the previous church or other built structures. If they are graves then the strong signals are presumably air gaps, if markers of graves lower down, then it is more likely stone of some sort which is reflecting signal. The potential for them being remnants of grave monuments comes from the fact that they seem to form larger outlines around a central non-reflecting material. Potentially their depth means that they lie c. 5cms above the 40ns interface referred to in the 2-dimensional data. They fall into three main groupings, marked "1", "2" and "3" in Figure 26.

Time Slice at 39ns (Figure 27)

At this depth most of the previous outlines coalesce into rectangular or near rectangular shapes, potentially indicating areas of voids at the top of formal graves. The images are very closely packed and it is not clear exactly how many of these features are present. There are at least four potential graves (marked "1" to "4" in Figure 27) but this does not include the full area of strong signal and it seems likely that there are more such features.

Time Slice at 51ns (Figure 28)

A similar density of areas of strong signal return is visible at this level and there is at least one full shape which looks likely to be the interior of a grave (marked "3") in Figure 28. The really interesting point, however, is that these possible air gaps do not coincide in position with the previous set with the exception of position "1", suggesting that there is more than one level of grave. Comparison of the features marked "3" in Figures 27 and 28 makes this very plain. The difference in level of 12ns would be 0.6m if this were soil or building materials but, if these are air gaps, then the difference is 1.8m (because of the much higher transmission velocity through air).

Time Slice at 62ns (Figure 29)

Very little of the previous patterning remains by this depth, the major exception being the grave marked "1". This can be seen to extend a little further eastwards than previously observed. It is not obvious what the remainder of the patterning represents or whether this is likely to be buried voids or building materials.

Time Slice at 77ns (Figure 30)

The edge of the feature marked as potential grave "1" is still visible but the alignment relative to the Vestry differs slightly from Figure 29 so, assuming this is the edge of a grave, this may also indicate layering in the burials. There is an end of a second potential grave to the South. The biggest change in patterning is within the centre of

the Vestry where a possible rectangular feature shows in near complete outline. It is not possible to tell whether or not this is a built structure but the form is anything but random so it is probably reasonable to assume that it is.

Time Slice at 80ns (Figure 31)

This is the lowest level at which potentially man made features are visible. There are three potential graves in the data, none of which corresponds to features higher up in the subsurface. None of the areas is a complete rectangle or suitably shaped for the interior of a stone coffin but all are large enough to constitute part of a grave.

2-Dimensional Data: 400MHz

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.

All 2-dimensional data is presented from North to South (left to right). The 2-dimensional data from the 400MHz survey have been affected worse than any other data set by the transmissions of the Abbey's fire monitoring system. This manifests itself, as can be seen in Figure 32, as strong speckling particularly in the deeper parts of the radargrams.

Survey lines 2 and 4 were recorded at 50cm and 1m from the West wall of the Vestry (Figure 32). Both show the distinction between the subsurface of the current church and the historic subsurface beneath. Both also contain blocks of signal which typically indicate the position of graves. There is no separate signal for the top and bottom because these are too close together for the radar to resolve and, as with the North Transept, no diagonal air reflections which would indicate larger vault-type graves. The depth of these features is reasonably uniform, c. 37ns.

The data in survey lines 10 and 12 is very similar to that of the previous two radargrams (Figure 33). Like line 4, line 12 shows two possible graves. Line 10 has a signal block which may indicate continuity with the more northerly of these although it is very much less substantial. All three potential graves lie at a depth of c. 38ns. There seem to be a few signals lower down but these are mostly obscured by the transmissions of the fire monitoring system. Line 10 was recorded at 2.5m and line 123m from the West wall of the Vestry.

At the eastern end of the Vestry, line 15 also shows evidence of a potential grave at c. 38ns depth but line 17, although it does contain signal responses, does not (Figure 34). These lines were recorded at 3.75m and 4.25m from the Vestry West wall.

3-Dimensional Data: 400MHz

As for the 250MHz data, the full set of survey lines has been incorporated into a 3-

dimensional data set on the basis of their respective positions along survey reference line 2. Time slices have been extracted from the data set on the basis of changes in patterning. All time slices are presented so that East is at the top of the page. There is a certain amount of striping across these time slices, especially as the depth increases. This is the effect of interference from the fire alarm monitoring transmissions and should be ignored.

Time Slice at 37ns (Figure 35)

The first possible graves appear at this depth. There are at least three of these, quite probably more given the amount of anomalous material distributed across the full area of the floor. As for the 250MHz data, it appears that the West Vestry wall cuts across a line of graves.

Time Slice at 40ns (Figure 36)

More graves appear very slightly lower down. 3ns is equivalent to 1.5cm through soil or 4.5cm through air. From the other anomalous material distributed around these possible graves it appears likely that the area has either been re-used in the past or there are other graves present which are not fully delineated.

Time Slice at 55ns (Figure 37)

There is relatively little material below 40ns with the exception of one large expanse on the western edge of the Vestry which could potentially be a deeper grave. The striping in this time slice is very intrusive but is related to interference from the alarm system and does not represent the extant archaeological remains.

Commentary: The Vestry

Although the time slices from the Vestry are not easy to understand, the overall impression left is of a crowded burial space, potentially with more than one layer of graves present.

It is unfortunately not possible to be prescriptive about the material causing the strong reflections which means that identification of the anomalies as either air or building materials depends primarily on the patterning in the data, particularly in the horizontal plane. That said, it is very likely that whichever material is providing the reflections seen in the various time slices relates to graves since there is relatively little in the way of other features likely to be present beneath the historic Abbey church floor. None of these strong signals appears to be echo effects (or ringing) from features above. Even if the patterning is not readily understandable, it does represent archaeological material.

Both surveys indicate a high density of graves, the possibility of some graves intercutting and there is also evidence in both surveys to suggest more than one level of burial. This is consistent with the important devotional role of St Margaret's shrine.

Detectability of Air Gaps

During the survey it was possible to identify locations where voids existed beneath the church floor. At one such location, close to the western edge of the survey area in the North Transept, the depth of the void was measured to 55cm and markers placed on the GPR data to indicate its position. Figure 38 illustrates that it is not possible to distinguish this size of air gap from the remainder of the signal returns in the near subsurface. A gap of 55cm is equivalent to 3.67ns which is too small for a low frequency radar to detect. As a comparison, the wavelength of the 400MHz antenna in air is 75cm. It is therefore not possible to map the air gaps directly beneath the church floor or to distinguish these from the other features at the same level.

Conclusions & Recommendations

The survey objectives have all been achieved. GPR can be used successfully to investigate the subsurface of the present church and the archaeological remains beneath it. There are some limitations. Both the depth of these remains and the soil conditions mean that only a low frequency radar is suitable for the task. This limits the quality of target definition but not to a point where it is no longer possible to locate large graves.

The surveys have established that the optimal frequency for dealing with the soil conditions and the depth of the archaeological remains is 250MHz. However, it is also possible to use a 400MHz antenna for comparative purposes. Although the soil conditions impact on the probing depth for this frequency of antenna, particularly where there is evidence of moisture from slower transmission velocity it assists in clarifying the location and definition of the shallower features. A higher frequency antenna, 1.5GHz, was also used in the centre of the Nave to see if further improvement could be made in target definition but the degree of attenuation is too great for this frequency on this site. It is therefore recommended that any future GPR surveys use both 250MHz and 400MHz antennas.

The data from the four surveys carried out have demonstrated that it is possible to identify the location and depth of large formal graves beneath the previous Abbey Church in spite of their depth below the current ground surface.

The greatest density of these graves lies below the Vestry at the East end of the building, to the West of St Margaret's Shrine. The distribution of potential graves in the North Transept is mostly apparent in two locations, at the East and West ends of the survey area. The central section appears to have fewer identifiable graves. This may be because of the presence of less formal burials, potentially intercutting each other, or because of intrusive investigations in the period between the destruction of the East end of the Abbey and the building of the current Abbey Church. To a lesser extent, this effect is also visible at the East end of the survey area. It is possible that this distribution relates to the layout of the Lady Chapel relative to the current church. It is recommended that this possibility is considered against such historical evidence as is available.

The large graves detected may or may not be royal graves. They are the largest and most formal burials. It is likely that less formal burials would not have been

detectable due to the lack of suitable associated detectable material, primarily air gaps, metallic artefacts or built structures. However these graves are not sufficiently large for internal air reflections to be visible. This may be a reflection of the size of the burial containers or of the volume of their contents.

In view of the density of the graves to the West of the Shrine and the possibility that the anomalous material may represent both burials and possibly the remains of stone built structures, it is recommended that the area to the East of the Shrine, outside the Abbey church should be considered for survey in case this assists with the interpretation of the area below the Vestry floor.

If it is possible to extend the survey to include more of the Lady Chapel, this could be considered also, particularly if it is possible to relate the current findings to what is known of its location.

A small section of the Nave was included in the survey of the North Transept. The results suggest that there may be a more substantial structure lying to the East of the crossing, approximately central to the Nave. The evidence is, however, not unequivocal. It is not possible to clarify this by using a different frequency of antenna. It may be possible to do so by extending the survey. However this would necessitate removal of some church furniture and should therefore only be considered if this becomes a practical proposition.

On the basis of the results included in this report, it is also potentially possible to survey the remainder of the church floor. Unfortunately this is not a practical proposition unless the fixed pews and other church furniture can be moved temporarily. Should any such rearrangement of the church furniture become necessary for any reason, then it is recommended that a GPR survey is carried out once the floor is clear of obstacles and before any remedial or other work is attempted. Increasing the area under investigation improves the interpretation of GPR survey results and usually aids understanding of the archaeological remains.

Acknowledgements

This survey was carried out by EMC Radar Consulting working in conjunction with OJT Heritage.

EMC Radar Consulting and OJT Heritage would like to thank the four volunteers who assisted with the practical aspects of the survey and dealing with Abbey visitors, Katy Jack, Vicky Hodgson, Julie Gilfillan and Kevin Malloy.

References

Jones, D. M. (2008) “Geophysical Survey in Archaeological Field Examination”, English Heritage, Swindon, UK.

Rodwell, W. (2012). “The Archaeology of Churches”, Amberley Publishing, Stroud, UK. ISBN 978 1 84868 943 5.

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.

EMC Radar Consulting
13 West End
Haddenham
Ely
CB6 3TD
Tel: 01353 741033
e-mail: erica@emcradar.co.uk

Appendix: Figures

Plan of Survey areas o/s

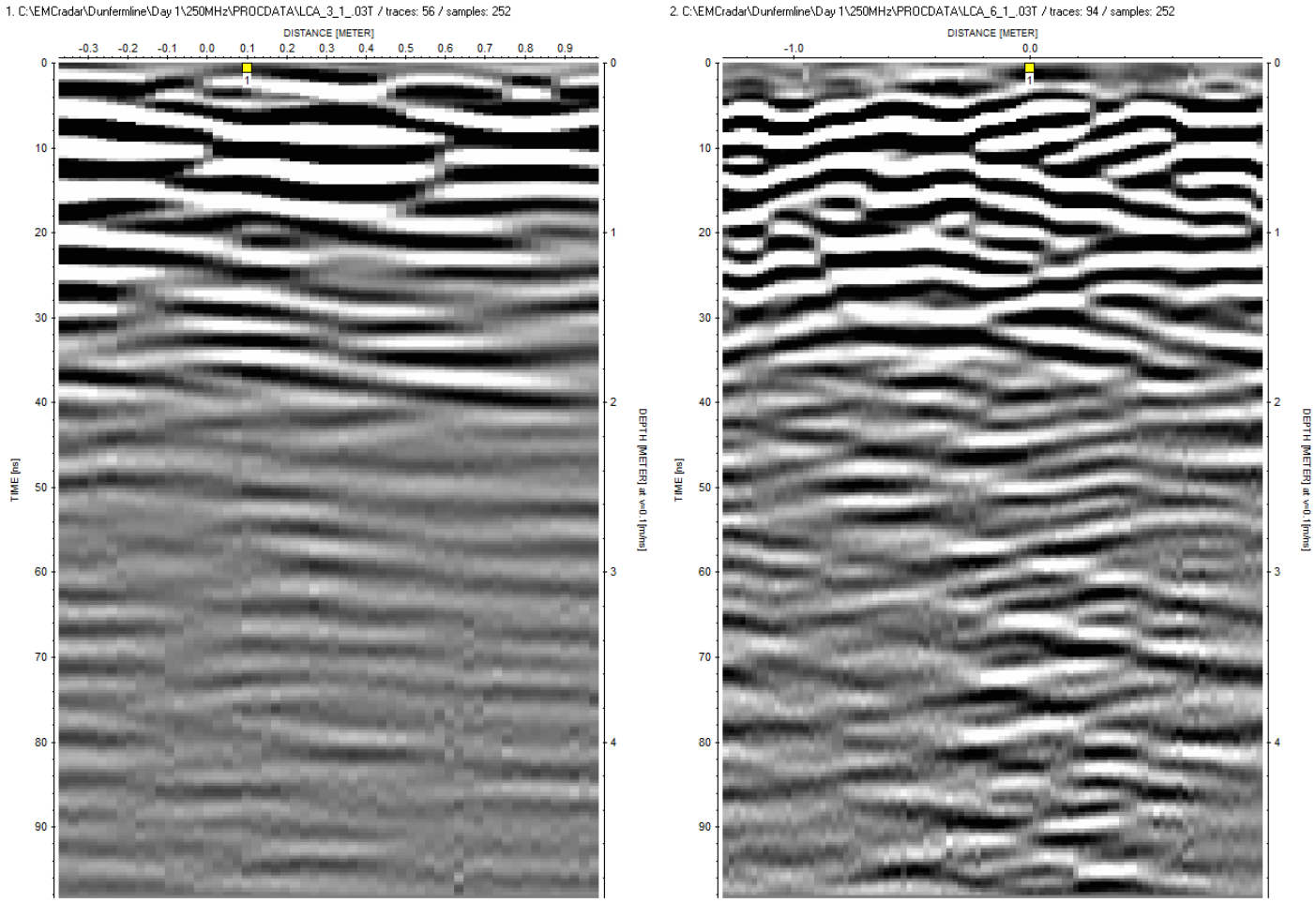

Figure 2: Lines 3 and 6 of the 250MHz data showing reflections from the near subsurface in both lines and from deeper archaeological material in Line 6 (rhs).

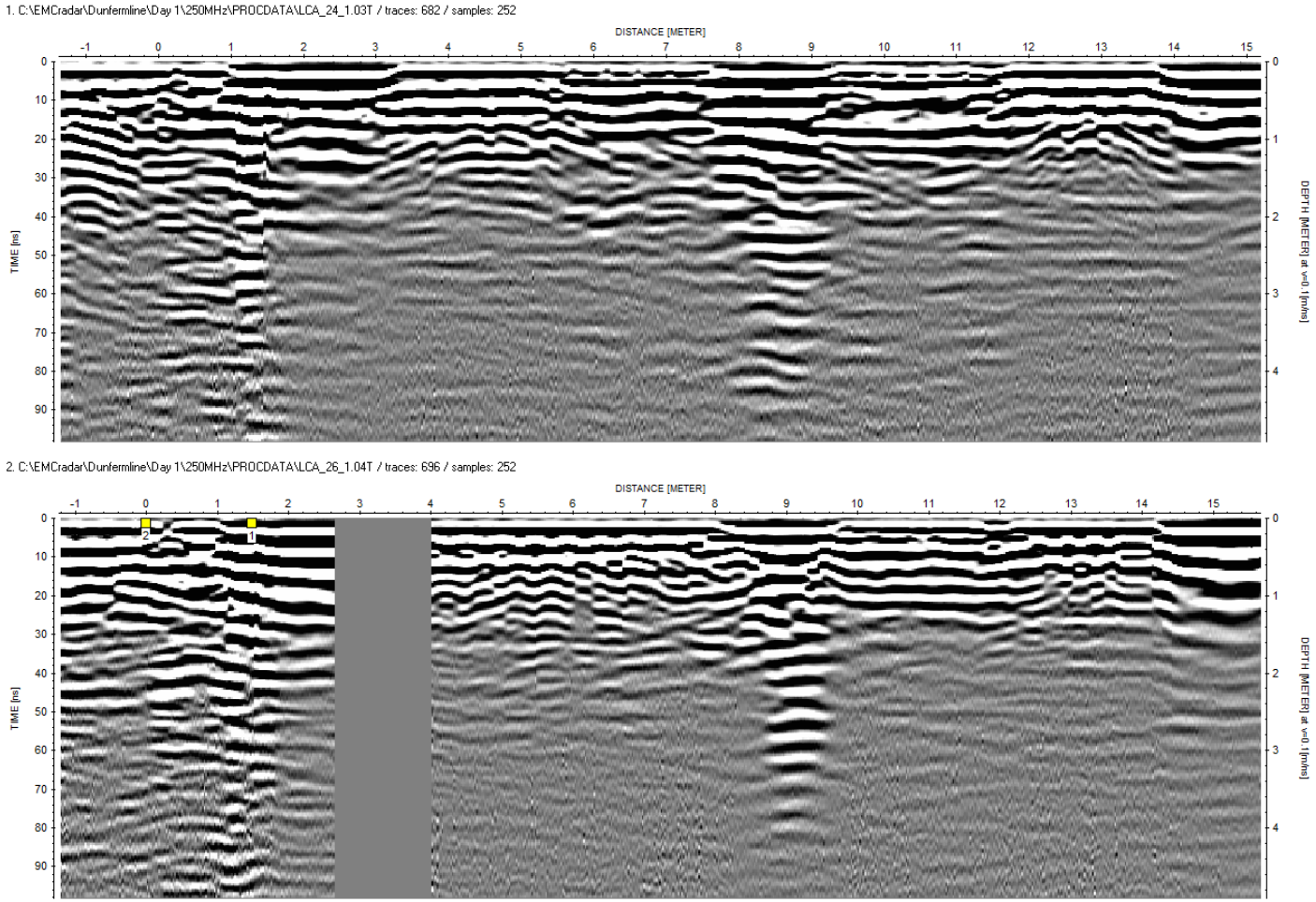

Figure 3: Lines 24 and 26 of the 250MHz data crossing both the North Transept and the Nave, showing potential graves in both locations.

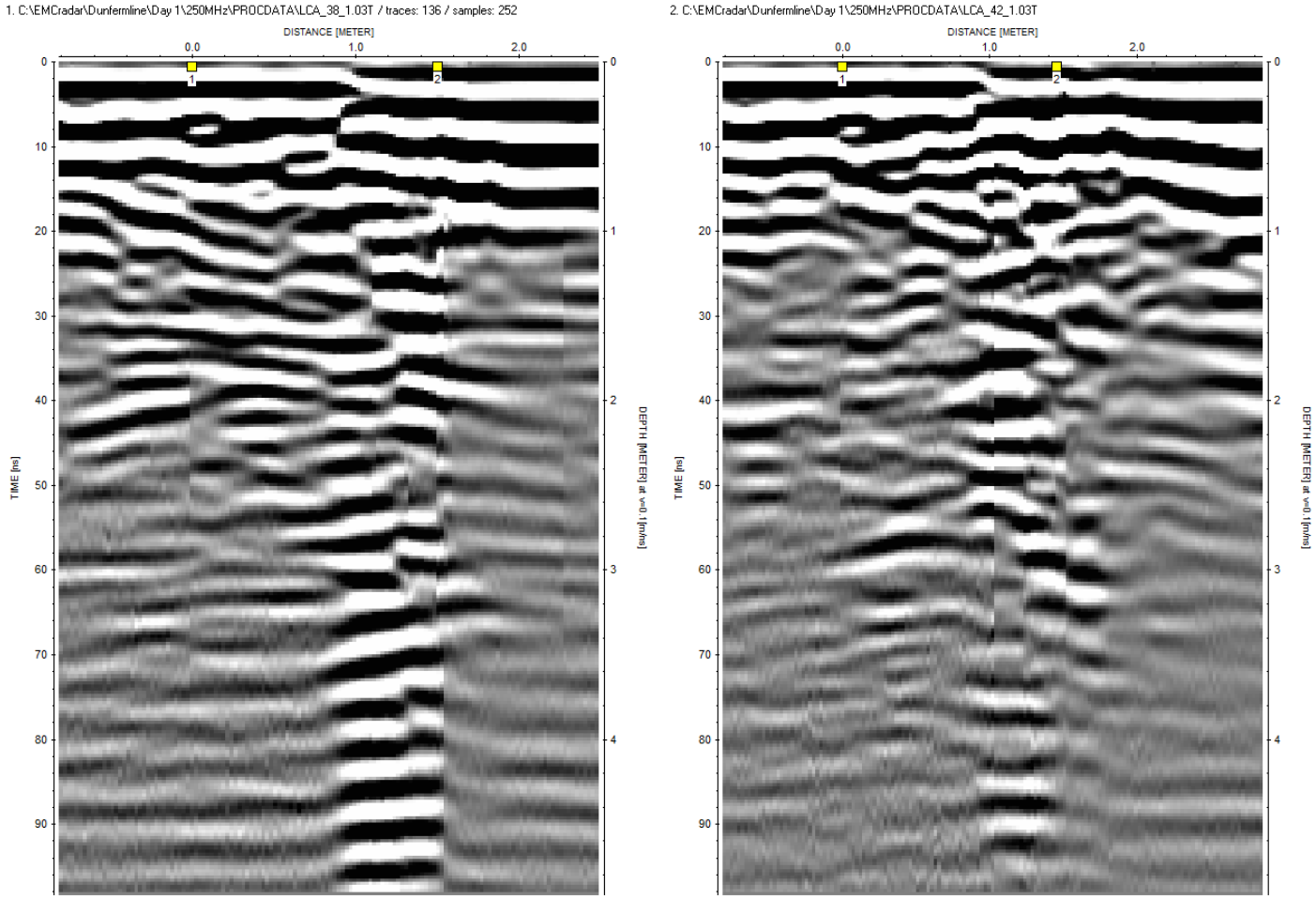

Figure 4: Survey lines 38 and 41 from the 250MHz data showing signal reflections which might indicate burials in the historic subsurface.

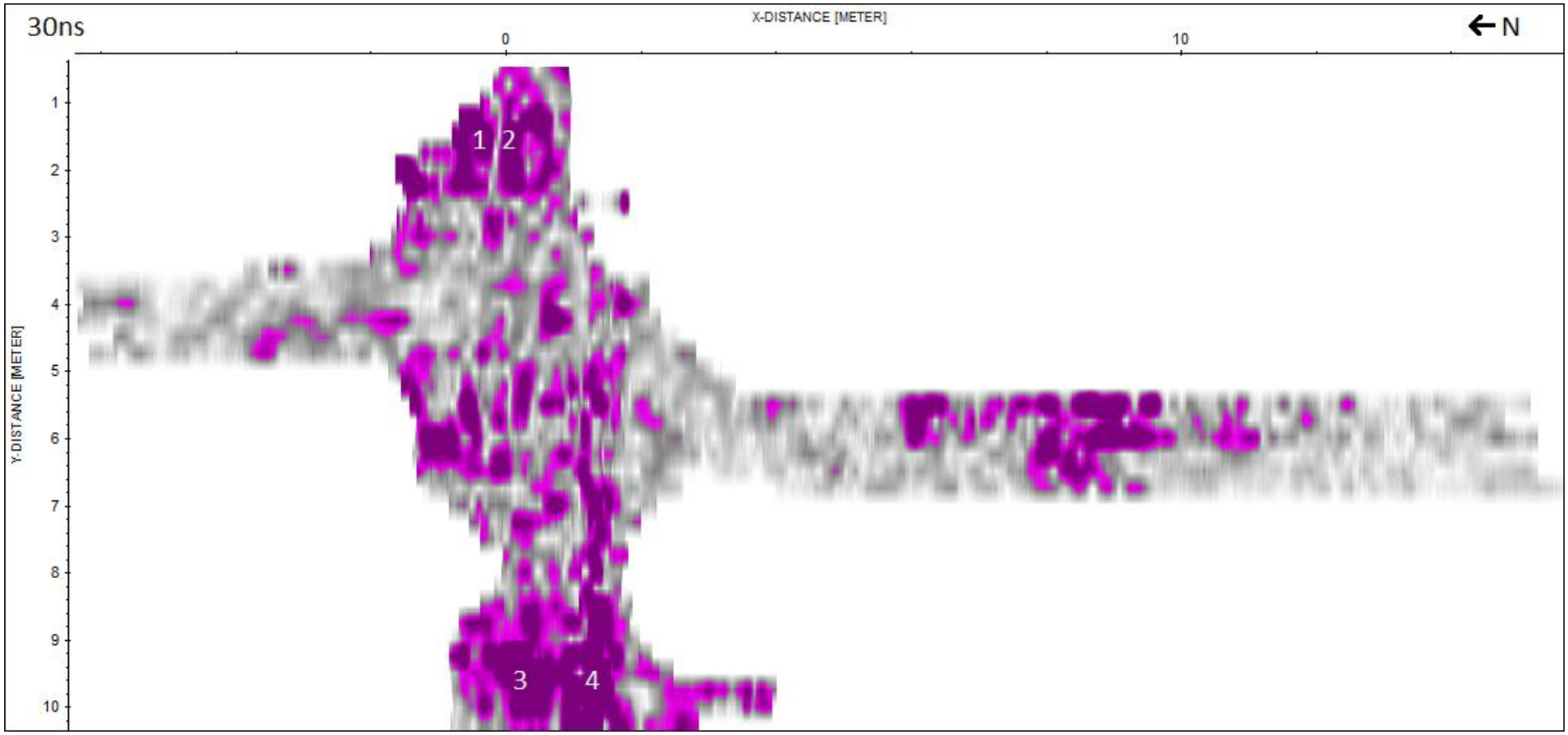

Figure 5: Time Slice extracted at c. 30ns showing 4 outlines which might represent ancient graves.

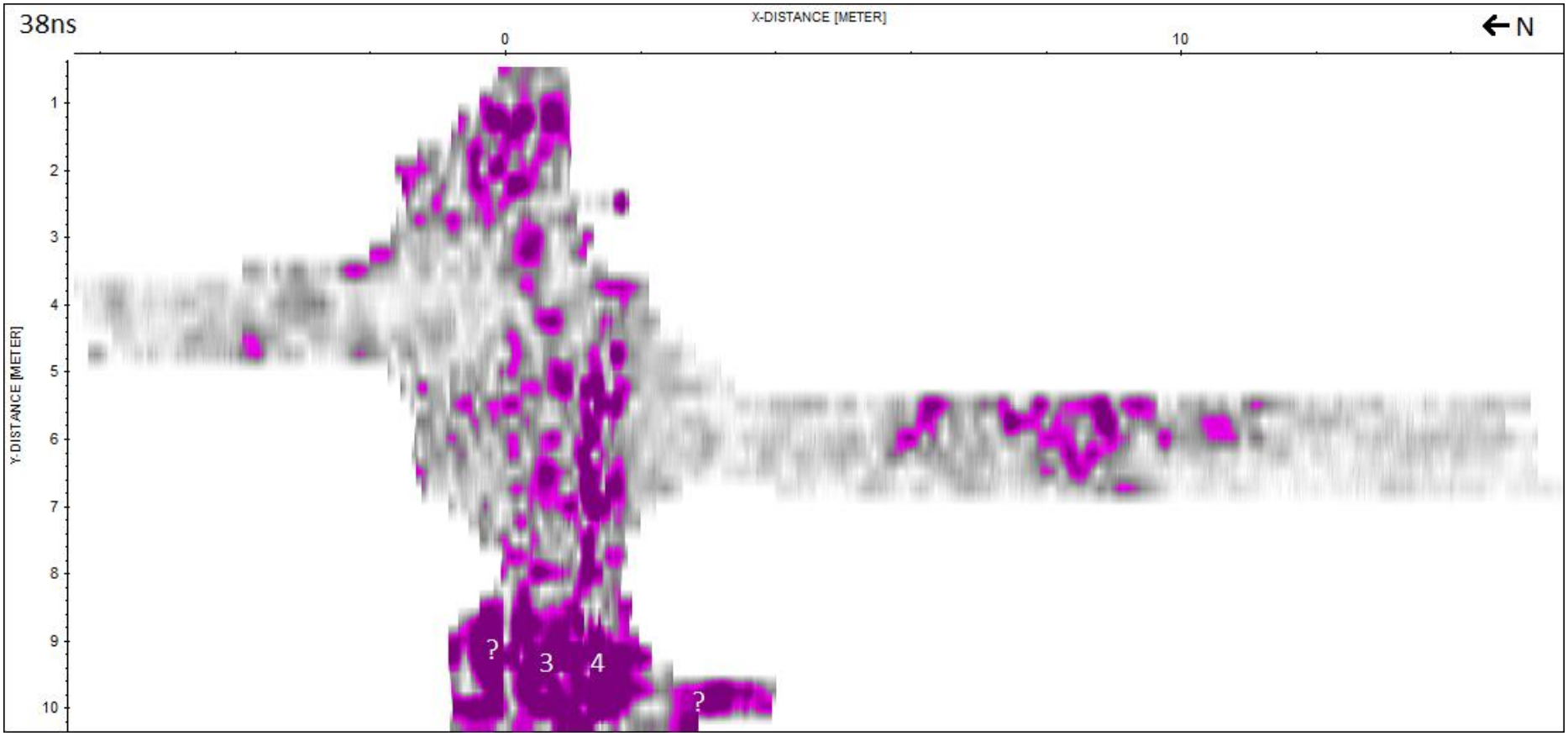

Figure 6: Time Slice at c. 38ns showing further development of potential graves and an East/West linear feature.

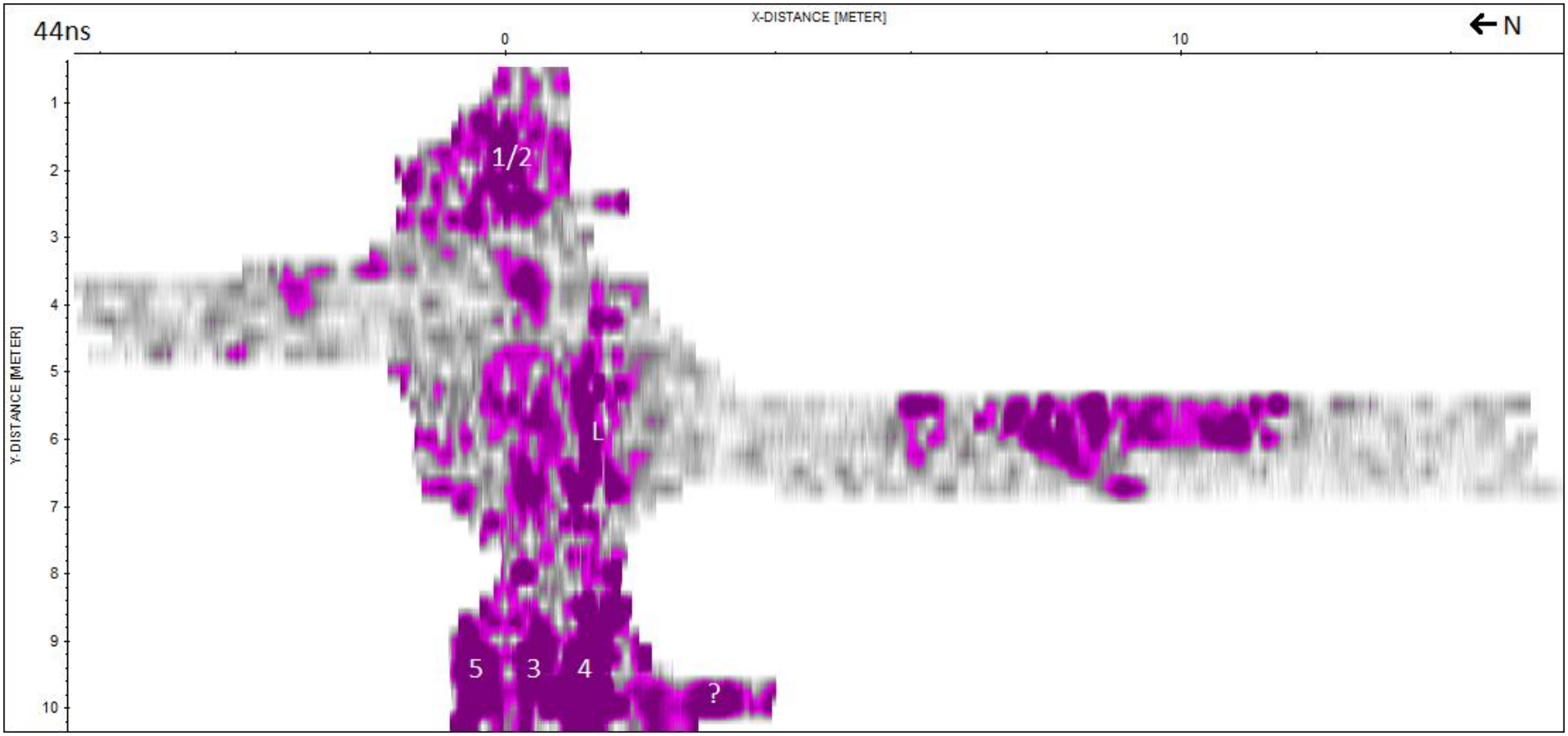

Figure 7: Time Slice at c. 44ns showing development of potential graves in the area of the North Transept and a major subsurface feature below the Nave.

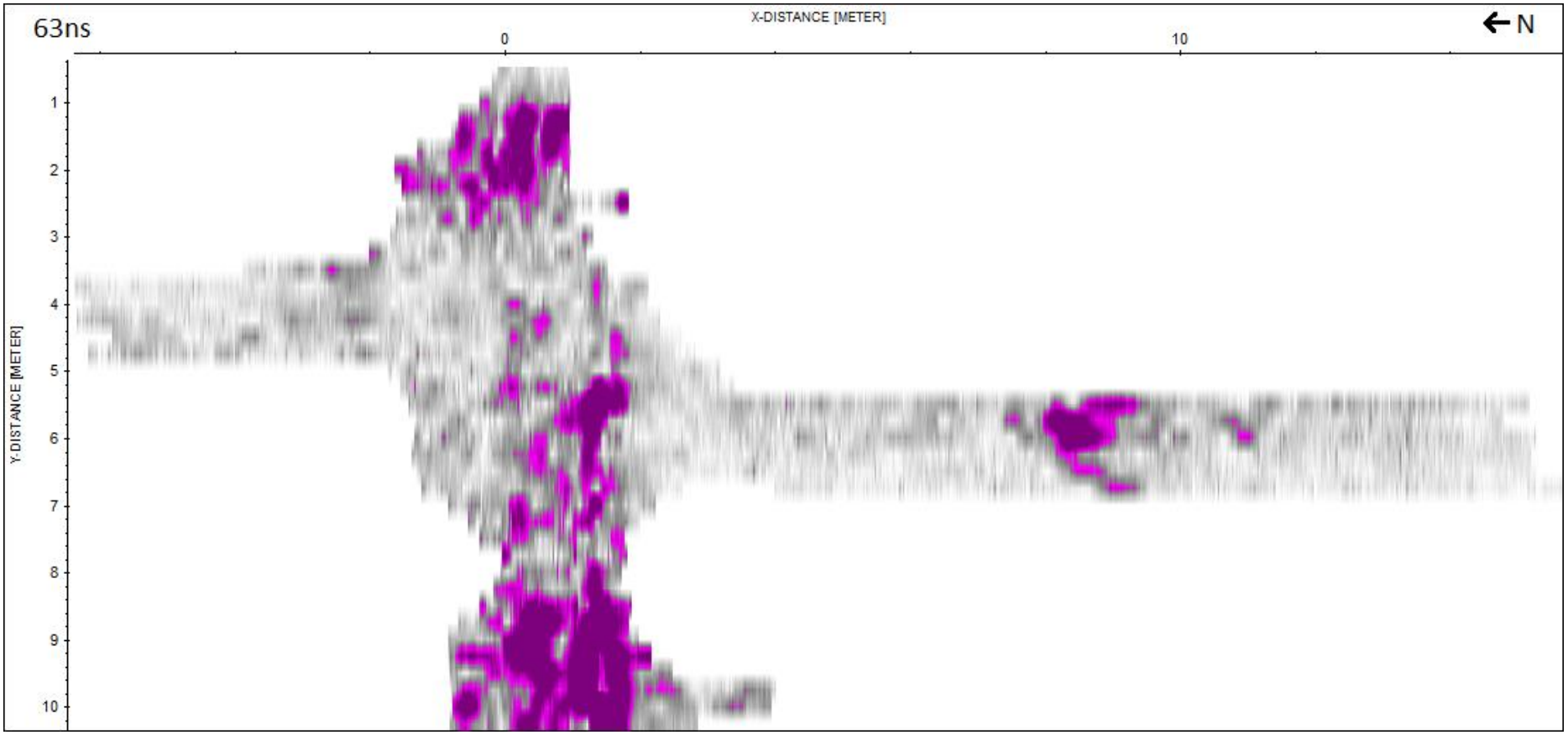

Figure 8: Time Slice at c. 63ns showing development of potential graves and central feature.

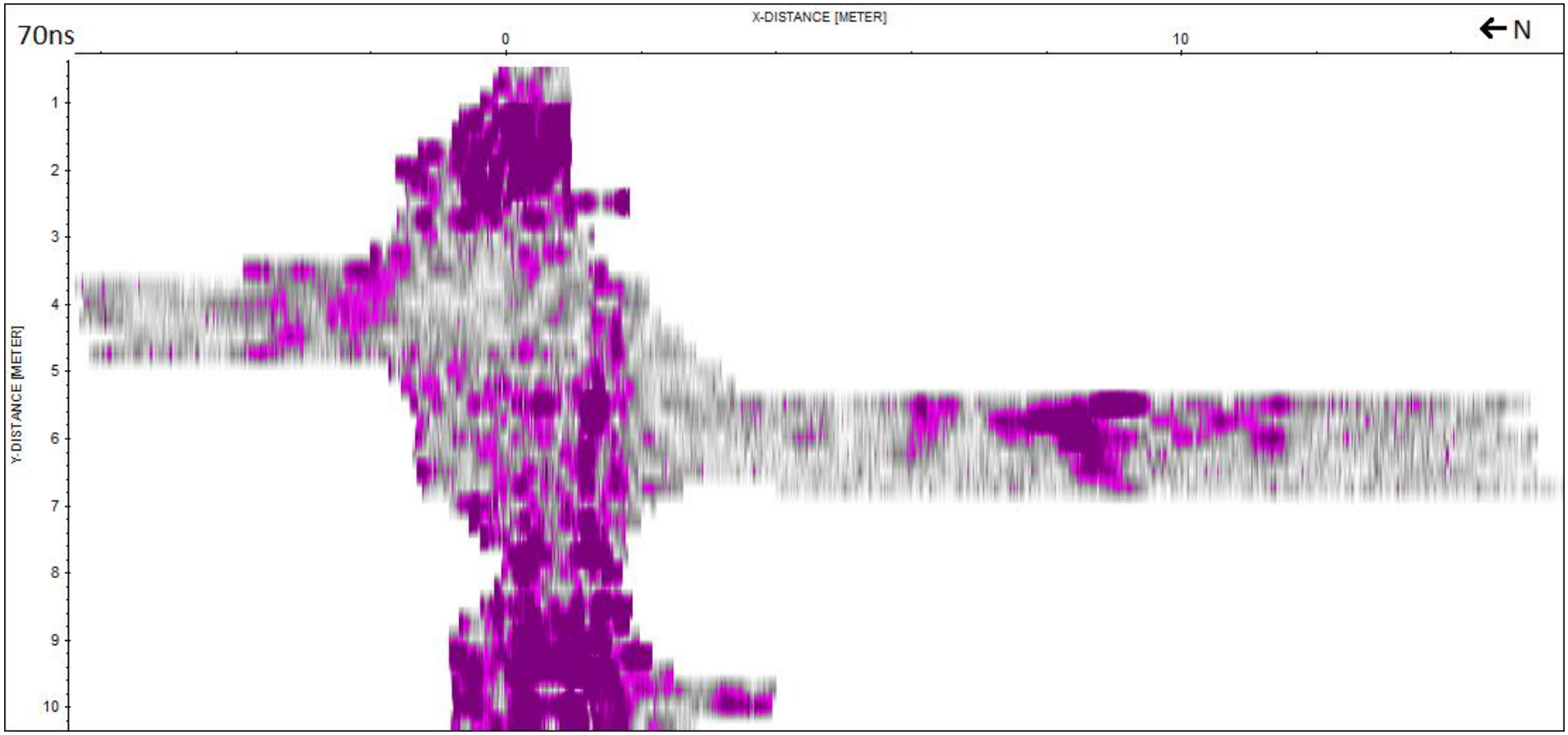

Figure 9: Time Slice at c. 70ns showing changes in patterning in the three principal areas of interest.

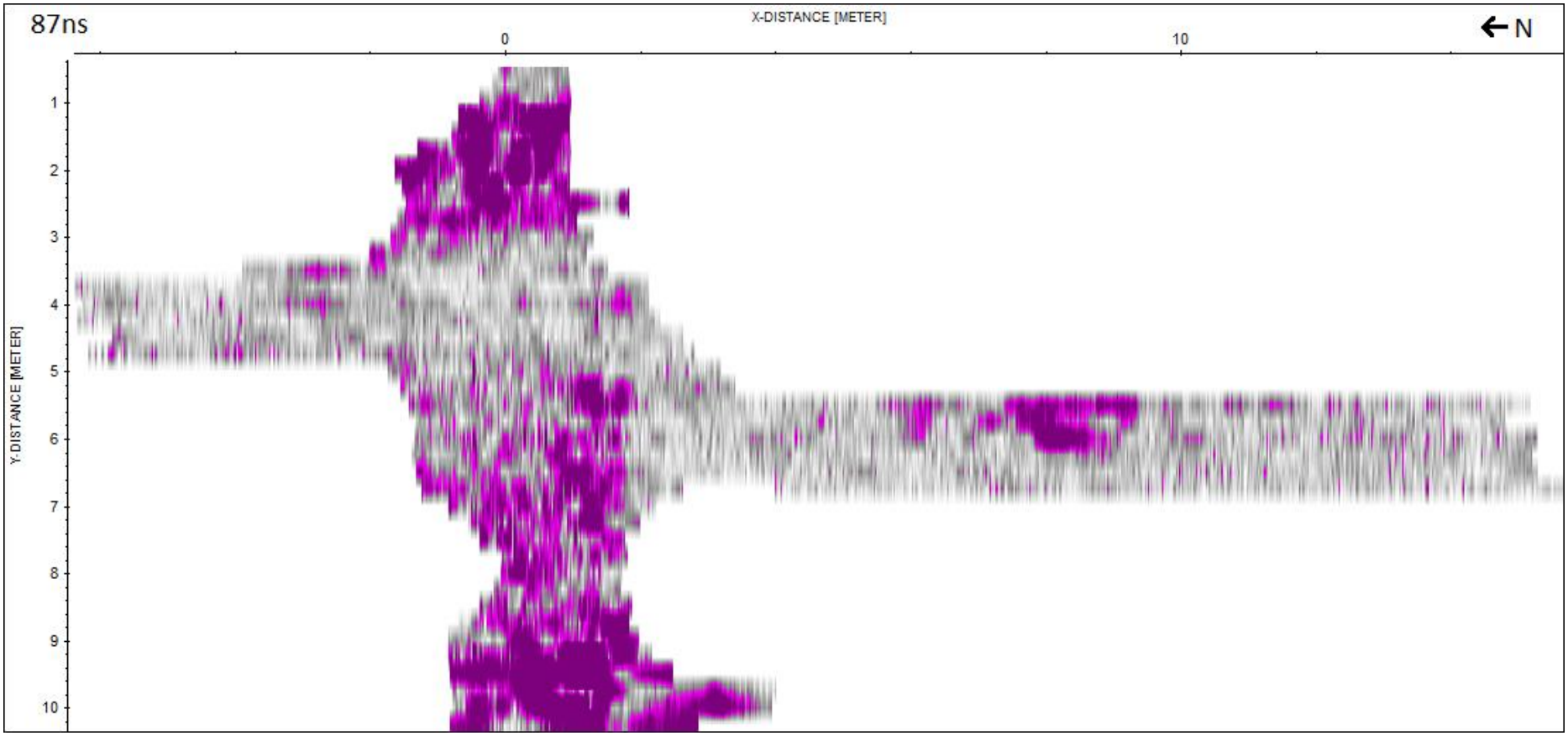

Figure 10: Time Slice at c. 87ns showing primarily echo effects.

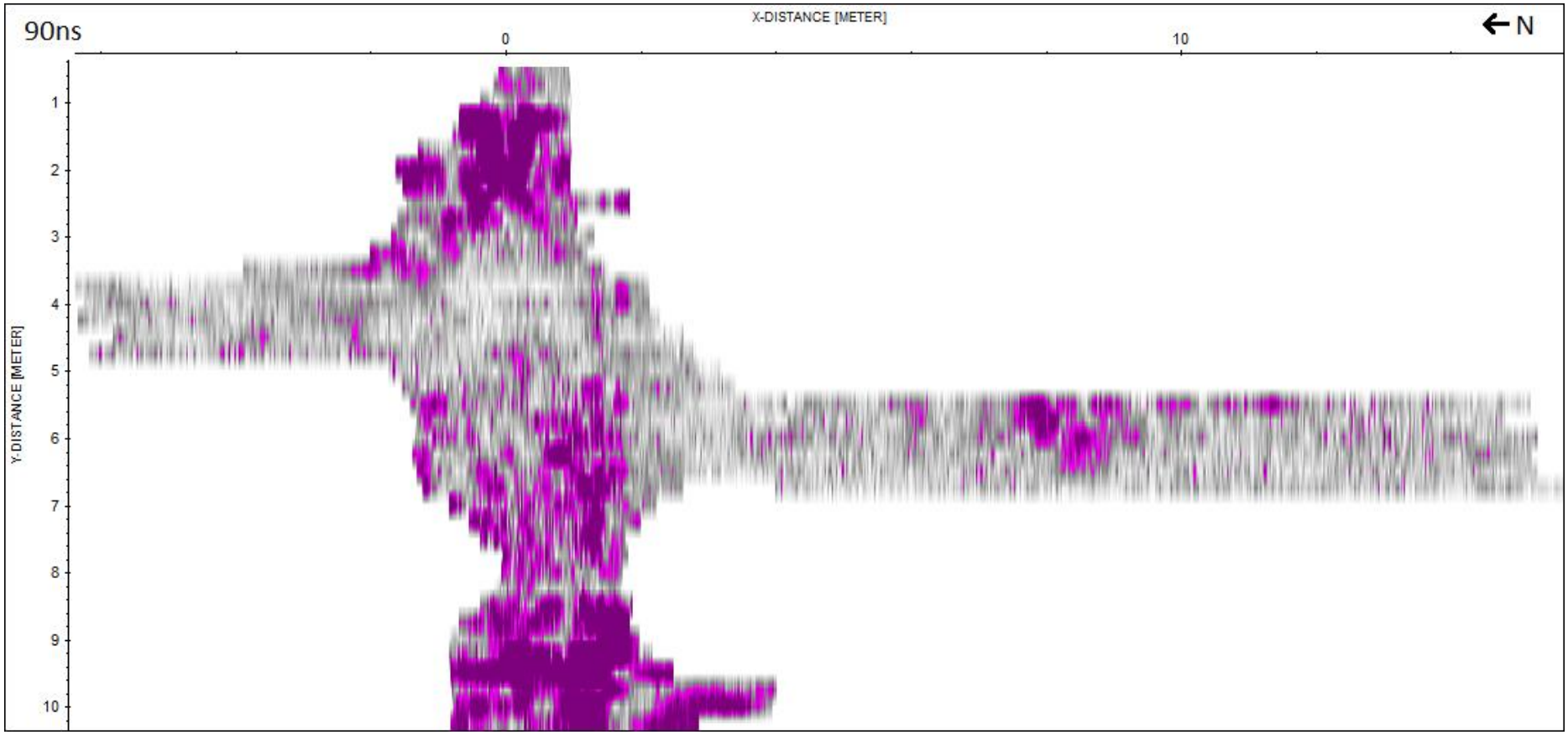

Figure 11: Time Slice at c. 90ns showing echo effects and at least one possible deeper grave at the western end.

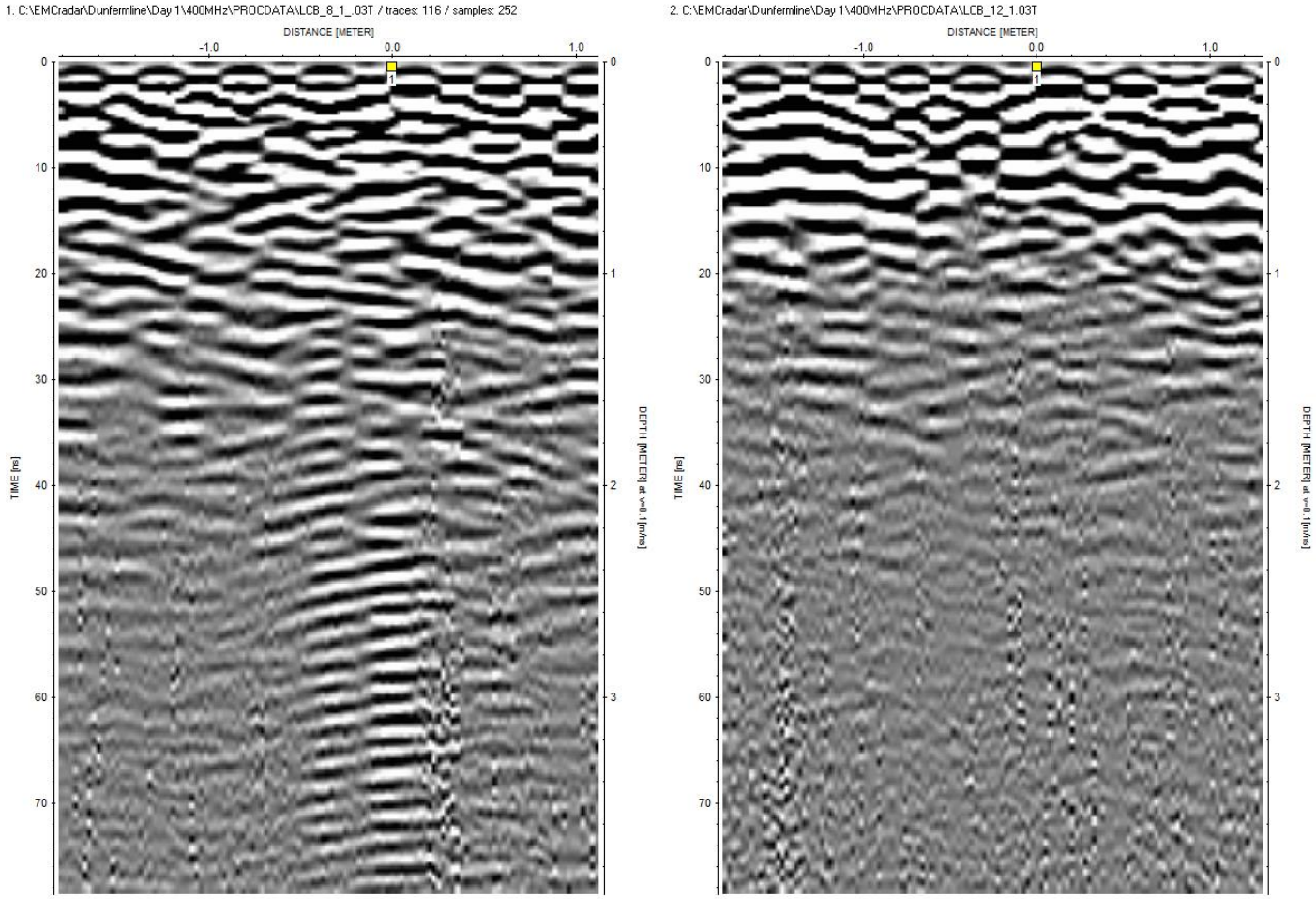

Figure 12: Survey lines 8 and 12 from the 400MHz data showing some deeper reflections and, for line 8, considerable ringing.

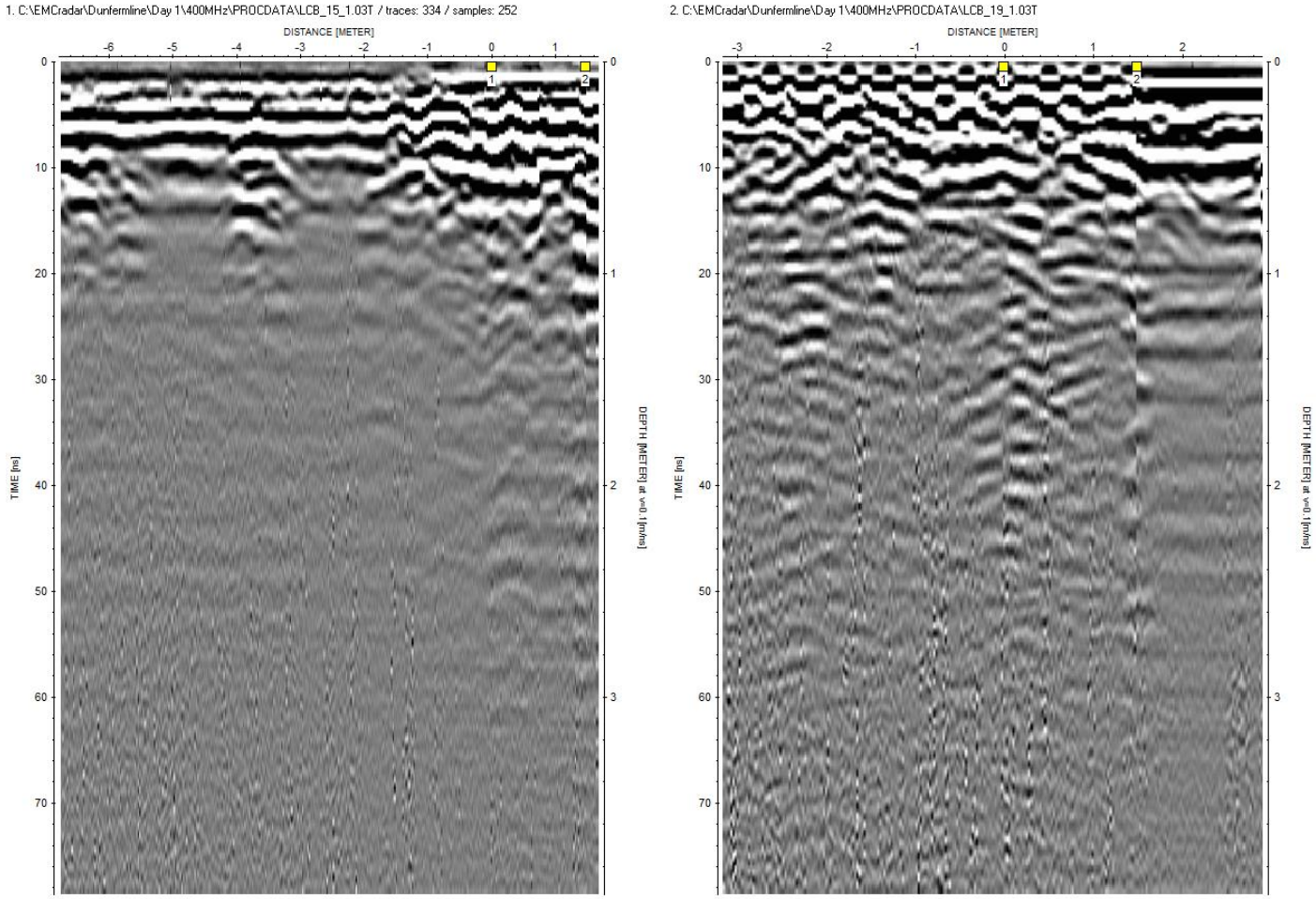

Figure 13: Survey lines 15 and 19 from the 400MHz survey showing potential archaeological remains in the area of the shop.

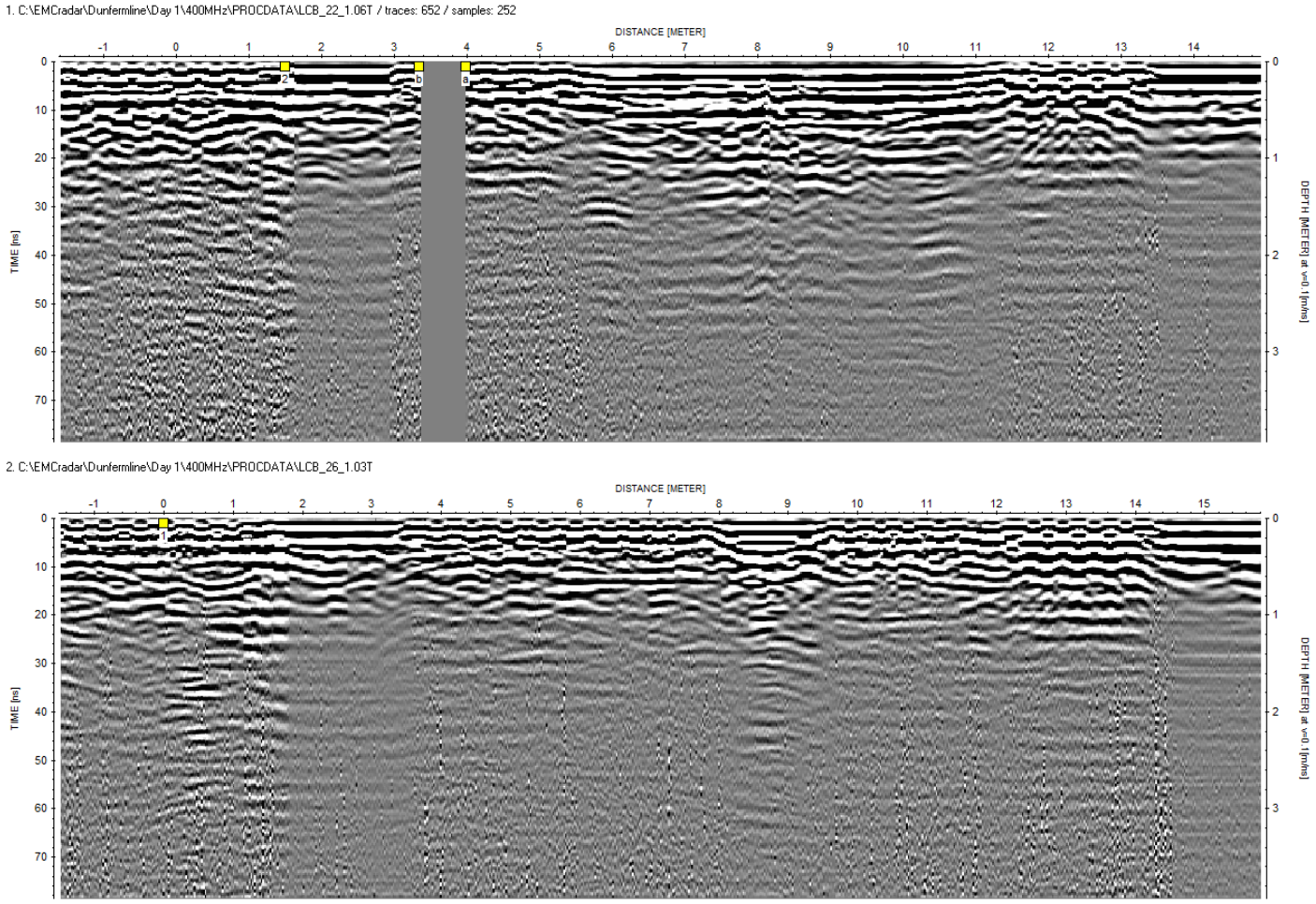

Figure 14: Survey lines 22 and 26 covering part of the Nave as well as the North Transept.

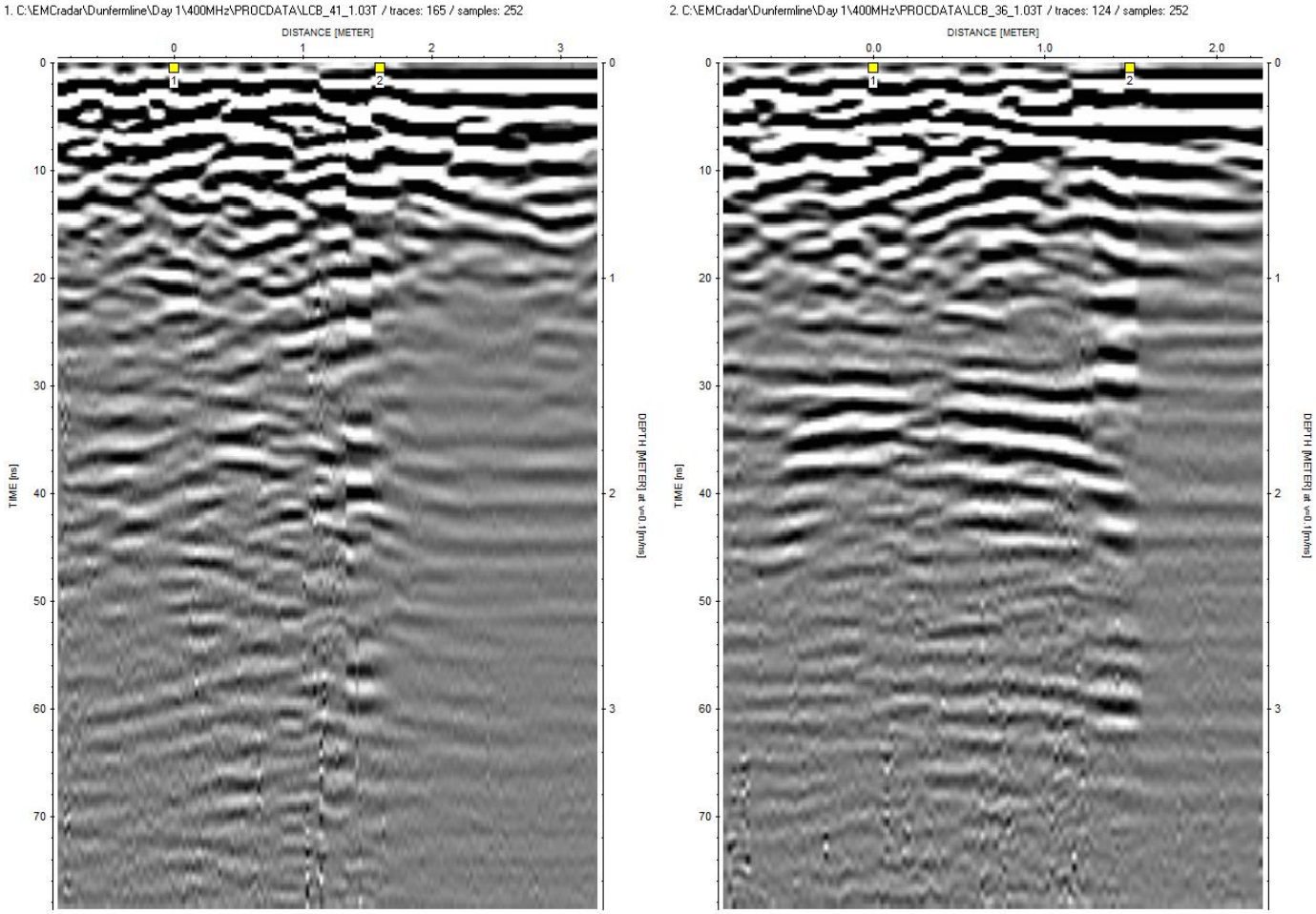

Figure 15: Survey lines 41 and 36 showing substantial archaeological remains in the western area of the North Transept.

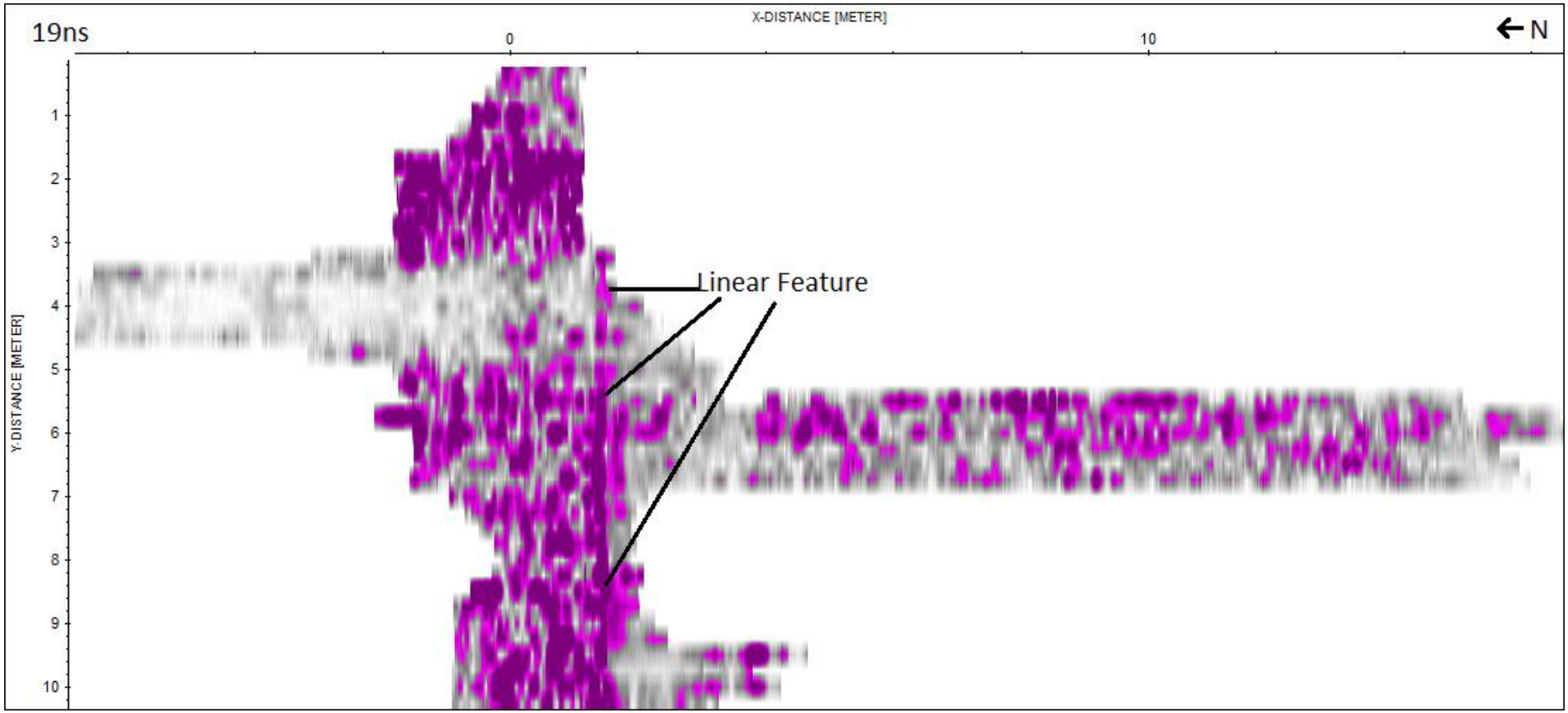

Figure 16: Time Slice at c. 19ns illustrating a linear feature in the near subsurface (i.e. probably relating to the current church).

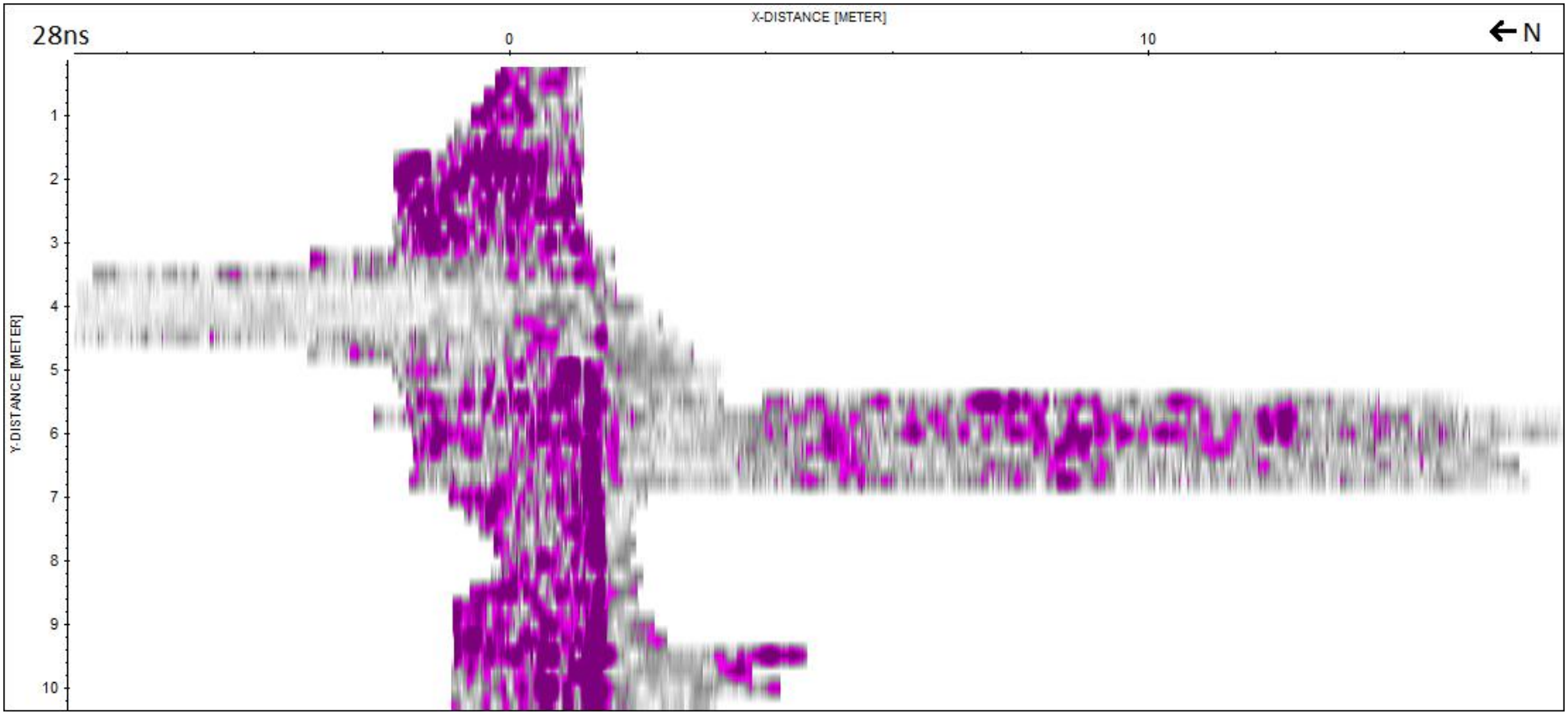

Figure 17: Time Slice at c. 28ns showing a possible feature in the centre of the Nave.

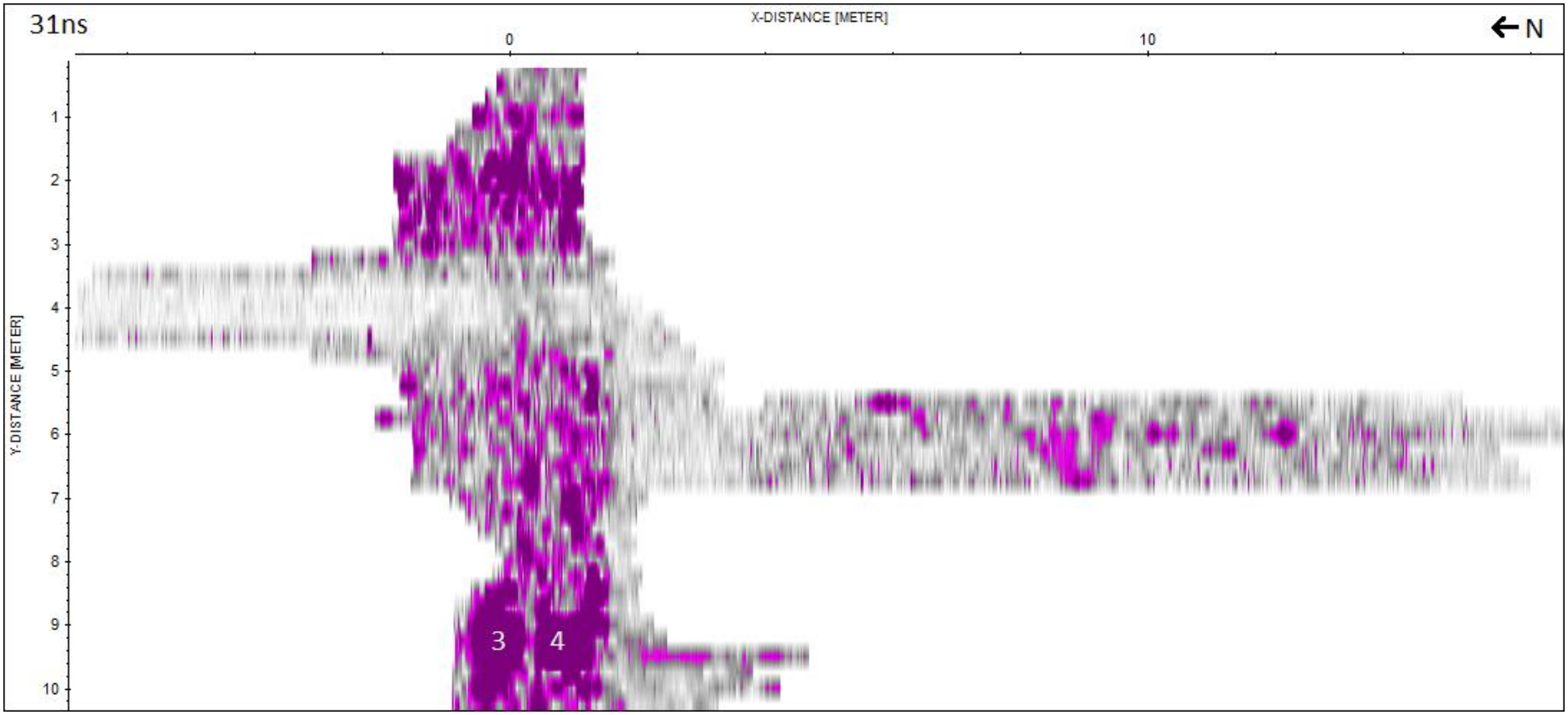

Figure 18: Time Slice extracted at c. 31ns showing two possible graves at the western edge of the North Transept survey.

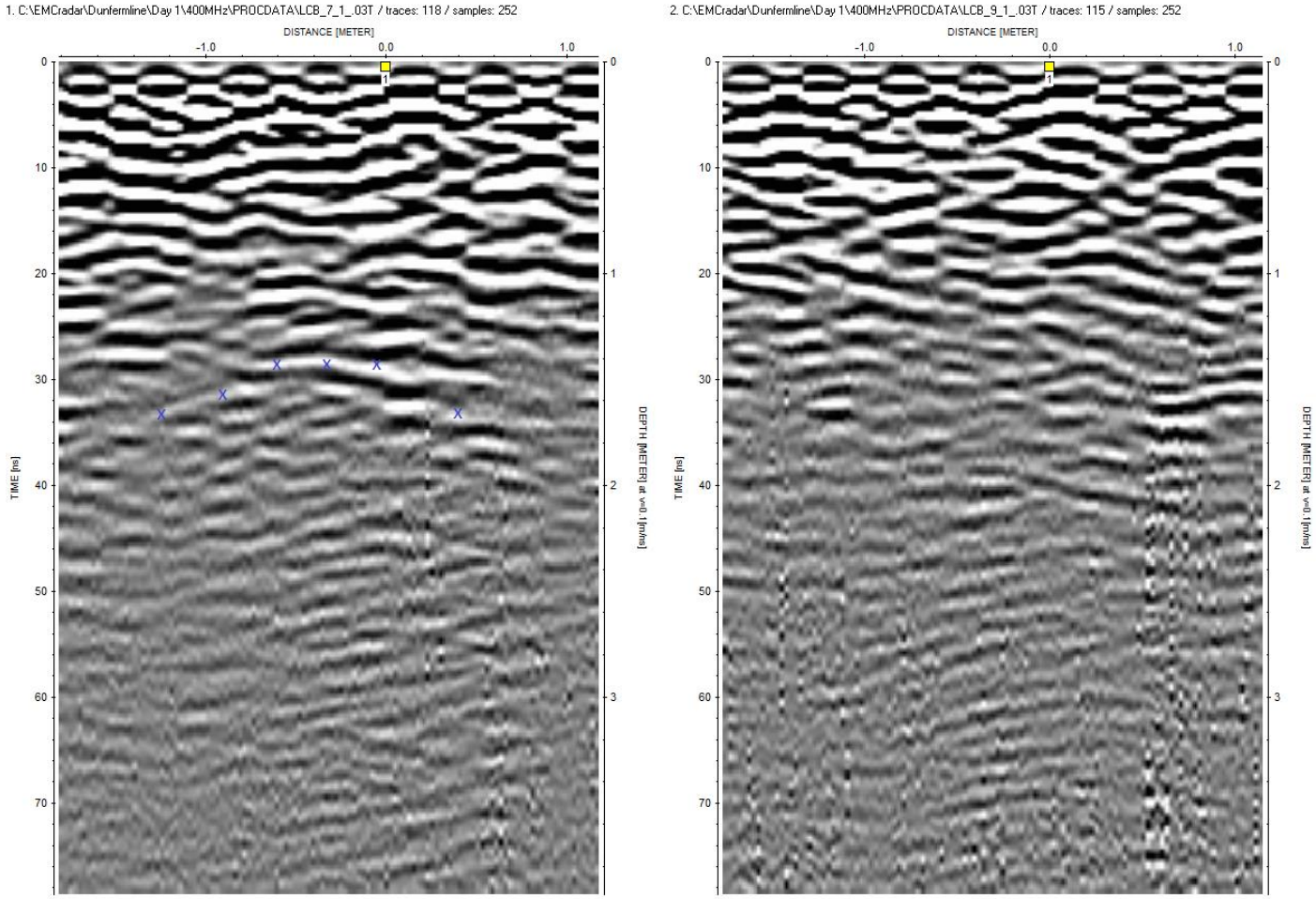

Figure 19: Survey lines 7 and 9 showing a possible curved upper surface (marked with blue "x"s in line 7) and an apparent absence of metal, unlike line 8 (Figure 12).

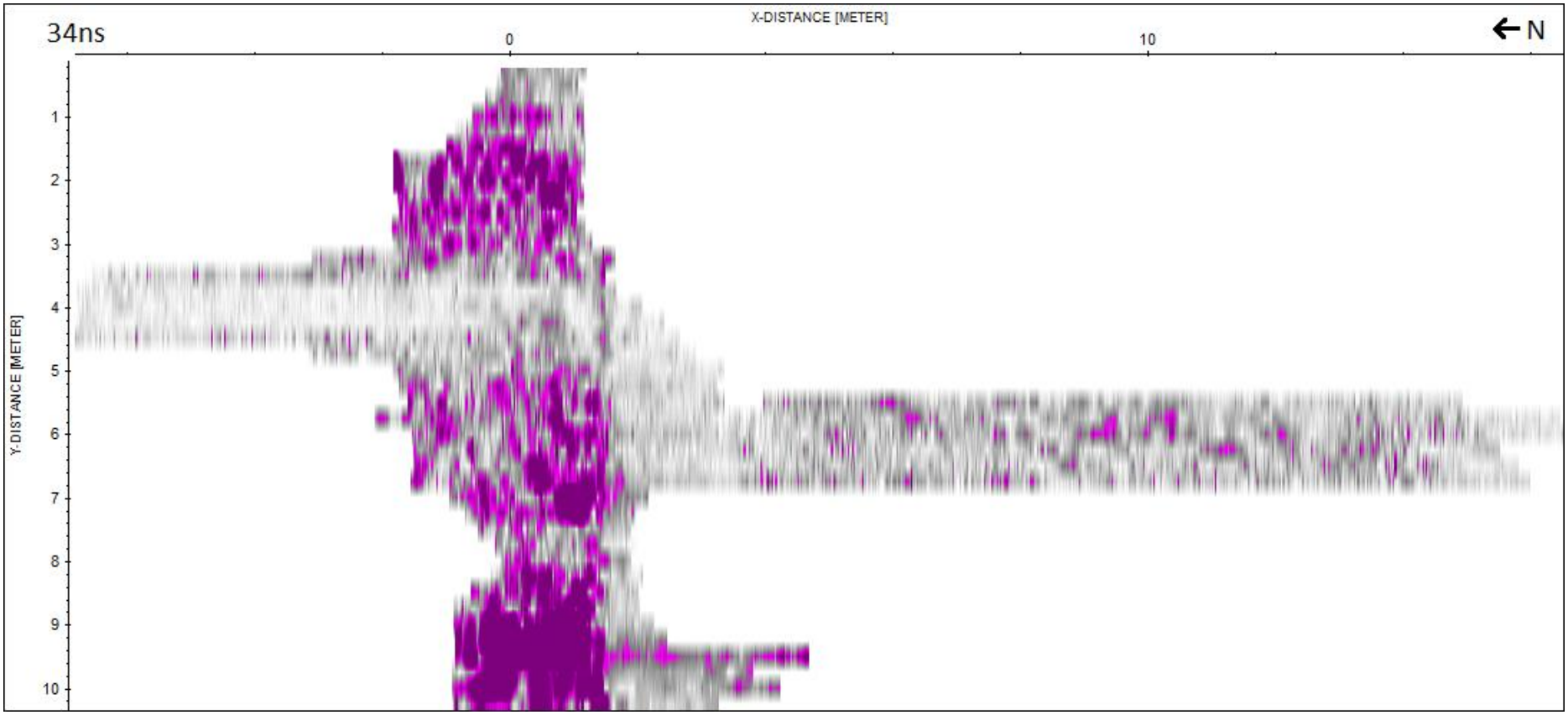

Figure 20: Time Slice extracted at c. 34ns showing probable graves at the western end and possible grave remains in the centre of the North Transept.

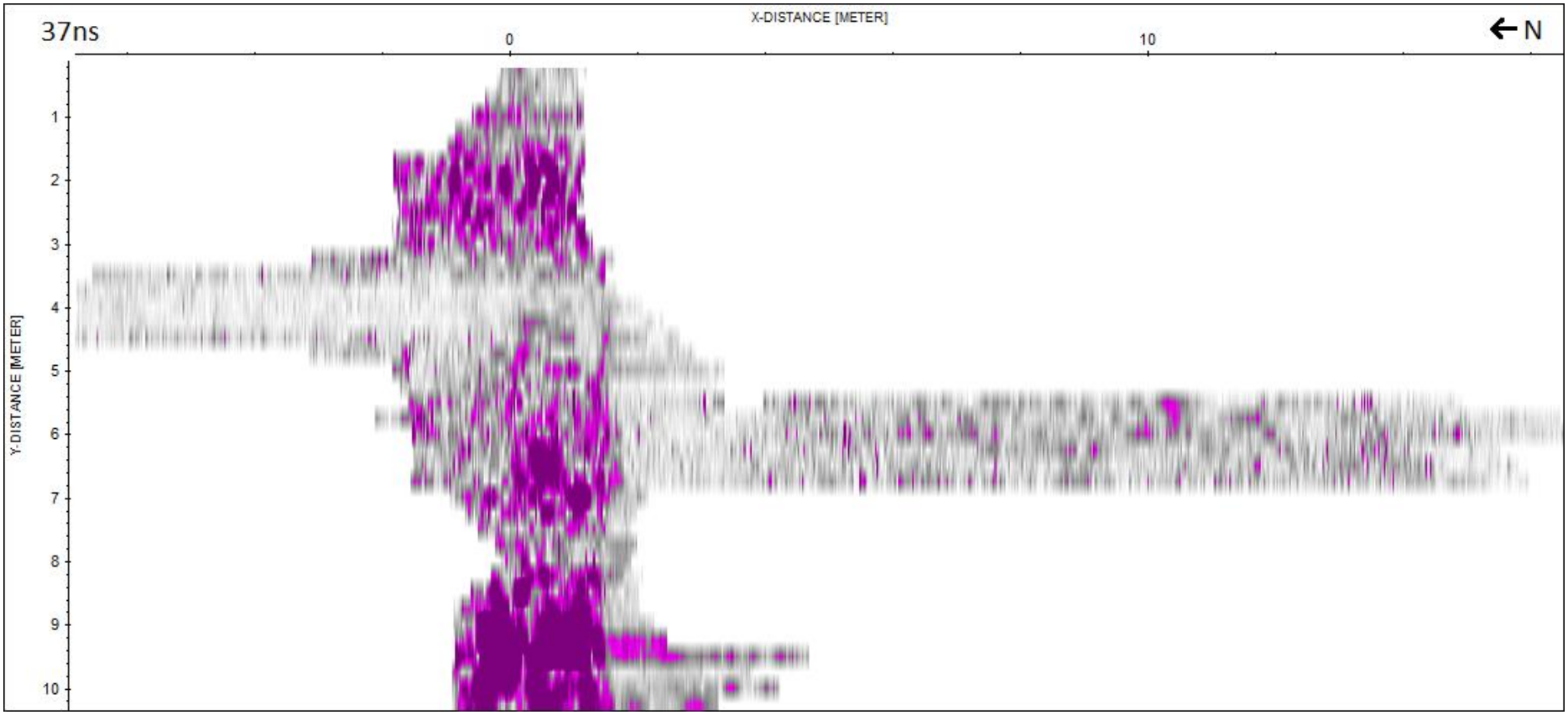

Figure 21: Time Slice extracted at c. 37ns showing graves at the western end and possible graves in the centre and East of the North Transept.

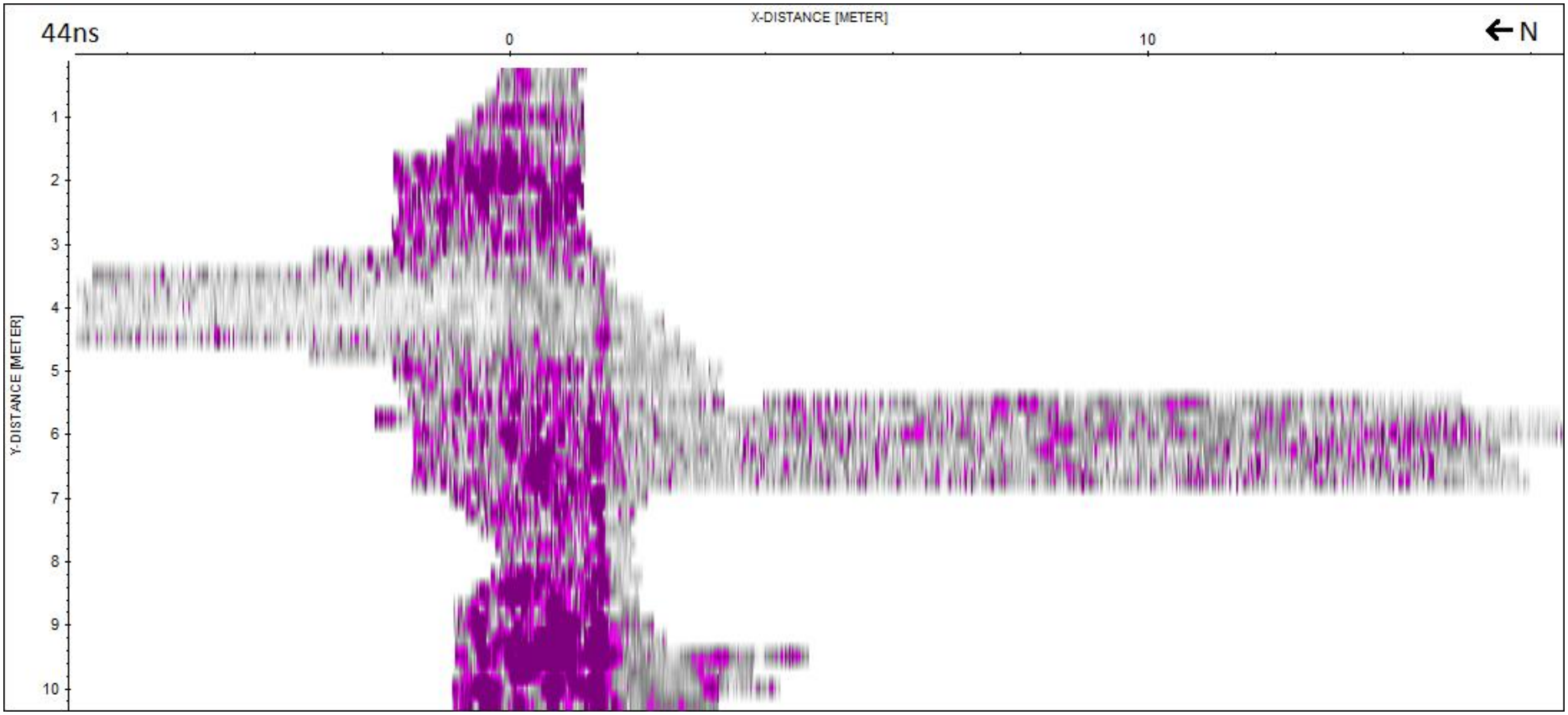

Figure 22: Time Slice extracted at c. 44ns showing significant anomalies at the East and West ends of the North Transept.

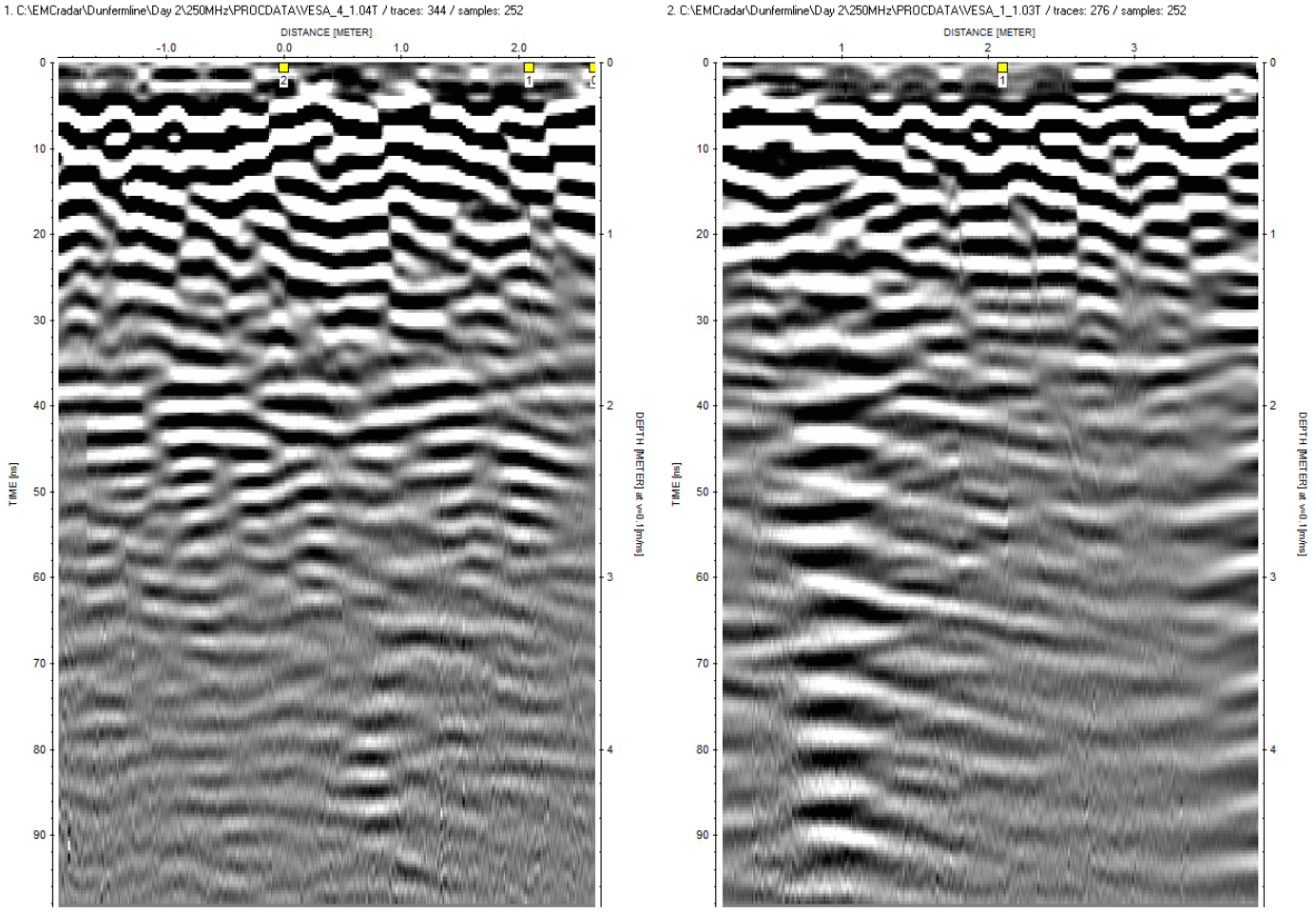

Figure 23: Survey lines 4 and 1 from the 250MHz survey of the Vestry.

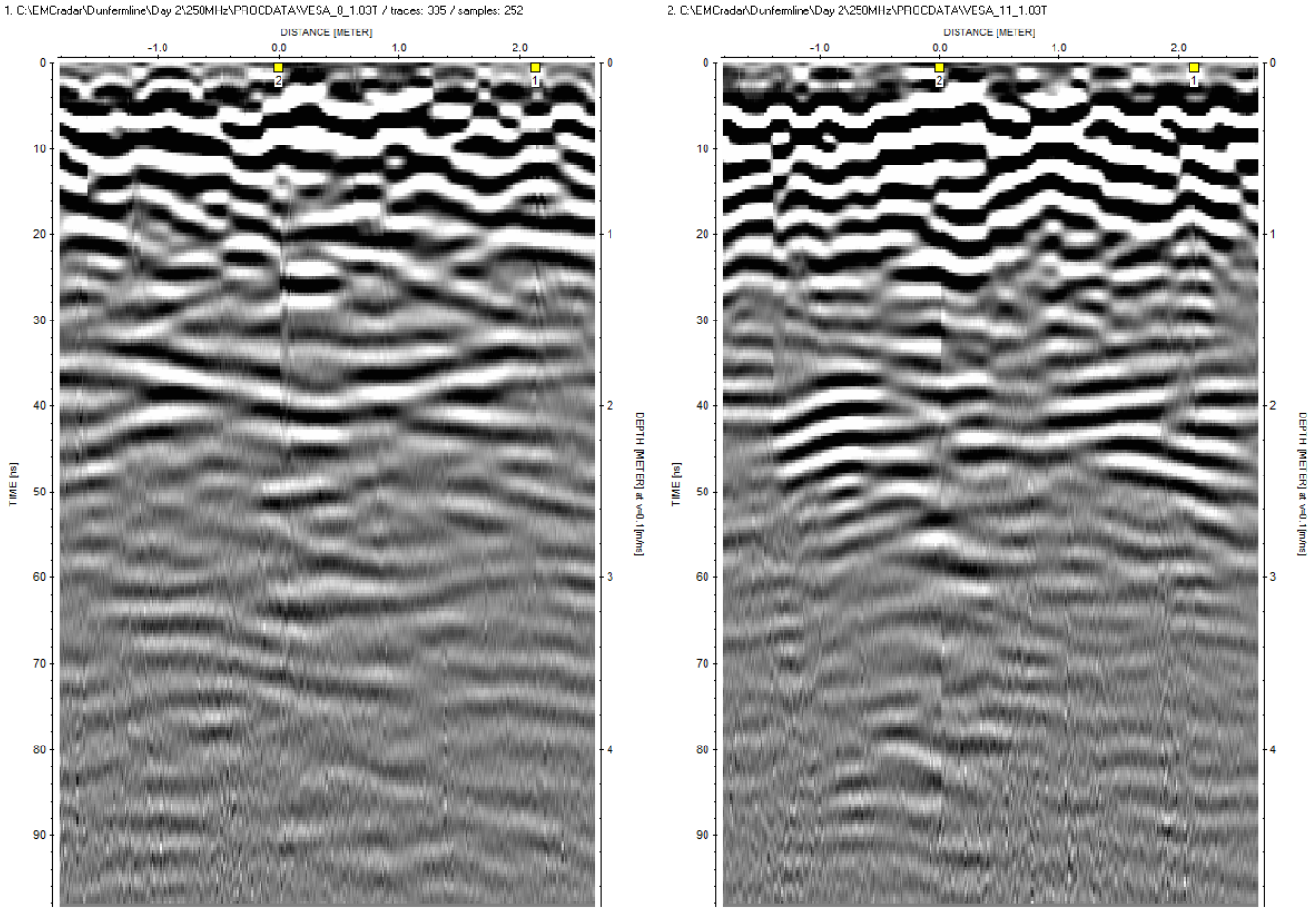

Figure 24: Survey lines 8 and 11 from the 250MHz survey of the Vestry.

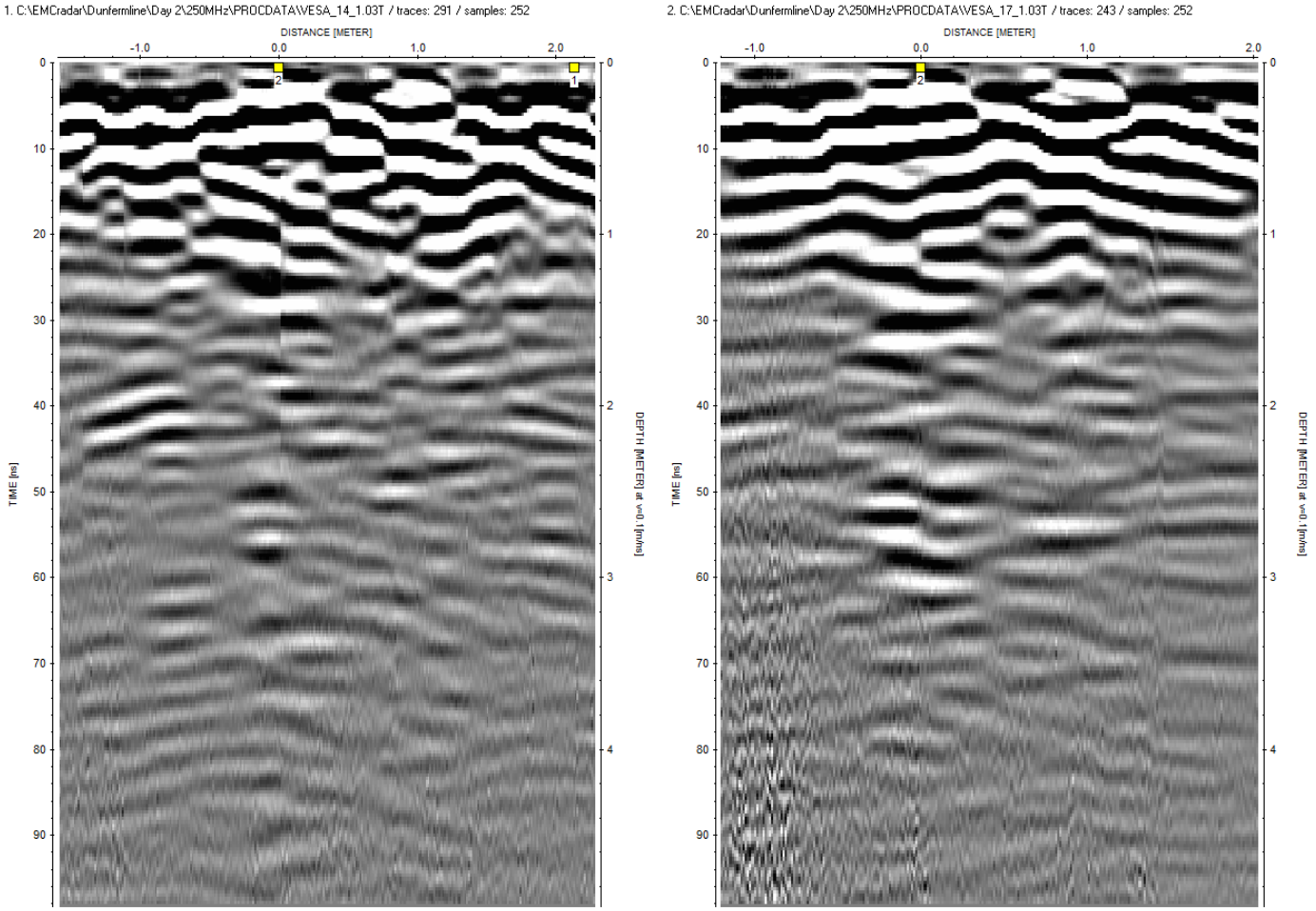

Figure 25: Survey lines 14 and 17 from the 250MHz survey of the Vestry.

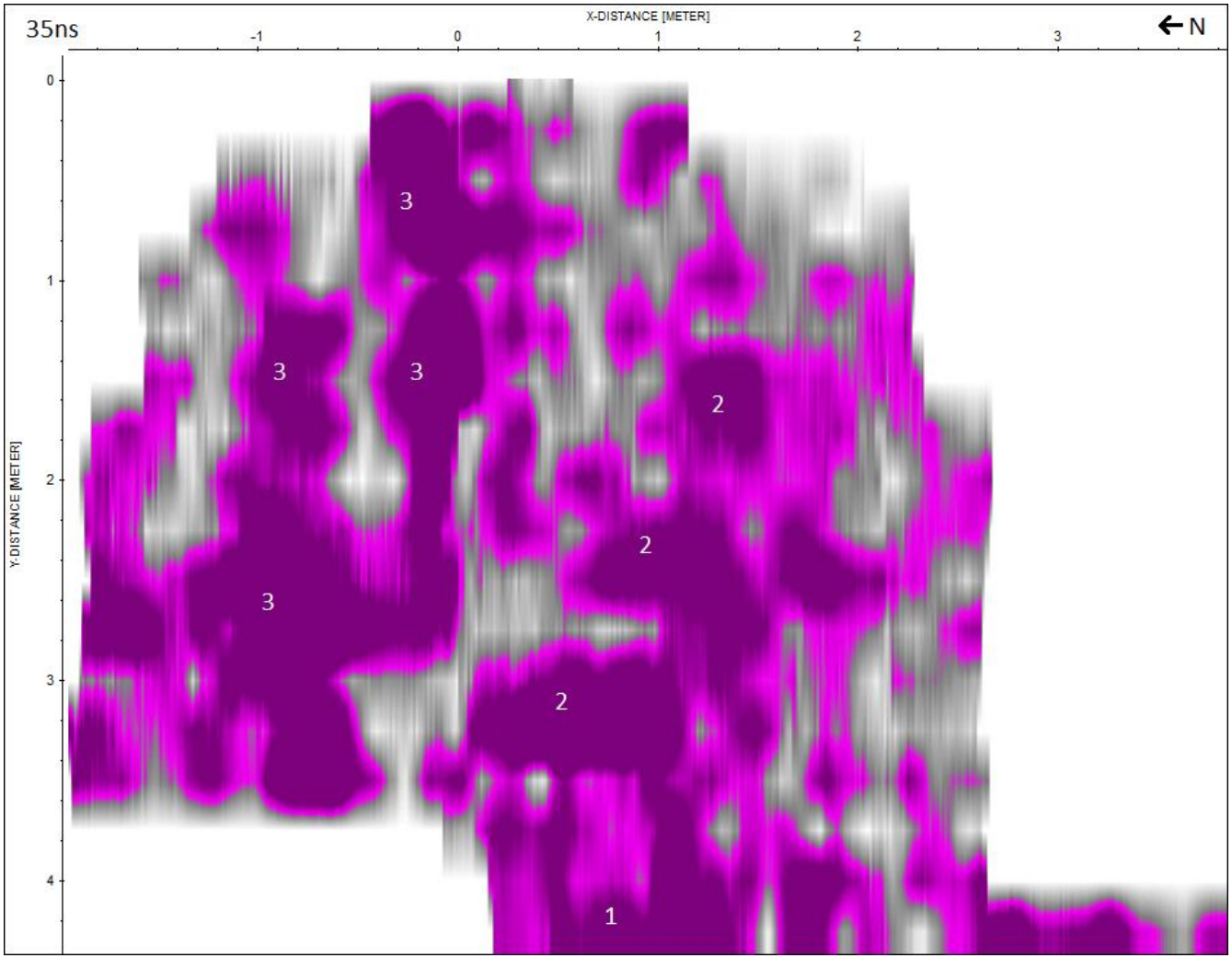

Figure 26: Time Slice at 35ns (Vestry, 250MHz).

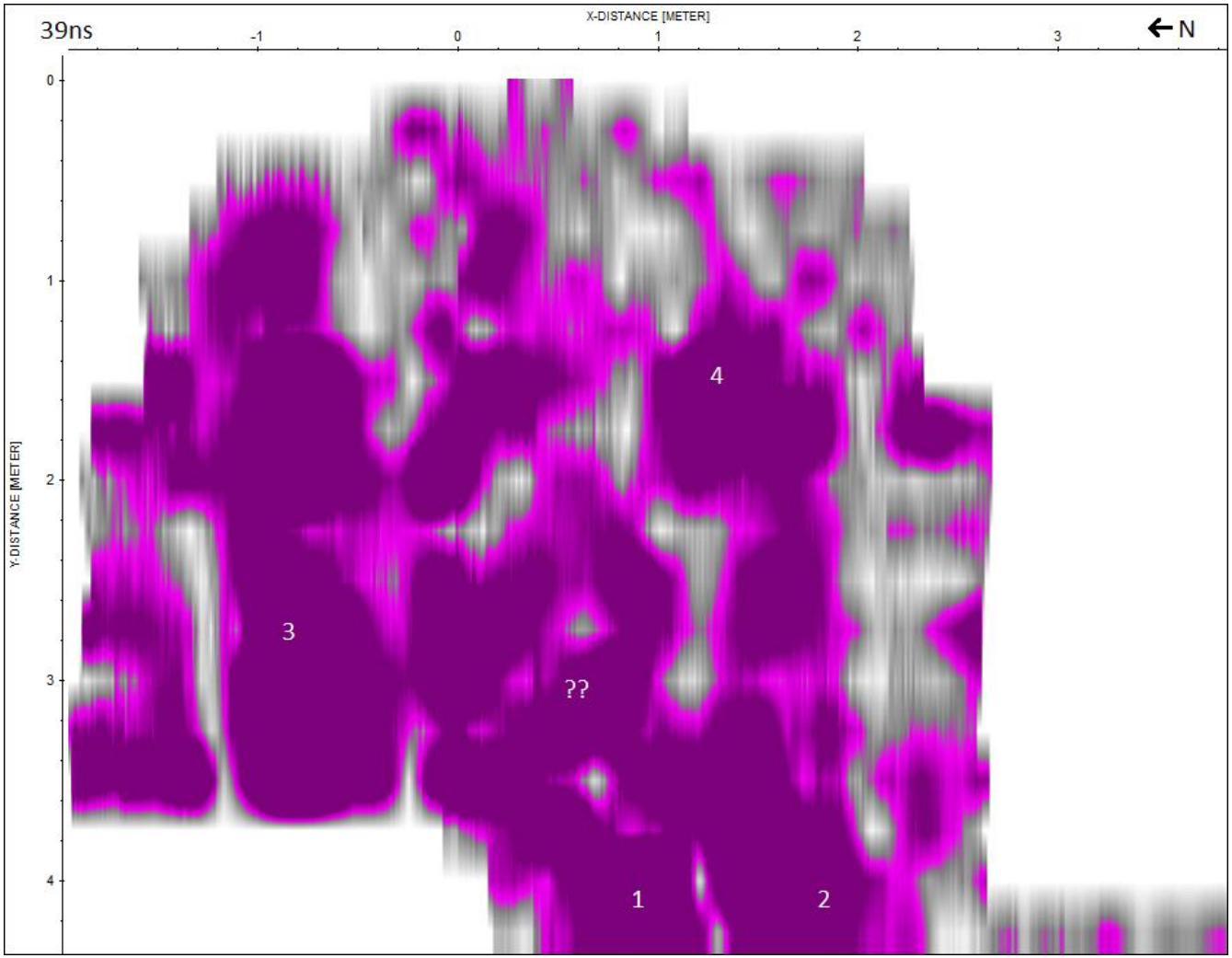

Figure 27: Time Slice at 39ns (Vestry, 250MHz).

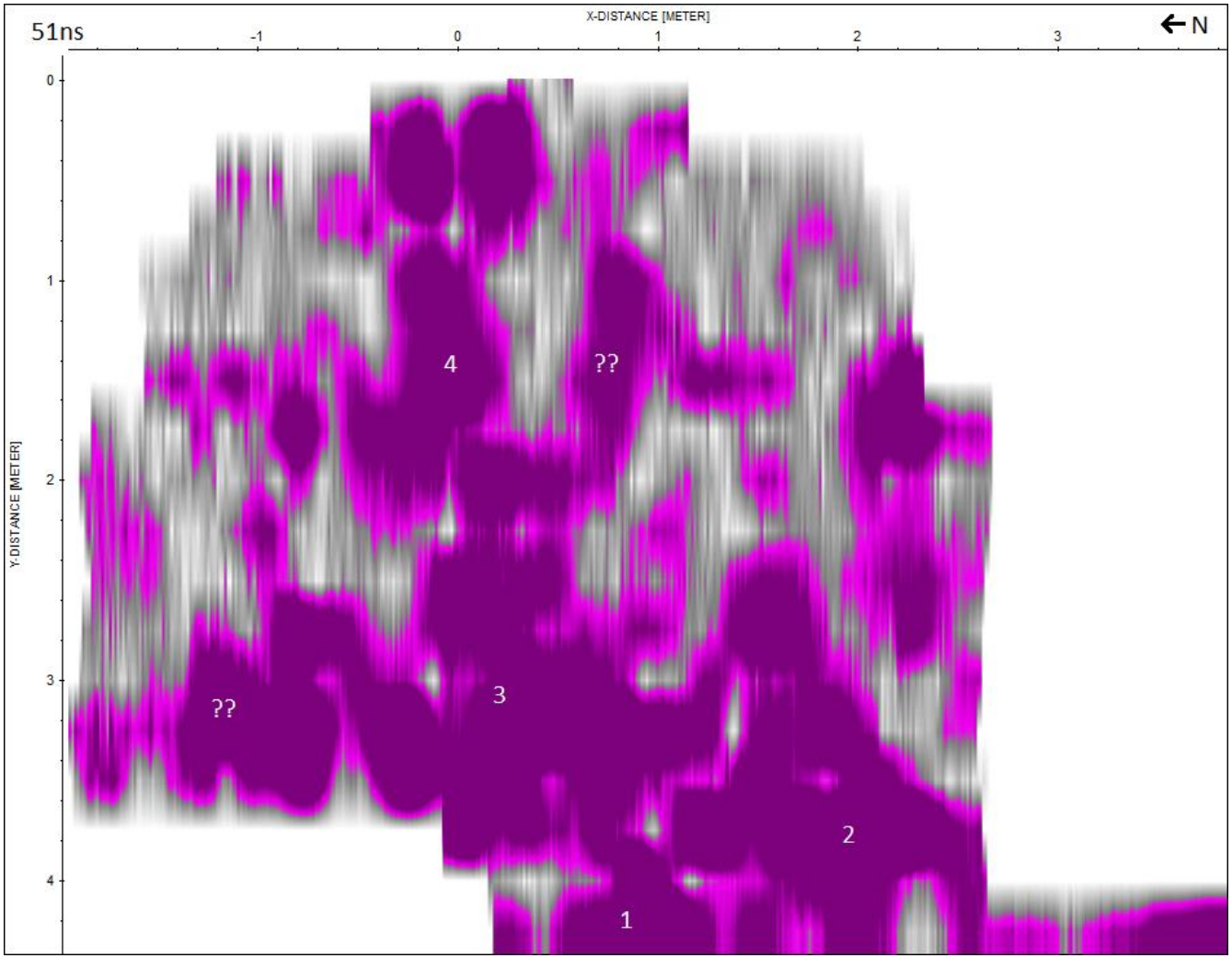

Figure 28: Time Slice at 51ns (Vestry, 250MHz).

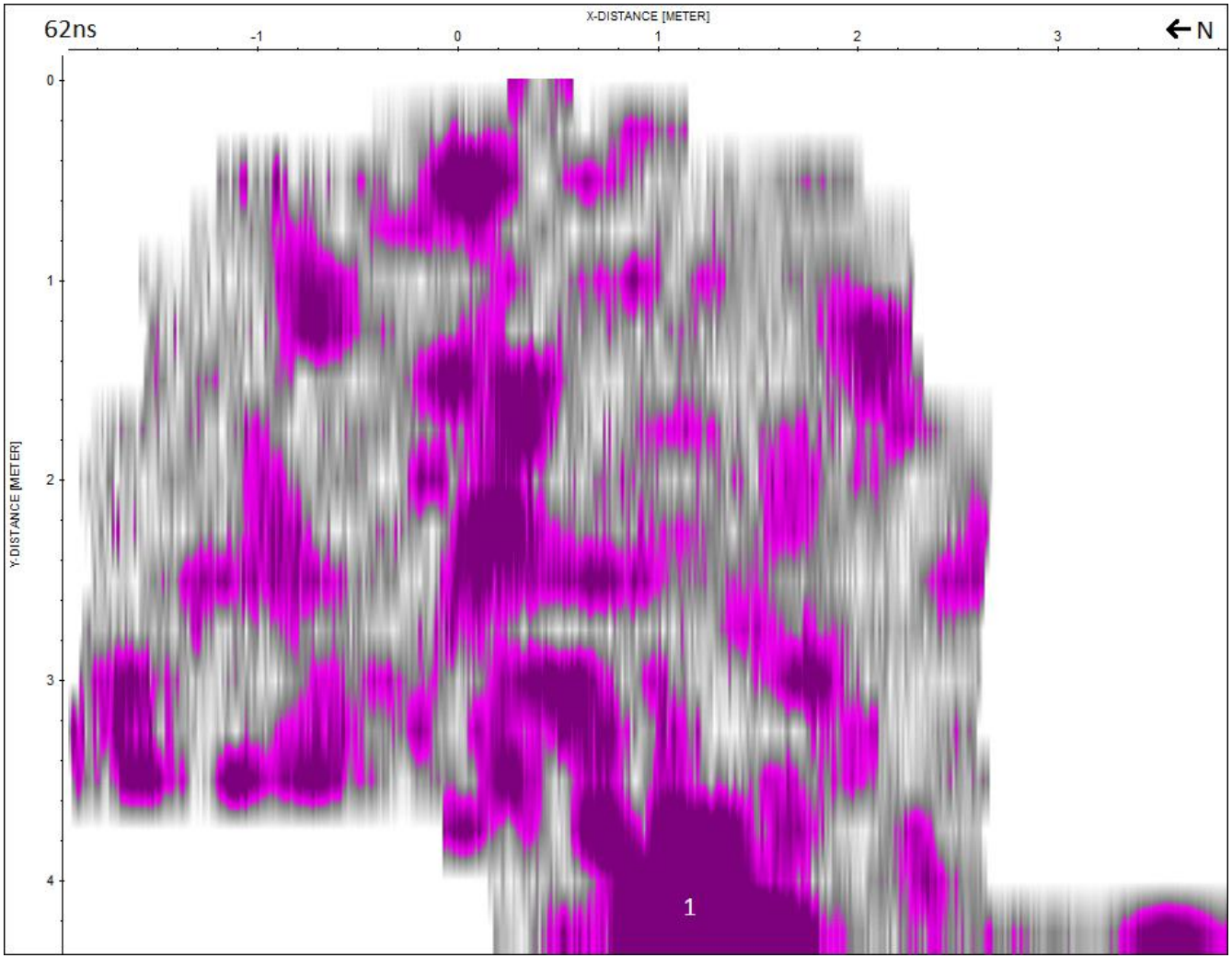

Figure 29: Time Slice at 62ns (Vestry, 250MHz).

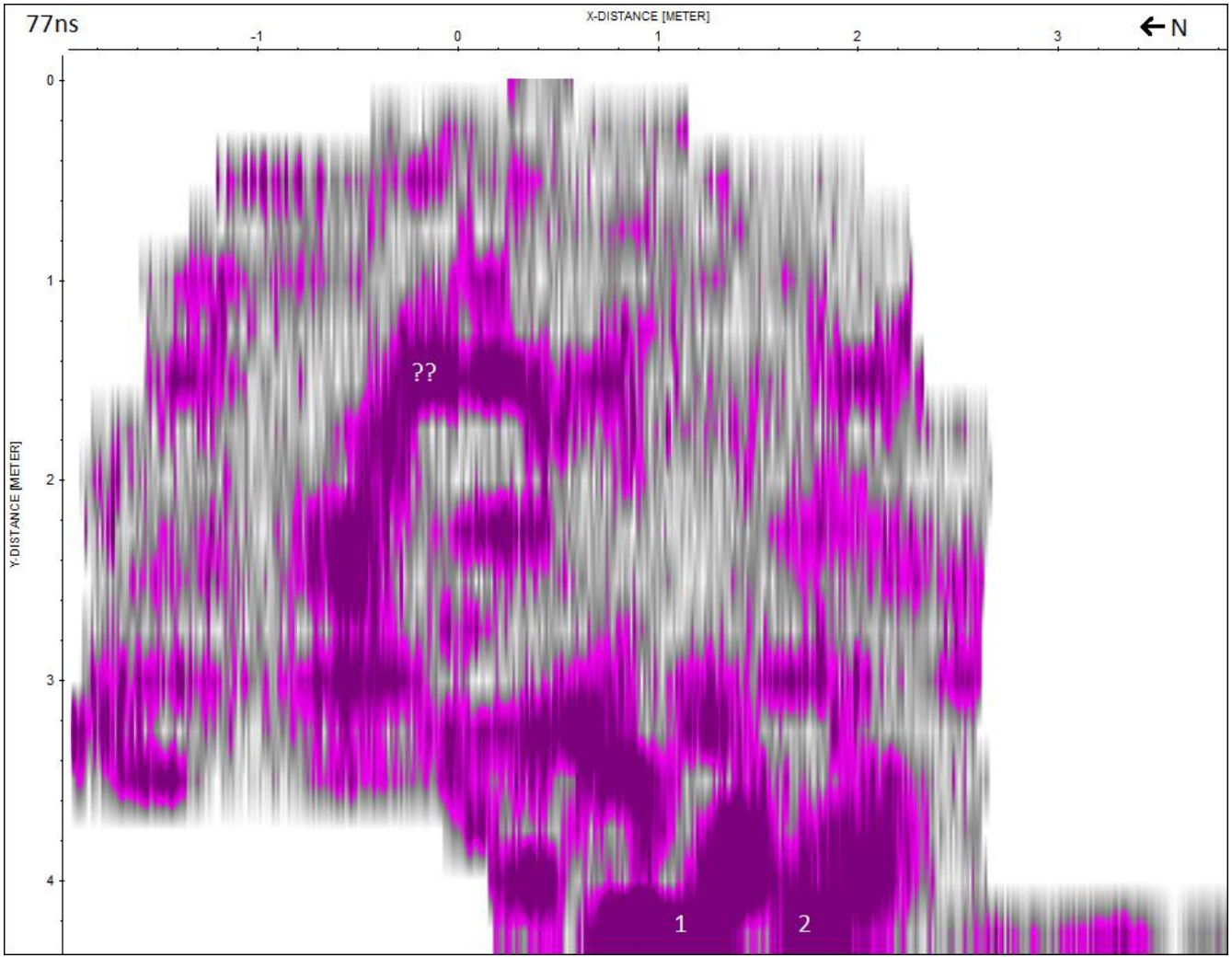

Figure 30: Time Slice at 77ns (Vestry, 250MHz).

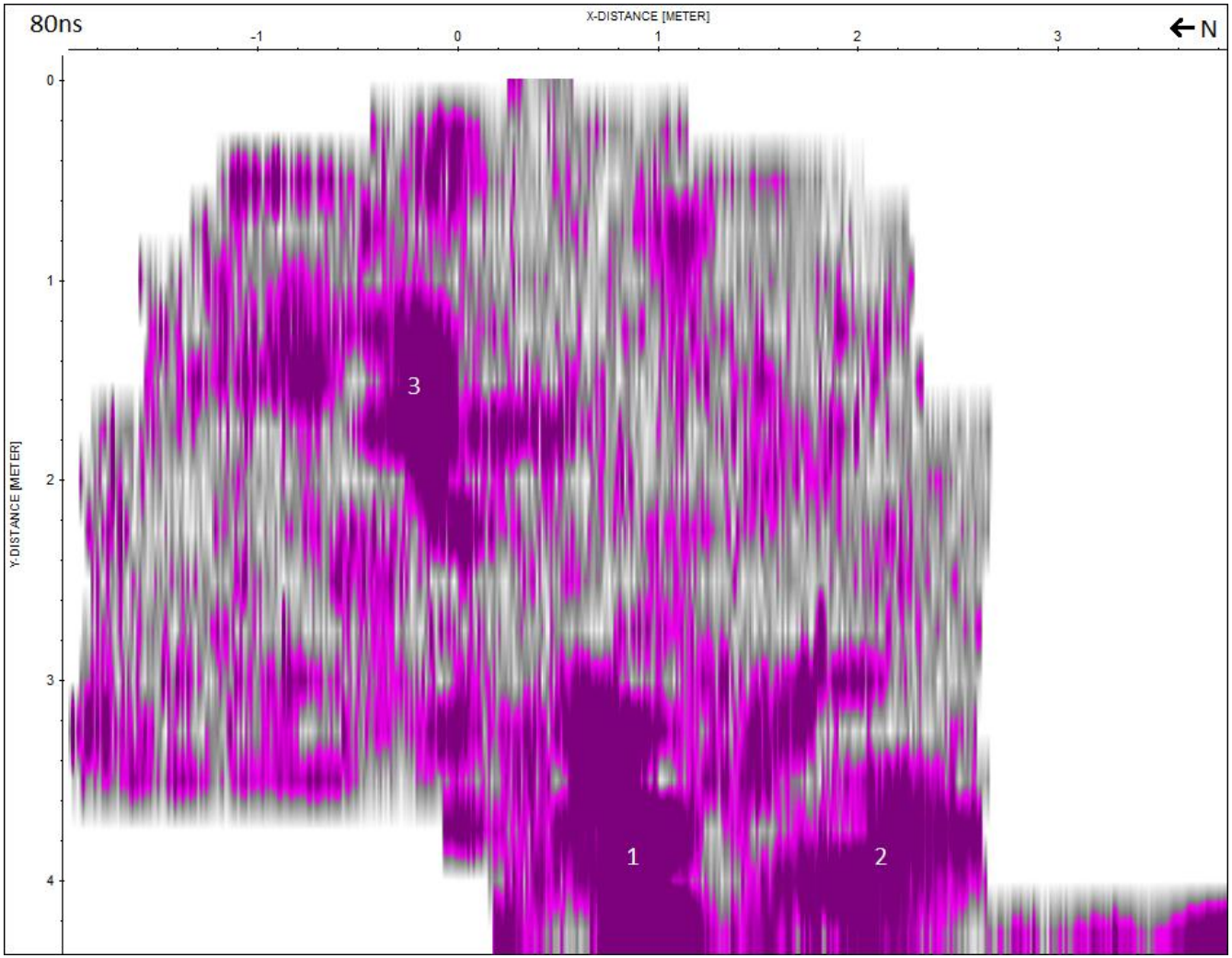

Figure 31: Time Slice at 80ns (Vestry, 250MHz).

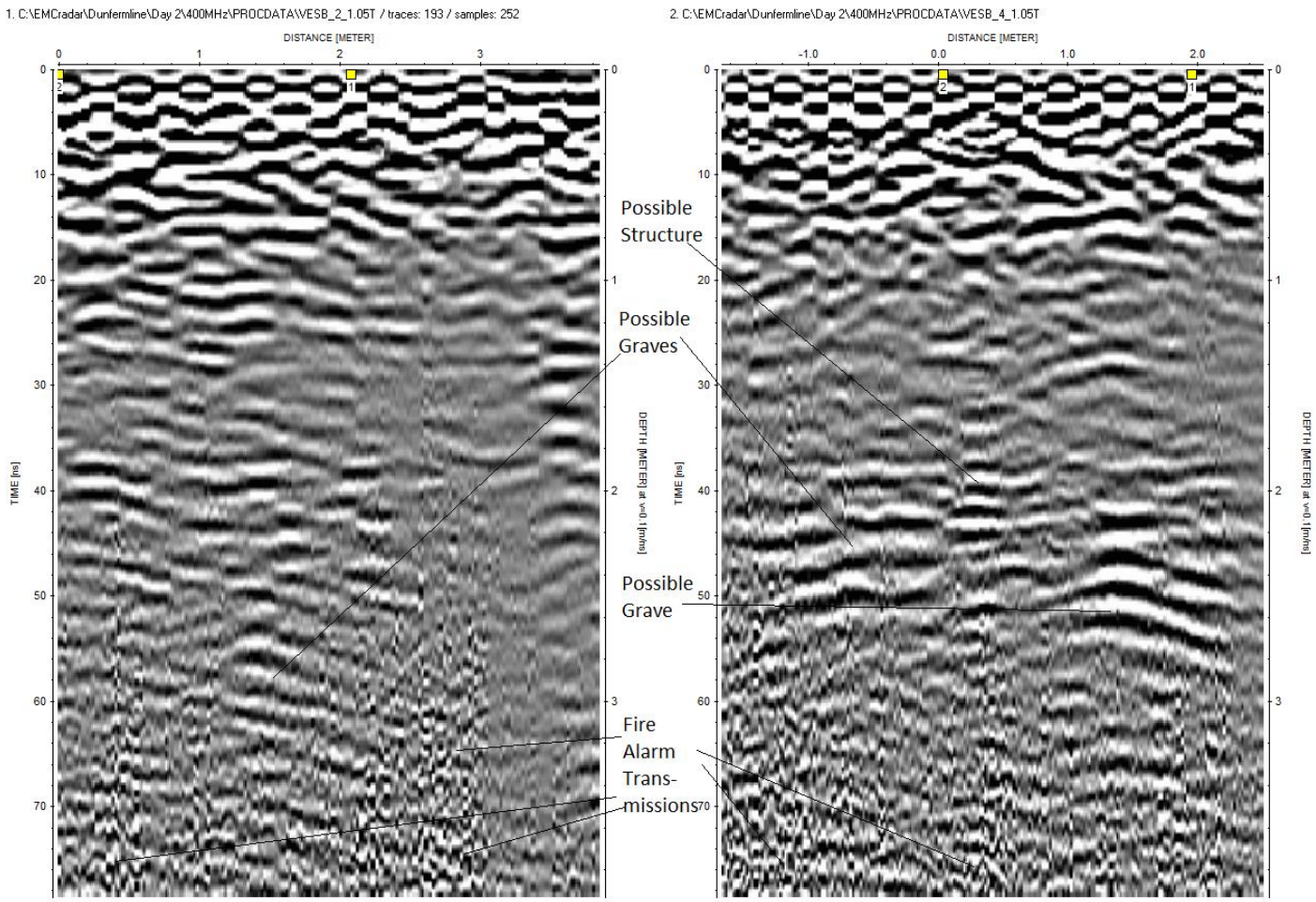

Figure 32: Survey lines 2 and 4 from the Vestry (400MHz)

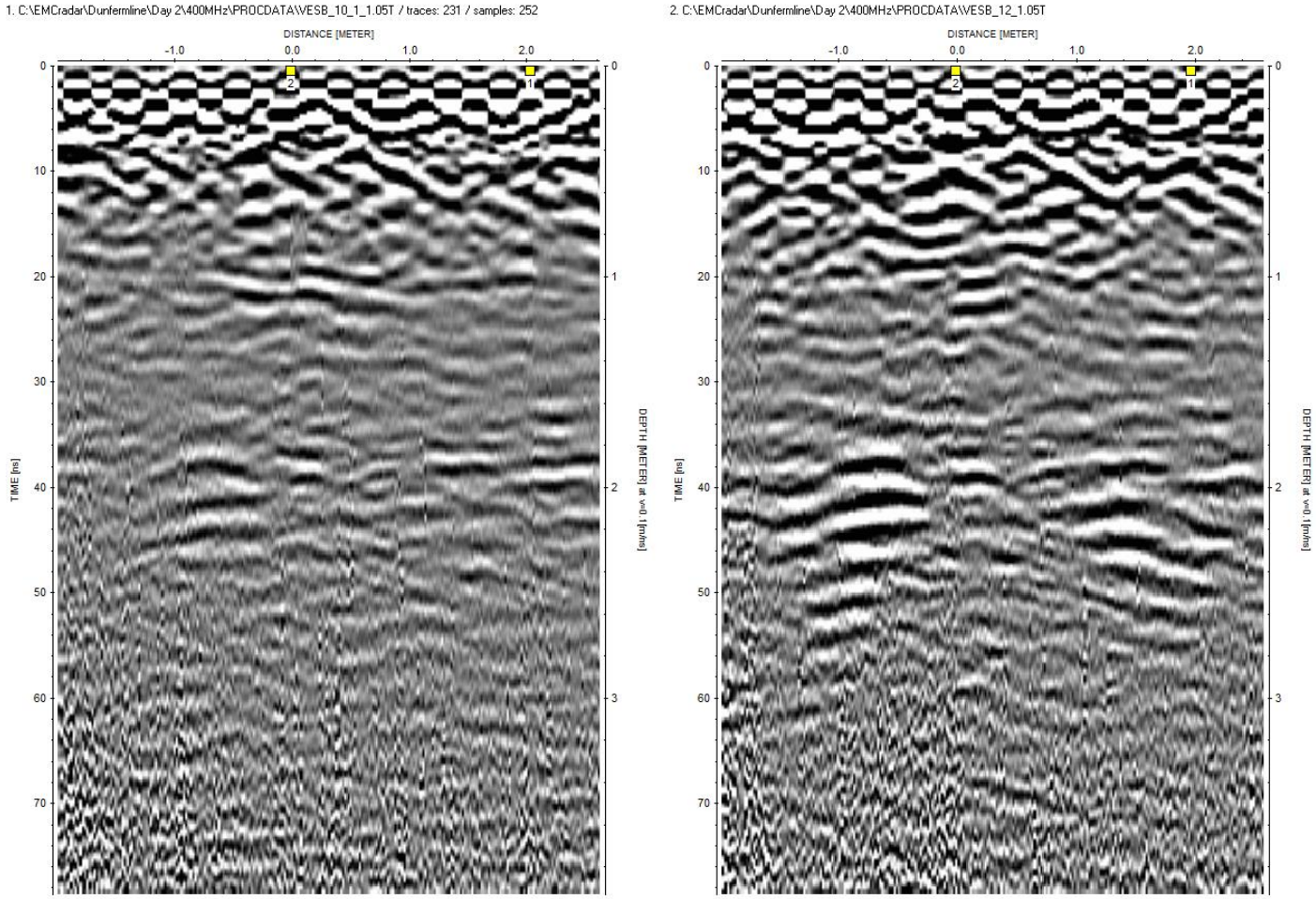

Figure 33: Survey lines 10 and 12 from the Vestry (400MHz).

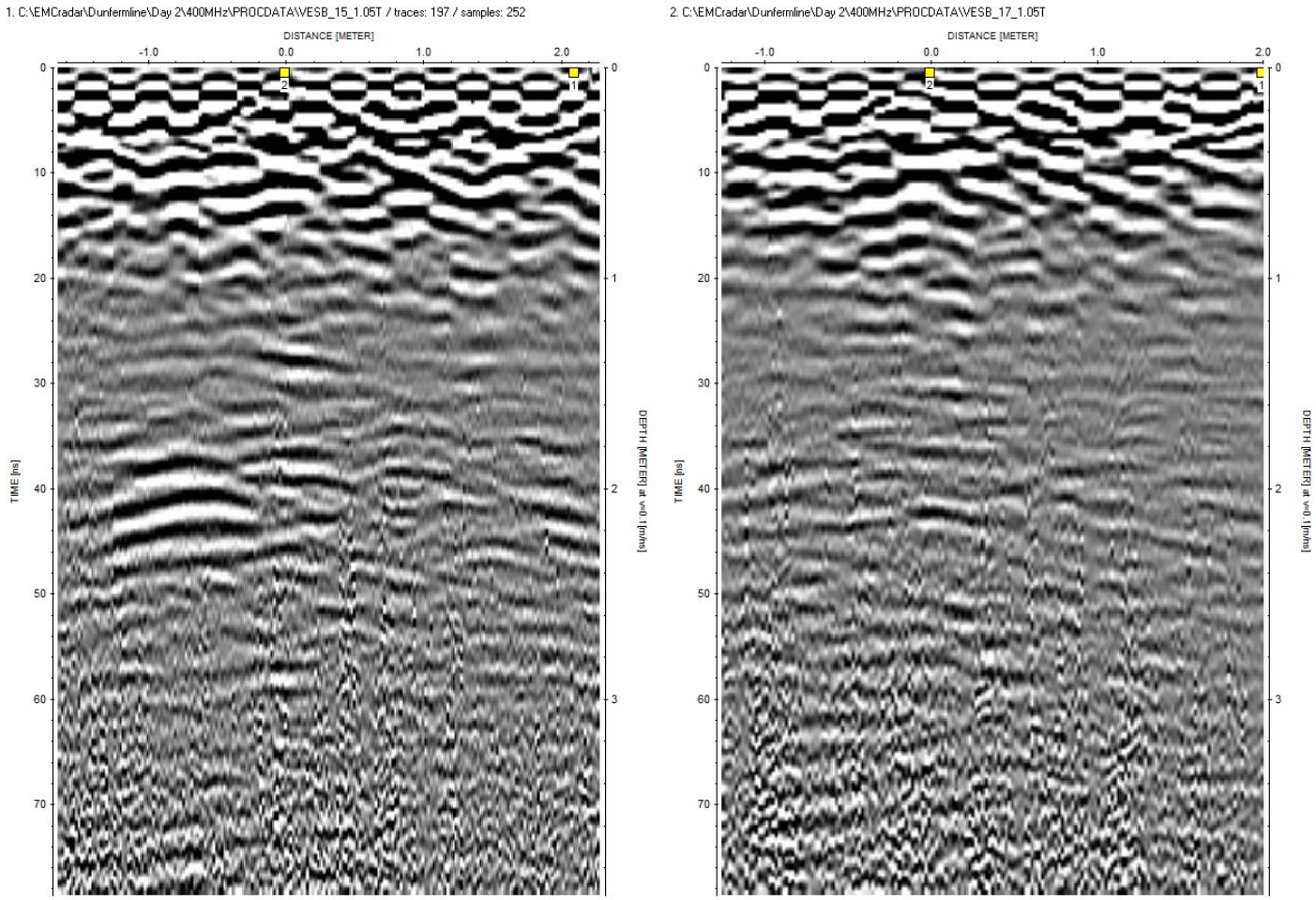

Figure 34: Survey lines 15 and 17 from the Vestry (400MHz).

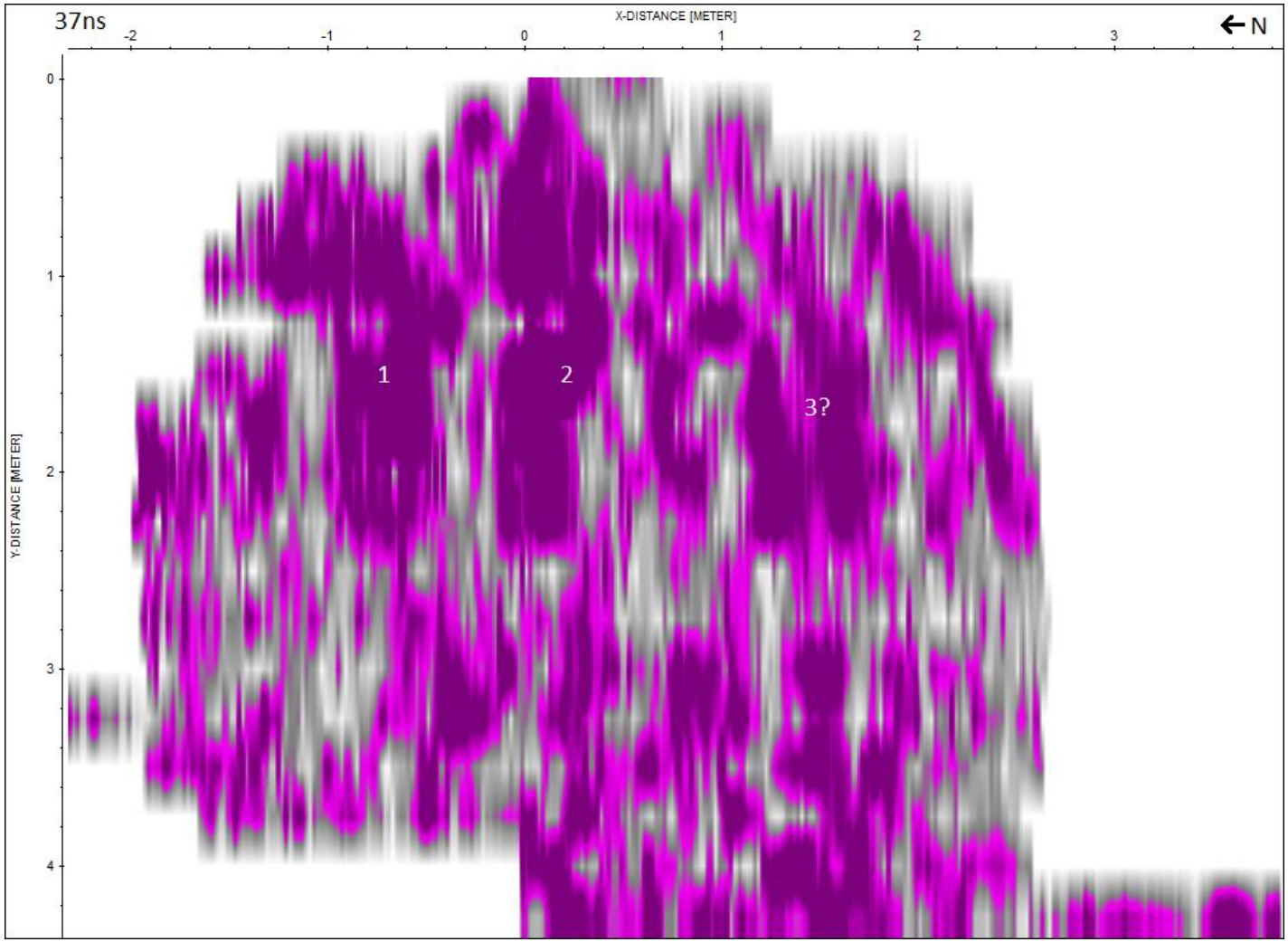

Figure 35: Time Slice at 37ns (Vestry, 400MHz) showing the location of possible graves.

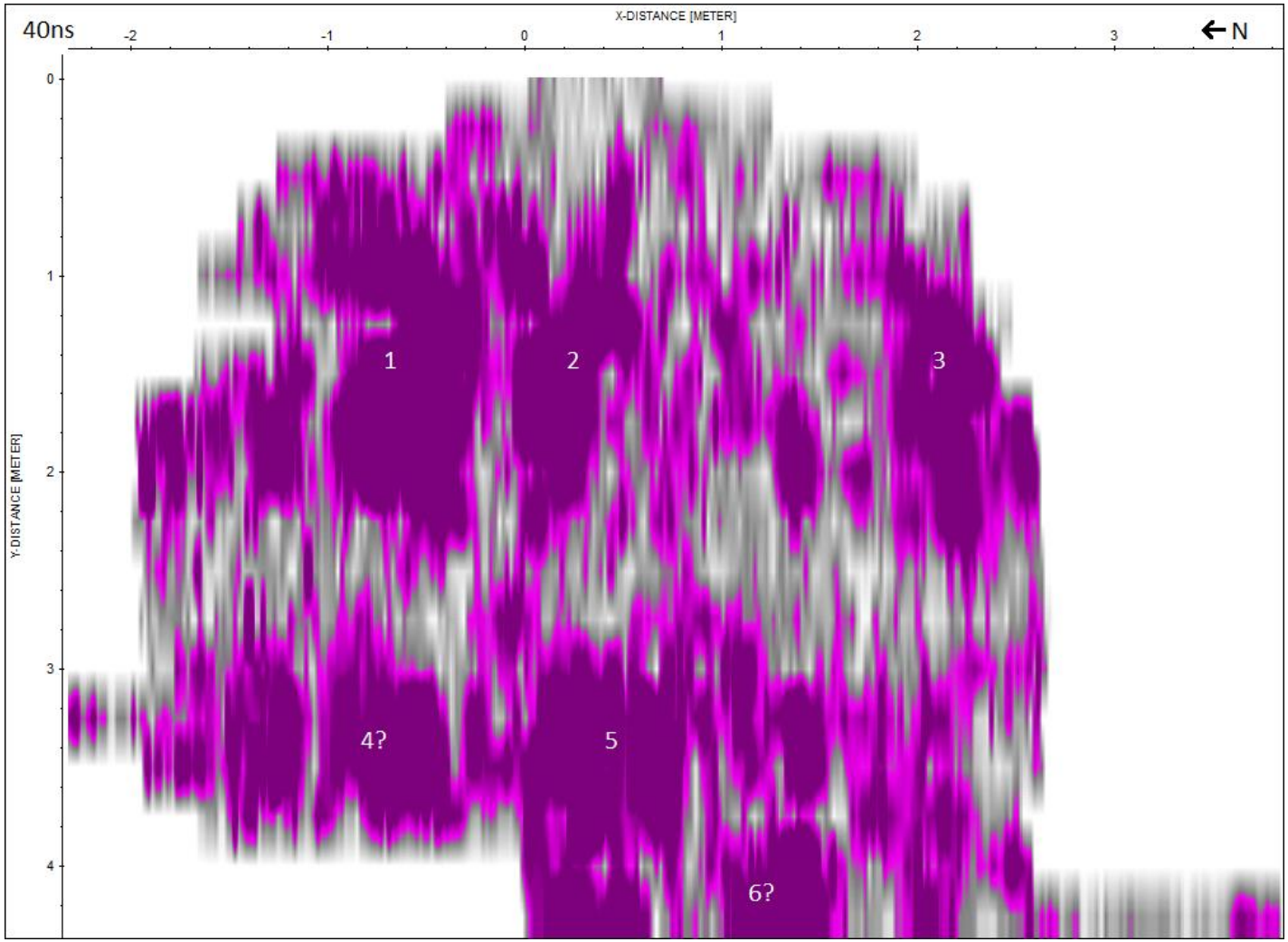

Figure 36: Time Slice at 40ns (Vestry, 400MHz) showing additional graves.

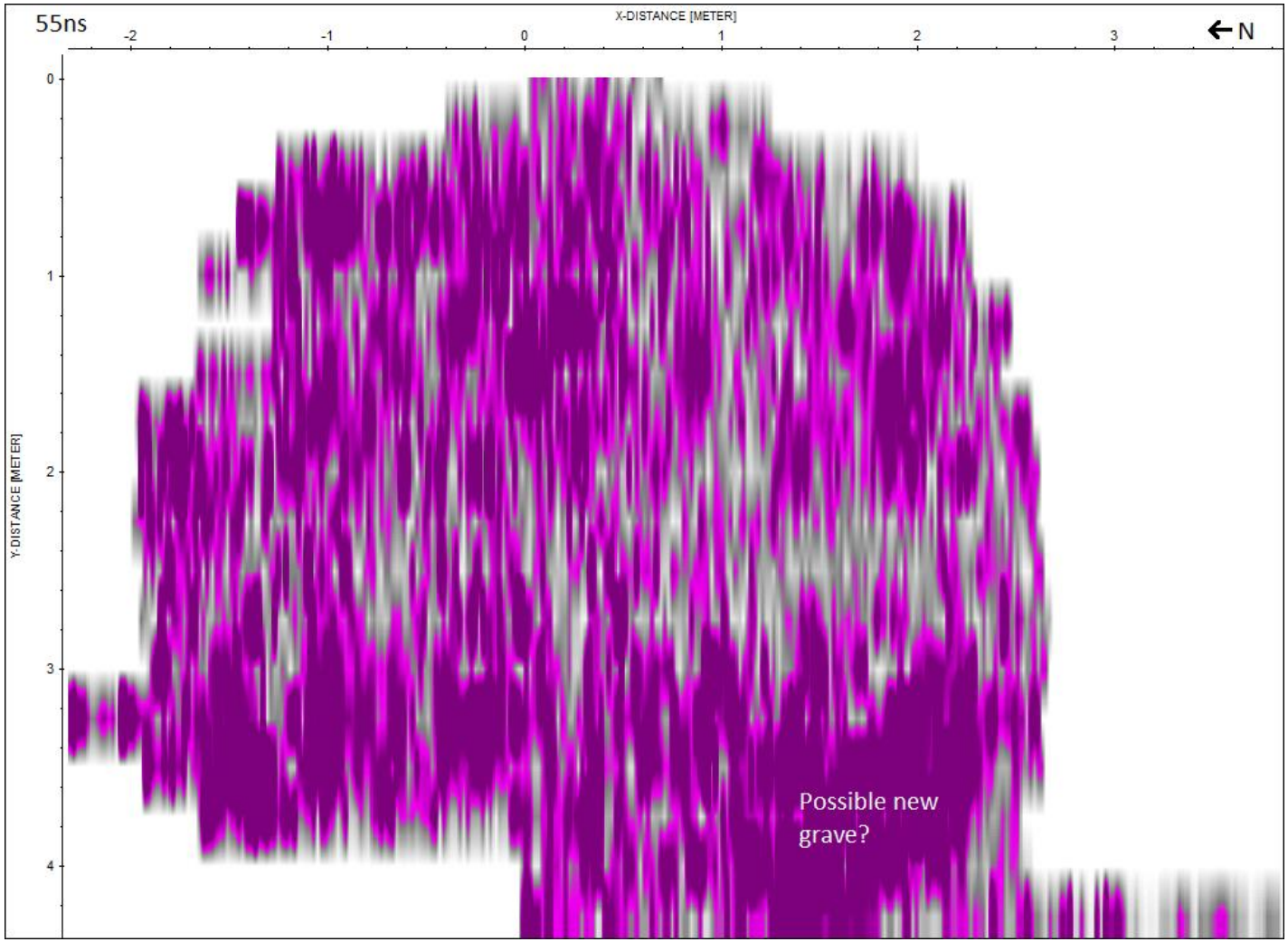

Figure 37: Time Slice at 55ns (Vestry, 400MHz) showing at least 1 possible additional grave lower down.

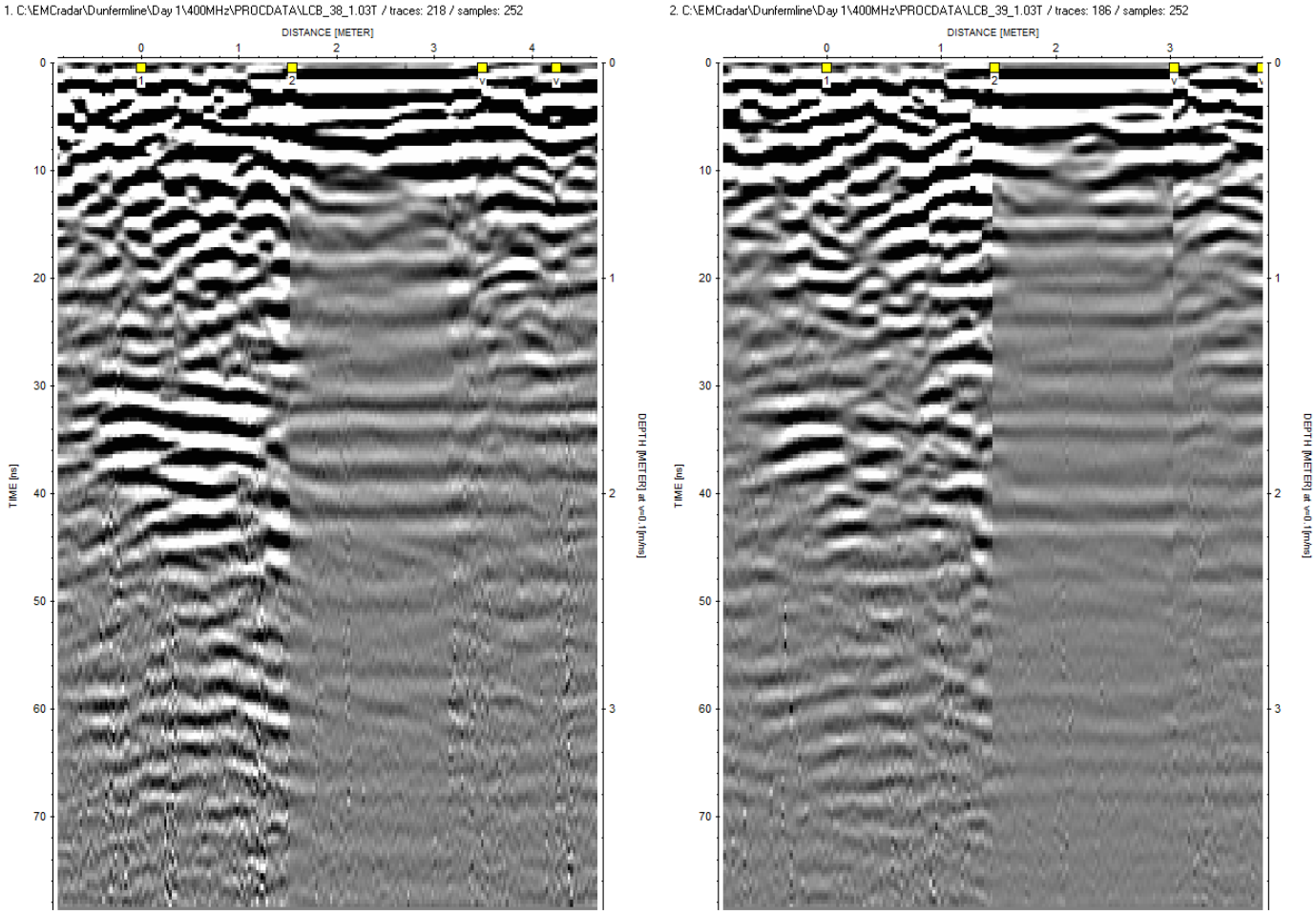

Figure 38: Sample data collected over voids (between markers "V") in the 400MHz survey of the North Transept.