1 **Subsurface Imaging a Viking-Age Churchyard using GPR with TDR: Direct**
2 **Comparison to the Archaeological Record from an Excavated Site in**
3 **Northern Iceland**

4
5 Brian N. Damiata^{ab*}, John M. Steinberg^a, Douglas J. Bolender^a, Guðný Zoëga^c, John W.
6 Schoenfelder^a

7 ^aFiske Center for Archaeological Research, University of Massachusetts Boston, 100 Morrissey
8 Boulevard, Boston, MA, 02125-3393, USA

9 ^bCotsen Institute of Archaeology, University of California, 308 Charles E. Young Drive North,
10 A210 Fowler Building/Box 951510, Los Angeles, CA, 90095-1510, USA

11 ^cThe Skagafjörður Heritage Museum, Glaumbaer, 560 Varmahlíð, Skagafjörður, Iceland

12 *corresponding author: Tel. +1 310 379 6428; FAX +1 310 206 4723; email:
13 brian.damiata@umb.edu

14
15 **Abstract**

16 The results of a ground-penetrating radar (GPR) survey over a Viking-Age Christian
17 churchyard (ca. AD 1000 – 1100) that was subsequently fully excavated are reported. During
18 excavation, broadband time-domain reflectometry (TDR) measurements of apparent relative
19 permittivity were made of various features which helped to constrain interpretations of the radar
20 data. Although four probes of different lengths were used (0.1, 0.15, 0.2 and 0.3 m), the longest
21 waveguide yielded effective frequencies that most closely matched the bandwidth of the radar
22 data, which was collected using a 500 MHz antenna.

23 The excavation revealed 25 graves. Comparison of the radar data to the archaeological
24 record indicated that all graves containing skeletal remains produced signatures from the bones,
25 but only half of those were interpreted as such prior to excavation. The skeletons of three adults

and two children as well as two pairs of isolated leg bones were identified beforehand, whereas five sets of remains (small child, infants and neonates) were noted only after reanalysis of the radar data following the excavation. Thirteen of the graves had been re-dug and their bones removed prior to AD 1100 presumably for interment to a nearby more recent churchyard. The only indication of burial pits in the radar profiles was a break in a sub-horizontal reflector that corresponded to a perforated in situ volcanic tephra sequence. Six of the 25 burial pits were identified prior to excavation, eight more after reanalysis, and 11 had no signature because of the absence of preserved tephra in their vicinity. The TDR measurements confirmed the general lack of contrast between backfill material within pits and soil surrounding pits. This study provides one of the best documented cases for comparison of radar data to the archaeological record for a fully excavated churchyard, and confirms the direct detection of skeletal remains by GPR.

Keywords: Christian cemetery; GPR; grave; Iceland; TDR; time-domain reflectometry; Viking Age

1. Introduction

Ground-penetrating radar (GPR) is an important geophysical tool for shallow subsurface imaging. The method is based on detecting contrasts in the electromagnetic properties of relative permittivity (electric) and relative permeability (magnetic) in soil. The former is strongly correlated to water content while the latter varies insignificantly for most field conditions that are likely to be encountered. For archaeological and forensic applications, GPR has proved useful in detecting unmarked burials and clandestine graves (e.g., Bevan, 1991; Buck, 2003; Conyers, 2006; Schultz, 2007; Ruffell et al., 2009; Fiedler et al. 2009; Doolittle and Bellantoni, 2010; Damiata et al., 2013).

In general, the presence of a grave can be identified in radar profiles by several means including: (1) the perforation or truncation of natural stratigraphy due to digging of the burial pit (Bevan, 1991; Mellett, 1992; King et al., 1993; Conyers, 2006; Damiata et al., 2013); (2) the slumping of the ground surface (Conyers, 2006; Doolittle and Bellantoni, 2010) and associated lateral changes in velocity (Unterberger, 1992) due to differences in compaction and homogeneity between undisturbed and backfill deposits; and (3) the detection of a burial container such as a casket or coffin (Mellett, 1992; Unterberger, 1992; Dionne et al., 2010). Rarer still is reported the direct detection of skeletal remains (Mellett, 1992; Damiata et al., 2013).

In a previous paper, Damiata et al. (2013) presented a case study in which GPR was used to discover the Viking-Age Christian churchyard that is considered in the present work (Fig. 1). As reported in that paper, several sets of hyperbolas (diffractions) on contiguous radar profiles were identified and interpreted to be graves. A targeted excavation was performed over the most pronounced set revealing the presence of a well-preserved adult skeleton. Comparison of the radar profiles to the archaeological record indicated that various long bones of the skeleton were directly detected. The only indication of the burial pit in the profiles was the break in a sub-horizontal reflector that corresponded to a perforation of a relatively thick, prehistoric, volcanic tephra sequence.

Subsequently, the churchyard has been fully excavated and the radar data reanalyzed. During the course of excavation, time-domain reflectometry (TDR) measurements of apparent

relative permittivity were made on various features in and around the churchyard. The TDR measurements were used to help constrain interpretations of the radar data. TDR is commonly used in the soil sciences to indirectly measure the moisture content of soils (Topp et al., 1980; Topp et al., 1982; Jones et al., 2002; Pettinelli et al., 2002; Robinson et al., 2003). Its use in archaeological studies has been limited—Leckebusch (2000) employed TDR to estimate radar velocities under a concrete floor in a medieval Swiss choir; Verdonck et al. (2009) made measurements on Bronze-Age burial mounds in Belgium to estimate radar velocity for migrating data; and Pettinelli et al. (2012) used it to estimate the relative permittivity and signal attenuation of radar waves for different volcanic units that cover the ruins at Pompeii.

The present study represents an extension of the preliminary work that was reported by Damiata et al. (2013) for a single grave, and provides a rare opportunity to directly evaluate the diffractions and reflections arising from various buried features of a Viking-Age Christian churchyard. This study is one of best documented cases for detecting in situ skeletons and partial remains by GPR surveying and is unique in that interpretations are both constrained by TDR measurements and verified through excavation. Note that this paper does not deal with 11th century mortuary practices nor with burial customs in this part of Iceland which are subjects to be reported upon elsewhere (Zoëga and Bolender in review).

2. Methods and Instrumentation

The present study was conducted as part of the Skagafjörður Archaeological Settlement Survey (SASS) in collaboration with the Skagafjörður Church Project (SCP). SASS was initiated in 2001 and has intensively investigated twenty-one present-day farms in the Langholt region of Skagafjörður (Steinberg, 2003; Bolender et al., 2008; Bolender et al., 2011; Damiata et al., 2013; Bolender, 2015; Steinberg et al., 2016). Over the course of several field seasons, a protocol was developed to investigate a given farm in order to: identify the presence of Viking-Age farmsteads, estimate their extent, determine their establishment date, locate individual structures and features that comprise a farmstead, and understand the function of some of the structures. The SCP was initiated in 2007 with the aim of establishing the frequency of spatial and temporal distribution of early Christian cemeteries as well as to examine developments in

burial practices and religious architecture (Zoëga and Sigurðarson, 2010; Sigurðardóttir, 2012; Zoëga, 2014, Zoëga, 2015).

The SASS protocol involves systematic hand coring, reconnaissance geophysical surveying, test excavation, targeted geophysical surveying, and traditional excavation. Using this protocol, the Viking-Age churchyard at the lower site on the present-day Stóra-Seyla farm was discovered in 2009. Based on tephrochronology, the churchyard was in existence after the deposition of the Landnam tephra ($AD\ 871 \pm 2$, Grönvold et al., 1995; $AD\ 877 \pm 4$, Zielinski et al., 1997) but had been abandoned before the deposition of the Hekla 1 tephra (H1, AD 1104; Þórarinnsson, 1970; Thorarinnsson, 1980). Of note is the presence of another churchyard whose remnants are partially visible at a site that is located several tens of meters uphill and to the southwest on the same farm (see Fig. 1). However, this churchyard does not appear to have been used contemporaneously as its occupation began at about the time of the falling of the H1 tephra (Zoëga and Sigurðarson, 2010).

2.1 *Ground-Penetrating Radar*

As part of the SASS protocol, GPR was used to provide high-resolution imaging of selected Viking-Age sites that had been previously detected through hand coring and reconnaissance electromagnetic surveying. In general, most sites were covered by tall grass with some having many hummocks (*púfur*) due to frost heaving. At Stóra-Seyla, the ground was “de-turfed” using a backhoe in order to provide a relatively flat surface, which ensured a good coupling between the system’s antenna and the ground surface. The specifics of the collection and processing of GPR data are briefly summarized here (see also Table 1 in Damiata et al., 2013).

The GPR surveying was conducted over an orthogonal grid that was established using a Trimble GeoXH Global Positioning System (GPS) receiver and a TOPCON GS905A robotic total station. Data were collected using a hand-towed Mala Geoscience RAMAC X3M radar system that was equipped with a shielded 500 MHz antenna. The antenna was oriented in the broadside mode with vertical scans collected at approximately 0.02 m along transects that were separated by 0.2 m. The orientation of a given transect was guided by fiberglass measuring tapes that had been stretched between the endpoints of those transects occurring at whole meter locations. The actual position along a given transect was determined by operator-placed fiducial

136 markers that were inserted into the data stream at 1-m intervals. The overall accuracy in real
137 world coordinates (ISN93) in terms of the correspondence between GPR data and excavated
138 material is estimated to be <0.15 m.

139 The raw data were processed using GPR Slice software (Goodman et al., 1995; 2007; 2009).
140 Initially, the two-way travel time sections were converted to depth sections by assuming a
141 constant velocity of 0.065 m/ns as determined by slope matching the tails of relatively shallow
142 point-source hyperbolas which appear in several profiles (see Damiata et al., 2013). The data
143 were then filtered (background removal, boxcar, and bandpass) and combined to produce a
144 pseudo three-dimensional data set. Next, horizontal depth-slice images of the squared amplitude
145 of reflected energy were generated—each with a thickness of approximately 0.065 m (2 ns),
146 normalized relative to each slice, and overlapping 50% with adjacent slices. Subsequently, the
147 depth sections were readjusted assuming a velocity profile based on TDR measurements as more
148 fully discussed below. Annotated radar profiles and overlay images (i.e., combining two or more
149 slices of squared amplitude onto a single image) for various features of the churchyard are
150 presented in Section 3.

151 *2.2 Archaeological Excavation*

152 The lower site at Stóra-Seyla was initially discovered in 2002 by hand coring and
153 reconnaissance electromagnetic surveying. In 2005, a limited GPR survey and targeted
154 excavations to ground-truth interpretations were performed as part of a pilot project to evaluate
155 the general effectiveness of GPR to image Viking-Age structures in Skagafjörður. However, the
156 survey did not extend far enough to cover the churchyard. Additional surveys in 2007 through
157 2009 led to its discovery which was completely unanticipated given the previously known
158 existence of the upper churchyard. The result is notable because it is the first documented case
159 of a churchyard being discovered in Iceland by using geophysical methods, as well as the only
160 known case, at that time, of two early Christian churchyards being located within the confines of
161 the same modern-day farm.

162 In 2009, a targeted excavation was placed over a suspected grave which revealed a well-
163 preserved skeleton of an adult as previously reported by Zoëga (2009), Damiata et al. (2013) and
164 Zoëga and Bolender (2014). Additional excavations conducted in 2012 and 2013 systematically

unearthed most of the remaining features of the churchyard. Features that were exposed included: the remnants of a circular enclosure wall composed of compacted turf with rocky foundation, the remnants of a small central church structure with post holes and compacted surface, and 25 graves. Of these graves, six contained the skeletons of adults or children, four the remains of infants or neonates, and two the partial remains (pairs of leg bones) of a juvenile and an adult. In addition, 13 other graves had been re-dug and their bones removed (ca. AD 1100) presumably for interment to the more recent upper churchyard (Zoëga and Bolender, 2014).

Fig. 2 is a schematic diagram of the main features of the lower churchyard that were unearthed with emphasis on the enclosure wall, central church structure, and graves. All listed depths are relative to the de-turfed ground surface in order to facilitate comparison with the GPR results. Note that the overall layout and size of the churchyard is typical for the time period in Iceland (Zoëga, 2014). Also, the in situ skeletons were in the supine position and orientated approximately east-to-west with the head situated at the western end.

2.3 Time-Domain Reflectometry

It is the contrast in relative permittivity that gives rise to diffracted and reflected energies that are recorded by GPR surveying. Thus, the stratigraphic deposits and archaeological features that may have produced reflections can be directly assessed by measuring their relative permittivity during the course of excavation. For the present case, TDR measurements were particularly useful in determining whether burial pits containing backfill material provided a sufficient contrast as compared to surrounding soil to produce the diffractions that were observed over graves containing skeletal remains.

The operating principles of TDR are somewhat similar to GPR. The measuring device consists of a pulse generator and a multi-rod probe which is configured to form a pronged waveguide that is inserted into the soil. An electromagnetic pulse is generated and sent along a coaxial cable that is attached to the probe. As the signal encounters the junction of the cable and the beginning of the waveguide, an impedance contrast produces an initial reflection. A second reflection arises when the signal encounters the end of the waveguide. The apparent relative

permittivity of the soil which lies between the waveguide is calculated according to (Soilmoisture Equipment Corp., 2012)

$$\epsilon_a = c \Delta t / L^2$$

where L is the length of the waveguide (m), c is the speed of light (≈ 0.29979 m/ns), and Δt is one-way travel time along the waveguide (ns).

In 2012 and 2013, TDR measurements were collected within and adjacent to the churchyard (see Fig. 2). The measurements were made using a Trase 6050X1 instrument (Soilmoisture Equipment Corp., Santa Barbara, CA, USA) which consists of two parallel stainless steel rods that form the pronged waveguide. The rods are 6 mm in diameter and spaced 0.05 m apart. Four pairs of rods with different lengths were used: 0.1, 0.15, 0.2 and 0.3 m. The probe was inserted either vertically on the prevailing ground (excavated) surface or horizontally at different depths along the sidewall of trenches and graves. Typically, a set of four measurements were made at a given sampling location, progressively using all four pairs of rods from the shortest to the longest in length. Care was exercised to minimize air gaps as the probe was repeatedly inserted and removed from the same location (see Annan, 1977). In addition, the probe was periodically zeroed (short circuited) and a measurement made in air to ensure proper functioning of the instrumentation.

Fig. 3 depicts representative TDR measurements that were collected in background soil to the south of the churchyard. The apparent relative permittivity was initially calculated using Eq. (1) and WinTrase software (v. 2.07) which employs the standard tangent-line fitting procedure to determine the times of reflection. Although the relative permittivity for non-clayey soils and rocks does not appear to be strongly frequency dependent above 500 MHz (e.g., see Davis and Annan, 1977; Or and Rasmussen, 1999; Robinson et al., 2003), it is important to note that the TDR measurement is a broadband response over the frequency range of approximately 20 kHz to 1.5 GHz (Heimovaara, 1994). As such, higher frequencies may become attenuated in lossy earthen materials (Or and Rasmussen, 1999; Robinson et al., 2005).

Following the methodology of Strickland (1970), the “maximum passable frequency” is (see Robinson et al., 2003, Eq. (14))

221 2 $f_{\max} = \ln 0.90 / 12\pi\tau = 0.35/\tau$

222 where τ is the rise time (sec) between 10 and 90% of the signal magnitude as illustrated in Fig.

223 3. Robinson et al. (2003) note that this frequency should be regarded more appropriately as an
224 “effective frequency” (f_{eff}) where the majority of energy of the signal is contained.

225 Accordingly, the apparent relative permittivity that is determined from the travel time to the apex
226 of the derivative TDR waveform corresponds to the signal’s group velocity whereas the time
227 based on the tangent-line procedure corresponds more appropriately to the phase velocity of the
228 leading edge.

229 As evident from the TDR waveforms, the derivative method yields a higher value of ϵ_a (i.e.,
230 longer travel time) as compared to the tangent-line method (compare Figs. 3B to 3D;
231 approximately 4 units higher on average for the present case). In addition, decreasing the length
232 of the probe generally led to progressively higher values of f_{eff} for the prevailing conditions at
233 Stóra-Seyla. Specifically, measurements using the 0.3-m probe yielded values in the range of
234 250 to 600 MHz, whereas the shorter length probes between 400 to 900 (0.1 m), 350 to 750 (0.15
235 m), and 300 to 700 (0.2 m) MHz, respectively (Fig. 4). Thus, the values of ϵ_a that are based on
236 the former most closely match the bandwidth of the GPR data which were collected using an
237 antenna with central frequency (air based) of 500 MHz with approximate bandwidth of 250 to
238 750 MHz. Note that a reduced effective bandwidth is expected when coupled to a lossy ground
239 which acts as a low-pass filter with attenuation of higher frequencies (Daniels, 2009).

240 Table 1 summarizes TDR measurements for various archaeological features of interest. For
241 brevity, the results for the 0.3-m probe are mainly considered except as noted. In addition,
242 values of relative permittivity (ϵ_r) that have been obtained from the literature for several relevant
243 geological materials are also listed. In the ensuing discussion, it has been assumed that there are
244 no material differences between the apparent relative permittivity as measured by TDR in this
245 study and relative permittivity as measured in the laboratory at specific frequencies as reported in
246 the literature. Also, the reflection coefficient for planar interfaces is given by (see Daniels et al.,
247 2003, Eq. 20 with $\theta_i = 0$)

$$(3) \quad R = \frac{\epsilon_1 - \epsilon_2}{\epsilon_1 + \epsilon_2}$$

where ϵ_1 is the apparent relative permittivity of the background soil and ϵ_2 is the apparent relative permittivity (or relative permittivity) of the embedded material that is being considered. Eq. (3) applies to planar interfaces and may not be strictly valid for relatively small features producing diffractions. However, this parameter provides a convenient means to qualitatively assess whether a given feature is capable of producing a recordable reflection (or diffraction), but noting that it is one of several factors. Thus, the absolute value of the reflection coefficient (i.e., R) has been included in the following qualitative evaluation.

3. Results and Discussion

This section presents comparisons between radar interpretations—as constrained by the TDR measurements—and the archaeological record from extensive excavation of the churchyard (see Fig. 2). Fig. 5 presents several radar overlay images that emphasize different features that were subsequently excavated, including post holes, enclosure wall, church foundation, and skeletons.

3.1 Natural Stratigraphy

The natural stratigraphy consists of a background soil with intermixed tephra layers. The soil is a moist brown andosol that derives from aeolian sediments of volcanic origin, but is not the direct product of eruptions (Parfitt and Clayden, 1991; Arnalds et al., 1995; Arnalds, 2004; 2008). The soil is characterized as non-cohesive but has an extremely high water-retention capacity (Arnalds, 2008). The TDR measurements indicate a relatively constant $\epsilon_a = 28$ for the upper 0.5 m but increases to ~40 at 1 m depth, thus consistent with a vadose zone having increasing moisture content with depth. Invoking the relation (Annan, 2009, Eq. 1.17)

$$(4) \quad v = c \epsilon_a$$

where v is the radar wave's velocity and c is the speed of light, a velocity profile of 0.057 m/ns from 0 to 0.5 m that linearly decreases to 0.047 m/ns at 1 m depth was deemed most

representative of the soil and was used to generate the depth-slice images that are shown in Fig. 5.

Although several tephra layers are naturally present, only the closely spaced pre-historic sequence—consisting of the Hekla 3 (H3, ca. BC 950; Dugmore et al., 1995) and the Hekla 4 (H4, ca. BC 2300; Eiríksson et al., 2000)—is sufficiently thick (typically at least 4 to 5 cm) and contrasting ($\epsilon_a = 21$; $R = 0.07$, assuming surrounding soil with $\epsilon_a = 28$) to produce a reflection (see later in text Figs. 9a and 9b with discussion of Grave 1). The relatively thick tephra layering probably acts as a barrier to the downward infiltration of water via capillary forces (e.g., see De Vleeschouwer et al., 2008). That being said, the reflection coefficient is slightly lower than the conservative rule-of-thumb threshold value of $|\pm 0.1|$ for detection (Annan, 2001).

3.2 Enclosure Wall

Fig. 5c is an overlay radar image that emphasizes the delineation of the circular enclosure wall. Excavated remnants of the wall consisted of patches of highly compacted turf overlying a more continuous rocky foundation. It was surmised during excavation that the bulk of the wall may have been dismantled when the churchyard was abandoned. Measurements over the location of the wall prior to excavation yielded $\epsilon_a = 24$ ($R = 0.04$, assuming surrounding soil with $\epsilon_a = 28$) which is non-detectable. An intact well-preserved turf wall ($\epsilon_a = 17$; $R = 0.12$, assuming surrounding soil with $\epsilon_a = 28$), though, is capable of producing a measureable reflection based on TDR measurements from Trench N (Fig. 6). It is concluded that the enclosure wall as delineated in the radar overlay image is primarily due to diffractions from the rocky foundation ($\epsilon_r = 10$; $R = 0.25$, assuming surrounding soil with $\epsilon_a = 28$).

3.3 Central Church Structure

Figs. 5a through 5c are overlay images that emphasize the delineation of the central church structure. The main features of interest are a compacted surface and four post holes that demarcate the corners of the structure. The compacted surface, which was too thin to measure by TDR, varied in thickness between approximately 2 to 20 cm and contained peat ash. The post

holes were sand-filled and lined with rocks at their bottoms. Both the sand ($\epsilon a = 9$; $R = 0.28$, assuming surrounding soil with $\epsilon a = 28$) and rocks have sufficiently large contrasts to produce diffractions. It is unknown as to why the post holes were filled with sand, but presumably the sand provided drainage and was deposited under and around the sunken wooden posts, a practice that has been noted in Norway and elsewhere in Iceland (Jensenius, 2010; Vésteinsson, 2000).

3.4 Burial Pits

As illustrated in Fig. 2, a total of 25 graves were identified through excavation including: three with skeletons of adults (Graves 1, 6 and 14), three with skeletons of young children (Graves 7, 17 and 25), four with remains of infants or neonates (Graves 2, 9, 13 and 24), and two with partial remains that consisted of pairs of leg bones from a juvenile and an adult (Graves 4 and 5). Thirteen graves were essentially devoid of skeletal remains but had clear indications of being re-dug and their bones removed presumably for interment at the upper churchyard (Graves 3, 8, 10 through 12, 15, 16, and 18 through 23). Some of these had scattered teeth or isolated small bones that had not been gathered. Finally, the remnants of two small wooden coffins were also found (Grave 16 which was empty and Grave 25 which contained the remains of a small child). Table 2 summarizes a description of the graves together with the reanalysis of the radar data.

The only indication of burial pits in the radar profiles was a break in a sub-horizontal reflector that corresponded to a perforation in the prehistoric tephra sequence (see Fig. 5), which resulted by digging the pit. Thus, pits were discernible only at those locations where the sequence was sufficiently preserved in the stratigraphic record. Only six of 25 burial pits were initially interpreted as such prior to excavation. An additional eight pits were identified after reanalysis while 11 others had no distinct signature.

The absence of signature from the burial pits themselves is due to lack of contrast between backfill material ($\epsilon a = 29$) and surrounding soil ($R = 0.01$, assuming $\epsilon a = 28$). There is little expected material difference between the two as the former is simply a mixture of the latter with minor amounts of prehistoric tephra distributed throughout. In addition, the soil consists of non-phyllosilicate clay which lacks cohesion but has high water-retention capacity (Arnalds, 2008).

Taken together with the prevailing climate (i.e., high precipitation and freeze-thaw cycles), the soil has likely undergone repeated rapid expansions and contractions over time, which has reduced any changes in material properties that may have been created by digging and filling a pit (e.g., introduction of air pockets).

Interestingly, the burial conditions at the lower churchyard differ from the upper churchyard which is located on glacial morainic deposits that contain gravel layers. There, a grave was cut through a gravel lens and the burial pit was directly detected because the backfill material contained gravel interspersed throughout, thus contrasting with the adjacent background sediments (see Fig. 9 in Damiata et al., 2013). However, the skeletal remains in that grave were not preserved except for some teeth, probably due to enhanced interaction with groundwater traveling through the gravel lens and possibly to more acidic conditions.

3.5 Skeletal Remains

At the lower churchyard, all of the graves that contained skeletal remains produced signatures in the radar data but only half of those were initially interpreted as such prior to excavation. The skeletons of three adults and two children as well as two pairs of leg bones were identified beforehand whereas five sets of remains (one small child, two infants and two neonates) were only noted upon reanalysis after excavation.

Fig. 5d depicts an overlay image of the four graves with skeletal remains that were initially identified as such (Graves 1, 6, 14 and 17). Fig. 7 presents the radar profiles over Grave 7 (child's skeleton); Figs. 8a and 8b present the profiles over Graves 6 (adult's skeleton), 14 (adult's skeleton), 15 (empty), 17 (child's skeleton), and 22 (empty); and Figs. 9a and 9b show the profiles over Graves 1 (adult's skeleton), 2 (empty), 3 (empty), 4 (pair of juvenile's leg bones), and 5 (pair of adult's leg bones). An expanded figure showing the diffractions from the adult's skeleton in Grave 1 was presented in Damiata et al. (2013; see Fig. 4). For that grave, the hyperbolas occur on eight adjacent profiles that span a transverse length (i.e., west to east, perpendicular to the direction of the profiles) of approximately 2 m.

All of the radar profiles that were collected over the skeletons have hyperbolas (diffractions) to some degree although not as pronounced as the case for Grave 1. Typically, the hyperbolas

are seen on four to five adjacent profiles; the lack of them from the emptied graves is a clear indicator that they emanated from the skeletal remains. This observation confirms the interpretation and modeling results that were presented by Damiata et al. (2013) for the skeleton in Grave 1. Note that the contrast between well-preserved bone ($\epsilon_r = 13$) and backfill material ($R = 0.19$, assuming $\epsilon_a = 28$) is expected to produce a relatively strong response. The lack of initially identifying the smaller skeletons (i.e., child, infants and neonates) is mainly attributed to their overall small sizes as targets. For these cases, diffractions were observed on only one or two profiles and thus were initially assumed to be caused by small isolated point sources such as rocks.

For the most part, the skeletal remains were well preserved. In general, the brown andosols in Iceland have a neutral pH (6.5-7) and low organic content (<8%; see Arnalds, 2008). These conditions, together with the relatively cold climate, tend to support the preservation of bone in moist environments. The preservation is also attested to by the relatively high yields of collagen (i.e., an organic protein) from contemporaneous animal and human bones that were AMS radiocarbon dated. In general, fresh defatted bone can yield as much as 25% collagen by weight but well-preserved archaeological samples are typically between 0.8 to 3.5% (Ambrose, 1990; Ambrose and Norr, 1992). The yield for animal bones from the site was typically greater than 10% and as high as 19% ($n = 11$; unpublished data).

4. Summary and Concluding Remarks

A GPR survey was conducted over a Viking-Age Christian churchyard in northern Iceland that was subsequently fully excavated. During the course of excavation, TDR measurements of apparent relative permittivity were made on various features which helped to constrain final interpretations of the radar data. The study provided a unique opportunity to make direct comparisons between the radar results and the archaeological record.

The survey had successfully detected the remnants of the churchyard which included a circular enclosure wall, a central church structure, and graves. About one half of the graves contained skeletal remains and all of these produced diffractions (hyperbolas) in the radar data, although only about one half of these were initially identified as such prior to excavation.

Similarly, only about one half of the burial pits could be identified even after excavation, and all of these because of a break in a sub-horizontal reflector that was associated with a perforated prehistoric tephra sequence. In areas where the tephra sequence was not preserved in general, burial pits could not be identified. The TDR measurements verified the lack of contrast between backfill material within pits and the soil surrounding pits.

The present work represents one of the best documented cases for the detection of skeletal remains by GPR and supports the interpretations and modeling results that were presented by Damiata et al. (2013) for a single grave. As noted above, all 12 graves that contained skeletal remains produced signatures in the radar data. However, five of these were relatively small targets (one with small child, two with infants, and two with neonates) whose signatures appeared on one or two profiles only, and were initially attributed to small point-source features such as rocks. Also, the general lack of contrast between backfill material and surrounding soil made distinguishing between graves and other features difficult, which further contributed to the under-identification.

Clearly, the setting of an ancient churchyard can be quite complex as demonstrated here with some graves containing skeletal remains of various dimensions, others having their remains completely or partially removed, and still others which contained remnants of wooden coffins. For most studies, the number of graves that are identified by GPR surveying should be considered conservatively a minimum estimate. For some studies, it may be appropriate to develop a ranking system to categorize “anomalies” based on various criteria (e.g., number of diffractions, depth to top of diffractions, orientation, etc.) as has been done by the authors on other projects (Steinberg et al., 2012; Damiata and Steinberg, 2015).

In general, the detection of bone depends on various factors. The bones that were detected in this study provided a measurable contrast with respect to background soil and backfill material which had $\epsilon_a > 25$. In general, bone can vary between 6 (dried) and 13 (well preserved). Correspondingly, dry loamy soils typically range from 4 to 10 whereas wet loamy soils from 10 to 30. For regions with dry and rainy seasons, it may be more advantageous to survey during certain times of the year to increase the likelihood of detecting bone by maximizing the contrast (see also Fig. 9 in Damiata et al., 2013).

Although incorporation of TDR into GPR surveys for archaeological studies has been limited to date, it provides a direct measurement of apparent relative permittivity that can be used to constrain interpretations, and thus should be more widely adopted. Depending on site-specific conditions, an appropriate length probe with effective frequency that most closely matches the radar's central frequency with consideration to loading should be used. For cemetery and forensic applications, we advocate the use of TDR as a rapid screening tool to measure the apparent relative permittivity of background soil prior to any surveying. This information, in turn, can be used to help realistically assess the likelihood of directly detecting skeletal remains subject to prevailing local conditions, and thus justifying, either one way or the other, the suitability and need for GPR.

Finally, Damiata et al. (2013; Fig. 9) presented a simplified analysis for the likelihood of detecting bone based on the reflection coefficient for planar surfaces. The general correspondence between relative permittivity and "freshness" (i.e., retention of organic content and hydrating fluid) of bone suggests the possibility of using GPR to assess the state of preservation, for example, by amplitude analysis. Clearly, additional laboratory studies are needed to fully define the relationship between relative permittivity and organic content of ancient bones. In addition, a forward modeling approach that takes into account, for example, the backscatter (reflectivity) cross section of cylindrical shapes that idealize long bones would be more realistic than using the planar reflection coefficient. These topics are the subject of ongoing study.

5. Acknowledgements

The SASS project has been funded by the US National Science Foundation (BCS #0453892, BCS #0731371, RAPID #1242829, EAGER #1038339, EAGER #1345066) and the Wenner-Gren Fund for Anthropological Research. The excavation of the cemetery at Stóra-Seyla received additional funding from Fornleifasjóður (The Archaeological Fund of Iceland). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation or supporting institutions or individuals. Products or instruments mentioned should not be construed as endorsements. This work was done in conjunction with SCP, an interdisciplinary

archaeological project run by the Skagafjörður Heritage Museum, aimed at locating and excavating the earliest Christian cemeteries in Skagafjörður. The SASS and SCP projects have operated under permits granted by The Archaeological Heritage Agency of Iceland and the National Museum of Iceland. We wish to thank Steinunn Fjóla Ólafsdóttir and Guðmundur Þór Guðmundsson of Stóra-Seyla and the community in Skagafjörður for their continued support of the project. We thank two reviewers for their constructive comments. This work is dedicated to the Lacedaemonians.

References

- Ambrose, S.H., 1990. Preparation and characterization of bone and tooth collagen for isotopic analysis. *Journal of Archaeological Science* 17, 431-451.
- Ambrose, S.H., Norr, L., 1992. On stable isotope data and prehistoric subsistence in the Soconusco region. *Current Anthropology* 33, 401-404.
- Annan, A.P., 1977. Time-domain reflectometry – Air-gap problem for parallel wire transmission lines. In: Report of Activities, Part B, Paper 77-1B, Geological Survey Canada, Ottawa, ON, Canada, 59-62.
- Annan, A.P., 2001. Ground Penetrating Radar: Workshop Notes, Sensors and Software, Inc., Mississauga, Ontario, Canada, 192 pp.
- Annan, A.P., 2009. Electromagnetic Principles of Ground Penetrating Radar. In: Jol, H.M. (Ed.), *Ground Penetrating Radar: Theory and Applications*, Elsevier, New York, Chapter 1, 3-40.
- Arnalds, Ó., 2004. Volcanic soils of Iceland. *Catena* 56, 3-20.
- Arnalds, Ó., 2008. Soils of Iceland. *JÖKULL* 58, 409-421.
- Arnalds, Ó., Hallmark, C.T., Wilding, L.P., 1995. Andisols from 4 different regions of Iceland. *Soil Science Society of America Journal* 59, 161-169.
- Bevan, B.W., 1991. The search for graves. *Geophysics* 56, 1310-1319.
- Bolender, D.J., 2015. From Surplus Land to Surplus Production in the Viking Settlement of Iceland. In: Morehart C. and De Lucia, K. (Eds.), *Surplus: The Politics of Production and the Strategies of Everyday Life*, University of Colorado Press, Boulder, CO, pp. 153-174.
- Bolender, D.J., Steinberg, J.M., Damiata, B.N., 2011. Farmstead relocation at the end of the Viking Age: results of the Skagafjörður archaeological settlement survey. *Archaeologica Islandica* 9, 77-101.
- Bolender, D.J., Steinberg, J.M., and Durrenberger, E.P., 2008. Unsettled Landscapes: Settlement Patterns and the Development of Social Inequality in Northern Iceland. In: Pool, C. and Cliggett (Eds.), *Economies and the Transformation of the Landscape*, Rowan and Littlefield, Lanham, MD, pp. 217-238.

475 Buck, S.C., 2003. Searching for graves using geophysical technology: Field tests with ground
 476 penetrating radar, magnetometry, and electrical resistivity. *Journal of Forensic Sciences*
 477 48, 5-11.

478 Conyers, L.B., 2006. Ground-penetrating radar techniques to discover and map historic graves.
 479 *Historical Archaeology* 40, 64-73.

480 Damiata, B.N., Steinberg, J.M., 2015. Results of Ground-Penetrating Radar Investigation along
 481 Sandy Pond Road Town of Bourne, Massachusetts. Boston, MA.
 482 http://www.fiskecenter.umb.edu/Research/Reports_Publications.html.

483 Damiata, B.N., Steinberg, J.M., Bolender, D.J., Zoëga, G., 2013. Imaging skeletal remains with
 484 ground-penetrating radar: comparative results over two graves from Viking Age and
 485 Medieval churchyards on the Stóra-Seyla farm, northern Iceland. *Journal of*
 486 *Archaeological Science* 40, 268-278.

487 Daniels, D.J., 2009. Antennas. In: Jol., H.M. (Ed.), *Ground Penetrating Radar: Theory and*
 488 *Applications*, Elsevier, New York, Chapter 4, 99-139.

489 Daniels, J.J., Wielopolski, L., Radzevicius, S., Bookshar, J., 2003. 3D GPR polarization analysis
 490 for imaging complex objects. *SAGEEP*, 585-597.

491 Davis, J.L., Annan, A.P., 1977. Electromagnetic detection of soil moisture: Progress report I.
 492 *Canadian Journal of Remote Sensing* 3, 76-86.

493 De Vleeschouwer, Van Vliët Lanoé, B., Fagel, N., 2008. Long term mobilization of chemical
 494 elements in tephra-rich peat (NE Iceland). *Applied Geochemistry* 23, 3819-3839.

495 Dionne, C.A., Wardlaw, D.K., Schultz, J.J., 2010. Delineation and resolution of cemetery graves
 496 using a conductivity meter and ground-penetrating radar. *Technical Briefs in Historical*
 497 *Archaeology*, 20-30.

498 Doolittle, J.A., Bellantoni, N.F., 2010. The search for graves with ground-penetrating radar in
 499 Connecticut. *Journal of Archaeological Science* 37, 941-949.

500 Dugmore, A.J., Cook, G.T., Shore, J.S., Newton, A.J., Edwards, K.J., Larsen, G., 1995.
 501 Radiocarbon dating tephra layers in Britain and Iceland. *Radiocarbon* 37, 379-388.

502 Eiríksson, J., Knudsen, K.L., H. Haflidason, H., Heinemeier, J., 2000. Chronology of late
 503 Holocene climatic events in the northern North Atlantic based on AMS ¹⁴C dates and
 504 tephra markers from the volcano Hekla, Iceland. *Journal of Quaternary Science* 15, 573-
 505 580.

506 Fiedler, S., Illich, B., Berger, J., Graw, M., 2009. The effectiveness of ground-penetrating radar
 507 surveys in the location of unmarked burial sites in modern cemeteries. *Journal of Applied*
 508 *Geophysics* 68, 380-385.

509 Gabriel, C., 1996. Compilation of the dielectric properties of body tissues at RF and microwave
 510 frequencies. Report AL/OE-TR-1996-0004, Armstrong Laboratory, Air Force Material
 511 Command, Brooks Air Force Base, TX, 16 pp.

512 Gabriel, S., Lau, R.W., Gabriel, C., 1996. The dielectric properties of biological tissues: II.
 513 Measurements in the frequency range 10 Hz to 20 GHz. *Physics in Medicine and Biology*
 514 41, 2251-2269.

- 515 Goodman, D., Nishimura, Y., Rogers, J.D., 1995. GPR time slices in archaeological
516 prospection. *Archaeological Prospection* 2, 85-89.
- 517 Goodman, D., Steinberg, J., Damiata, B., Nishimura, Y., Piro, S., Schneider, K., 2007. GPR
518 imaging of archaeological sites. In: Wilson, L., Dickinson, P., Jeandron, J. (Eds.),
519 Reconstructing HumaneLandscape Interactions, Dig 2005 Conference, Developing
520 International Geoarchaeology, October 21-23, Saint John, Canada. Cambridge Scholars
521 Publishing, pp. 202-217 (Chapter 11).
- 522 Goodman, D., Piro, S., Nishimura, Y., Schneider, K., Hongo, H., Higashi, N., Steinberg, J.,
523 Damiata, B., 2009. GPR archaeometry. In: Jol, H.M. (Ed.), *Ground Penetrating Radar:
524 Theory and Applications*. Elsevier, New York, pp. 479-508.
- 525 Grönvold, K., Óskarsson, N., Johnsen, S.J., Clausen, H.B., Hammer, C.U., Bond, G., Bard, E.,
526 1995. Ash layers from Iceland in the Greenland GRIP ice core correlated with oceanic and
527 land sediments. *Earth and Planetary Science Letters* 135, 149-155.
- 528 Hammon III, W.S., McMechan, G.A., Zeng, X., 2000. Forensic GPR: finite-difference
529 simulations of responses from buried human remains. *Journal of Applied Geophysics* 45,
530 171-186.
- 531 Heimovaara, T.J., 1994. Frequency domain analysis of time domain reflectometry waveforms.
532 1. Measurement of the complex dielectric permittivity of soils. *Water Resources Research*
533 30, 189-199.
- 534 Irastorza, R.M., Mayosky, M.A., Grigera, J.R., Vericat, F., 2011. Dielectric properties of natural
535 and demineralized collagen bone matrix. *IEEE Transactions, Dielectrics and Electrical*
536 *Insulation* 18, 320-328
- 537 Jensenius, J., 2010. Bygningstekniske og arkeologiske bemerkninger om trekirker i Norge i
538 vikingtid og middelalder. *Collegium Medievale* 23, 149-180.
- 539 Jones, S.B., Wraith, J.M., Or, D., 2002. Time domain reflectometry applications. *Hydrological*
540 *Processes* 16, 141-153.
- 541 King, J.A., Bevan, B.W., Hurry, R.J., 1993. The reliability of geophysical surveys at historic
542 period cemeteries: An example from the Plains Cemetery, Mechanicsville, Maryland,
543 *Historical Archaeology* 27, 4-16.
- 544 Leckebusch, J., 2000. Two- and three-dimensional ground-penetrating radar surveys across a
545 medieval choir: a case study in archaeology. *Archaeological Prospection* 7(3), 189-200.
- 546 Marino, A.A., Becker, R.O., Bachman, C.H., 1967. Dielectric determination of bound water of
547 bone. *Physics in Medicine and Biology* 12, 367-378.
- 548 Mellett, J.S., 1992. Location of human remains with ground-penetrating radar. In Hänninen, P.,
549 Autio, S. (Eds.), *Geological Survey of Finland, Special Paper 16, Fourth International*
550 *Conference on Ground Penetrating Radar*, pp. 359-365.
- 551 Or, D., Rasmussen, P., 1999. Effective frequency of TDR travel time-based measurement of
552 bulk dielectric permittivity. *Third Workshop on Electromagnetic Wave Interaction with*
553 *Water and Moist Substances*, Russell Agricultural Research Center, Athens, GA, 12-13
554 April, 257-260.

555 Parfitt, R.L., Clayden, B., 1991. Andisols – the development of a new order in soil taxonomy.
556 *Geoderma* 49, 181-198.

557 Penn, J.W., Bell, M.S., 1978. Electrical parameter values of some human tissues in the
558 radiofrequency radiation range. Report SAM-TR-78-38, USAF School of Aerospace
559 Medicine, Brooks Air Force Base, TX, 21 pp.

560 Pettinelli, E., Barone, P.M., Di Matteo, A., Mattei, E., Lauro, S.E., 2012. Mapping the
561 undiscovered ruins of Pompeii (Naples, Italy) using ground penetrating radar.
562 *Archaeometry* 54, 203-212.

563 Pettinelli, E., Cereti, A., Galli, A., Bella, F., 2002. Time domain reflectometry: calibration
564 techniques for accurate measurement of the dielectric properties of various materials.
565 *Review of Scientific Instruments* 73, 3553–3562.

566 Robinson, D.A., Jones, S.B., Wraith, J.M., Or, D., Friedman, S.P., 2003. A Review of advances
567 in dielectric and electrical conductivity measurements in soils using time domain
568 reflectometry. *Vadose Zone Journal* 2, 444-475.

569 Robinson, D.A., Schaap, M.G., Or, D., Jones, S.B., 2005. On the effective measurement
570 frequency of time domain reflectometry in dispersive and nonconductive dielectric
571 materials. *Water Resources Research* 41, W02007, doi:10.1029/2004WR003816.

572 Ruffell, A., McCabe, A., Donnelly, C., Sloan, B., 2009. Location and assessment of an historic
573 (150-160 years old) mass grave using geographic and ground penetrating radar
574 investigation, NW Ireland. *Journal of Forensic Science* 54, 382-394.

575 Schultz, J.J., 2007. Using ground-penetrating radar to locate clandestine graves of homicide
576 victims: forming forensic archaeology partnerships with law enforcement. *Homicide*
577 *Studies* 11, 15-29.

578 Sigurðardóttir, S., 2012. Skagfirska Kirkjurannsóknin, Miðaldakirkjur 1000-1300. Rit
579 Byggðasafn Skagfirðinga. Akureyri: Ásprent.

580 Soilmoisture Equipment Corporation, 2012. Operating Instructions, 6050X3K5B. Santa
581 Barbara, CA,

582 Steinberg, J.M., 2003. The Viking Age long-house at Glaumbaer Skagafjörður, Northern
583 Iceland. *Antiquity* 77, 295.

584 Steinberg, J.M., Bolender, D., Damiata, B.N., 2016 (in press). The Viking age settlement pattern
585 of Langholt, North Iceland: results of the Skagafjörður Archaeological Settlement Survey.
586 *Journal of Field Archaeology*.

587 Steinberg, J.M., Damiata, B.N., Schoenfelder, J.W., 2012. Results of Ground-Penetrating Radar
588 Survey at the Fanning Cemetery Mashantucket, Connecticut. Fiske Center for
589 Archaeological Research, University of Massachusetts Boston, Cultural Resources
590 Management Study No. 56, 79 pp.
591 http://www.fiskecenter.umb.edu/Research/Reports_Publications.html.

592 Strickland, J.A., 1970. Time-domain reflectometry measurements. Tektronix Inc., Beaverton,
593 OR.

- 594 Þórarinnsson, S., 1970. Tephrochronology and Medieval Iceland. In: Berger, R. (Ed.), Scientific
595 Methods in Medieval Archaeology, University of California Press, Berkeley, 295-328.
- 596 Thorarinnsson, S., 1980. Tephrochronology and its application in Iceland. In: Dercourt, J. (Ed.),
597 Geology of the European countries: Denmark, Finland, Iceland, Norway, Sweden, Graham
598 & Trotman Ltd., London, 162-165.
- 599 Topp, G.C., Davis, J.L., Annan, A.P., 1980. Electromagnetic determination of soil water
600 content: measurements in coaxial transmission lines. Water Resources Research 16, 574-
601 582.
- 602 Topp, G.C., Davis, J.L., Annan, A.P., 1982. Electromagnetic determination of soil water content
603 using TDR: I. Applications to wetting fronts and steep gradients. Soil Science Society of
604 America Journal 46, 672-678.
- 605 Ulaby, F.T., Bengal, T.H., Dobson, M.C., East, J.R., Garvin, J.B., Evans, D.L., 1990.
606 Microwave dielectric properties of dry soil. IEEE Transactions on Geoscience and Remote
607 Sensing 28, 325-336.
- 608 Unterberger, R.R., 1992. Ground penetrating radar finds disturbed earth over burials. In:
609 Hänninen, P., Autio, S. (Eds.), Geological Survey of Finland, Special Paper 16, Fourth
610 International Conference on Ground Penetrating Radar, pp. 351-357.
- 611 Vésteinsson, O., 2000. Forn kirkja og grafreitir á Neðra Ási í Hjaltadal. Reykjavík:
612 Fornleifastofnun Íslands.
- 613 Verdonck, L., Simpson, D., Cornelis, W.M., Plyson, A., Bourgeois, J., Doctor, R., Van
614 Meirvenne, M., 2009. Ground-penetrating radar survey over Bronze Age circular
615 monuments on a sandy soil, complemented with electromagnetic induction and fluxgate
616 gradiometer data, Archaeological Prospection 16, 193-202.
- 617 Wang, X., Huadong, G., Wang, C., Peirong, C., Yangshen, S., 1999. Relative dielectric constant
618 from dry rocks. Chinese Science Bulletin 44, 2286-2293.
- 619 Zielinski, G.A., Germani, M.S., Larsen, G., Baille, M.G.L., Whitlow, S., Twickler, M.S., Taylor,
620 K.C., 1997. Volcanic aerosol records and tephrochronology of the Summit, Greenland, ice
621 cores. Journal of Geophysical Research 102, 26625-26640.
- 622 Zoëga, G., 2009. Skagfirska kirkjurannsóknin - framvinduskýrsla 2009 (The Skagafjörður
623 Church Project – Progress Report) . Rannsóknaskýrslur Byggðasafns Skagfirðinga.
624 Sauðárkrókur: Byggðasafn Skagfirðinga.
- 625 Zoëga, G., 2014. Early church organization in Skagafjörður: The Skagafjörður Church Project.
626 Collegium Medievale 27, 23-62.
- 627 Zoëga, G., 2015. A Family Revisited: The Medieval Household Cemetery of Keldudalur, North
628 Iceland. Norwegian Archaeological Review 3652(June), 1-20.
- 629 Zoëga, G., Bolender, D.J., 2014. Uppgröftur 11. aldar kirkjugarðs á Stóru-Seylu 2012-2013
630 Skagfirska kirkjurannsóknin II áfangi (Excavation of an 11th century churchyard at Stóra-
631 Seyla 2012-2013, the Skagafjörður Church Project II phase 2). Byggðasafn Skagfirðinga
632 Rannsóknaskýrslur 2014/145.

- 633 Zoëga, G., Bolender, D.J., in review. An archaeology of moments: structure and contradiction in
634 an early Christian household cemetery in North Iceland. *Journal of Social Archaeology*.
- 635 Zoëga, G., Sigurðarson, G.S., 2010. Skagfirska kirkjurannsóknin (The Skagafjörður Church
636 Project). *Árbók hins íslenska fornleifafélags*, 95-115.

637

637

638 **Figure Captions**

639 Fig. 1. Index map showing the locations of Skagafjörður and the Stóra-Seyla farm in northern
640 Iceland. The archaeological remains of the upper Medieval churchyard are partially exposed at
641 the ground surface but there were no visible signs of the lower Viking-Age churchyard. “N”
642 denotes location of trench used for TDR vertical profiling as discussed in text (modified after
643 Damiata et al., 2013).

644 Fig. 2. Schematic diagram showing various features of interest that were excavated from the
645 lower churchyard with emphasis on enclosure wall, central church structure and graves.

646 Fig. 3. A) Representative TDR measurements that were collected using the 0.1-, 0.15-, 0.2- and
647 0.3-m probes inserted into background (undisturbed) soil to the south of the churchyard. B) TDR
648 waveform from 0.3-m probe showing tangent-line method to determine travel time. C)
649 Calculation of effective frequency based on 10 to 90% rise time and using Eq. (2) as described in
650 text. D) Derivative of the TDR waveform used to determine travel time for the derivative
651 method.

652 Fig. 4. Number of TDR measurements versus effective frequency range, binned at 50 MHz
653 intervals. Light shade – 10-cm probe, medium shade – 15-cm probe, dark shade – 20-cm probe,
654 and black – 30-cm probe.

655 Fig. 5. Selected depth-slice and overlay images of relative squared amplitude for the lower
656 churchyard. A) Image for the depth interval 17-24 cm bgs showing the location of post holes on
657 western side of central church structure. B) Image for the depth interval 4-11 bgs showing the
658 location of post holes on the eastern site of central church structure. C) Overlay image of four
659 slices encompassing the depth interval 21-37 cm bgs showing the circular enclosure wall and
660 compacted surface of the central church structure. D) Overlay image of two slices for the depth
661 intervals 93-99 and 106-112 cm bgs showing the locations of four of the five skeletons that were
662 excavated. Note that the anomalies associated with the skeletal remains appear more
663 quadrilateral or “blob-like” in appearance, as opposed to elongated, and is a consequence of
664 generating time slices (a smoothing process) from un-migrated data containing tails from
665 hyperbolic diffractions.

666 Fig. 6. A) Schematic diagram of the stratigraphy in trench N (see Fig. 1 for location) with
667 location of TDR measurements. B) Plot of apparent relative permittivity versus depth for
668 measurements using the 0.3-m probe. The probe was inserted horizontally into the side wall of
669 the trench except for lowest measurement, which the was inserted vertically into the floor.

670 Fig. 7. Radar profiles over Grave 7 (child’s skeleton). Upper left: Location of profiles with solid
671 circle showing depth below de-turfed surface with value at right. Upper right and lower: Profiles
672 with vertical arrows (yellow) indicate reflections from the prehistoric tephra sequence. Slanted
673 arrows pointing downward (red) show diffractions from skeletal remains. Note that for this
674 grave, the burial pit partially penetrated the H3 prehistoric tephra.

675 Figure 8a. Radar profiles over Graves 6 (adult’s skeleton), 14 (adult’s skeleton), 15 (empty), 17
676 (child’s skeleton), and 22 (empty). Upper: Location of profiles with solid circle showing depth

below de-turfed surface with value at right. Lower: Profiles with vertical arrows (yellow) indicate reflections from prehistoric tephra sequence. Slanted arrows pointing downward (red) show location of burial pit with perforated tephra sequence; slanted arrows pointing upward (red) show diffractions from skeletal remains.

Figure 8b. See previous caption.

Figure 9a. Radar profiles over Graves 1 (adult's skeleton), 2 (empty), 3 (empty), 4 (pair of juvenile's leg bones), and 5 (pair of adult's leg bones). Upper: Location of profiles with solid circle showing depth below de-turfed surface with value at right. Lower: Profiles with vertical arrows (yellow) indicate reflections from prehistoric tephra sequence. Slanted arrows pointing downward (red) show location of burial pit with perforated tephra sequence; slanted arrows pointing upward (red) show diffraction from skeletal remains.

Figure 9b. See previous caption.

Tables

Table 1. Summary of apparent relative permittivity values as measured by TDR and relative permittivity values as obtained from the literature.

Table 2. Summary of GPR results for detecting burial pits and skeletal remains.

① Topsoil	④ H1 Tephra Layer	⑦ Soil with H1 Inclusions
② Brown soil mixed with H1	⑤ Turf Wall and Mixed Grey-Brown Soil	⑧ Peat
③ Grey soil	⑥ Mixed Grey-Brown Soil	⑨ Peat with H3 Inclusions

Table 1. Summary of apparent relative permittivity values as measured by TDR and relative permittivity values as obtained from the literature.

Location	ε_a or ε_r	f_{eff} (MHz)	Comments ¹ /[Reference] ²
Background (Undisturbed) Soil			
Inside Churchyard	26 ± 2 ($n = 4$)	500 – 540	V30: deturfed surface
Surrounding Churchyard	30 ± 5 ($n = 13$)	430 – 570	V30: deturfed surface
South of Churchyard	<u>26 ± 0 ($n = 2$)</u>	490 – 500	V30: grass surface
Total	28 ± 4 ($n = 19$)		
Bottom Grave 3	42	520	V20: excavated surface; 0.82 m bds, tip on gravel
Bottom Grave 3	39	550	V15: excavated surface; 0.86 m bds, tip on gravel
Bottom Grave 15	29	500	V30: excavated surface; 0.54 m bds
Bottom Trench N	42	460	V20: excavated surface; 1.30 m bgs, in peat
Backfill Deposits			
Fill in Graves 17 and 26	26 ± 1 ($n = 2$)	400 – 500	V30: excavated surface; 0.17 and 0.52 m bds
Upcast between Graves	<u>31 ± 4 ($n = 3$)</u>	450 – 530	V30: excavated surface; 0.18, 0.42 and 0.49 m bds
Total	29 ± 4 ($n = 5$)		
H3/H4 Prehistoric Tephra Sequence			
Sidewall Grave 1	22 ± 2 ($n = 3$)	560 – 570	H30: sidewall; 0.55, 0.64, 0.65 m bds
Trench N	<u>20</u>	370	H15: sidewall; 1.12 m bgs
Total	21 ± 2 ($n = 4$)		
Enclosure Wall	24 ± 1 ($n = 3$)	430 – 560	V30: excavated surface; 0.1 m bds
Turf Wall			
Medieval Wall (Upper Farmstead)	16	480	H30: exposed face of wall
Trench N	<u>17 ± 3 ($n = 5$)</u>	520 – 610	H30: sidewall of trench; 0.4, 0.5, 0.6, 0.7, 0.8 m bgs
Total	17 ± 3 ($n = 6$)		

Sand-Filled Post Hole	9	777	V20: excavated surface; 0.22 m bds, tip on rock
Other			
Bone (Dry)	5 – 6		[1,2]
Bone (Hydrated, Well Preserved)	13		[3 – 6]
Loamy Soil (Dry)	4 – 10		[7]
Loamy Soil (Wet)	10 – 30		[7]
Sand (Dry)	2 – 6		[7]
Sand (Wet)	10 – 30		[7]
Rock	2 – 10		[8, 9]

¹ V: vertical probe, H: horizontal probe; 10, 15, 20, 30 – length of probe (cm); bds – below deturfed surface, bgs – below ground surface

² [1] Marino et al. (1967); see Figs. 2 and 3 for human cortical bone at 100 MHz

[2] Penn and Bell (1978); see Fig. 12 for human bone with low water content at 500 MHz

[3] Gabriel, C. (1996); see Fig. 4 for animal cortical bone at 500 MHz

[4] Gabriel et al. (1996); see Fig. 4d for porcine cortical bone at 500 MHz

[5] Hammon et al. (2000); see Table 1 and references cited therein for human bone at 450 MHz

[6] Irastorza et al. (2011); see Fig. 3 for bovine femur at 500 MHz

[7] Daniels (2004); see Table 4.1 at 100 MHz

[8] Ulaby et al. (1990); see Figs. 3 and 8 at 500 MHz

[9] Wang et al. (1999); see Fig. 1 at 500 MHz

Table 2. Summary of GPR results for detecting burial pits and skeletal remains.¹

Grave	Category	Condition ²	Age	Burial Pit Dimensions (cm)		Feature Detected ³			Comments
				Length	Width (W:E)	Burial Pit	Skeletal Remains	Coffin	
1	Adult	Skeleton	30 – 45 years	165	57:40	√	√	—	Perforation of H3-H4 tephra
2	Infant	Skeleton	0 – 3 months	70	35:27	√a	√a	—	Perforation of H3 tephra
4	Juvenile	Leg bones	14 – 16 years	160	60	√	√	—	Perforation of H3-H4 tephra
5	Adult	Leg bones	?	160	48	√	√	—	Perforation of H3-H4 tephra
6	Adult	Skeleton	30 – 45 years	140(160)	40:35	√	√	—	Perforation of H3-H4 tephra
7	Child	Skeleton	4 – 6 years	120	30:33	N	√	—	
9	Neonate	Skeleton	0 – 3 months	54	30	√a	√a	—	Perforation of H3-H4 tephra
13	Infant	Skeleton	0 – 3 months	60	22:15	N	√a	—	
14	Adult	Skeleton	30 – 45 year	154	40:30	√	√	—	Perforation of H3-H4 tephra
17	Child	Skeleton	10 – 12 years	125	32:25	√	√	—	Perforation of H3-H4 tephra
24	Neonate	Foetus	—	80	40:26	N	√a	—	
25	Child	Skeleton & Coffin	1.5 – 2.5 years	80	40:34	N	√a	N	
16	Infant	Empty Coffin	—	51	14:12	N	—	N	
3	Adult	Empty	—	160	62	√a	—	—	Perforation of H3-H4 tephra
8	Adult	Empty	—	180	50:40	√a	—	—	Perforation of H3-H4 tephra
10	Adult	Empty	—	172	55:80	√a	—	—	Perforation of H3-H4 tephra
11	Adult	Empty	—	159	42:30	N	—	—	
12	Infant	Empty	—	56	25:23	N	—	—	
15	Adult	Empty	—	161	25:23	N	—	—	
18	Adult	Empty	—	196	80:59	N	—	—	
19	Infant	Empty	—	51	21	N	—	—	
20	Adult	Empty	—	145	53?	√a	—	—	Perforation of H3-H4 tephra
21	Adult	Empty	—	129	32:40	√a	—	—	Perforation of H3-H4 tephra
22	Adult	Empty	—	167	40	√a	—	—	Perforation of H3-H4 tephra
23	Infant	Empty	—	48	23	N	—	—	

¹ Data for Category, Age and Burial Pit Dimensions taken from Table 1 in Zoëga and Bolender (2014)² Category determined by Burial Pit Dimensions for those without skeletal remains³ √ – interpreted by analysis of GPR data before excavation, √a – interpreted by reanalysis of GPR data after excavation, N – not detected