On the Ability of Geophysical Methods to Image Medieval Turf Buildings in Iceland

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ABSTRACT Structures in Iceland were traditionally built of turf, earth and, to a lesser extent, stone. As turf was the primary construction material, the contrast in geophysical parameters between building ruins and surrounding soil is expected to be low. To investigate the extent to which the remains of turf buildings can be detected by geophysical measurements, we applied several geophysical techniques to a known turf ruin in southwestern Iceland. The methods used were magnetics, ground-penetrating radar (GPR), electromagnetic induction (EMI), electrical resistivity tomography (ERT) and seismic Rayleigh-wave resonance mapping (RRM). Magnetics identified an accumulation of stones inside and beside the ruin. The in-phase component of the EMI measurements, which can be related to magnetic susceptibility, showed the same pattern. A very precise image of the stones lining the inside of the former turf walls was generated by GPR. In contrast, EMI conductivity and ERT imaged the actual turf in the walls. Turf walls have lower electrical conductivity compared with the surrounding soil, probably as a result of different porosities. The mapping of Rayleigh wave resonance clearly revealed the outline of the ruin, as indicated by weaker amplitudes compared with the surrounding soil. Overall the results indicate that geophysical methods can be used for subsurface mapping of Icelandic turf structures and that the combined application of the methods maximizes this potential. Copyright © 2015 John Wiley & Sons, Ltd.

Key words: Magnetics; ground-penetrating radar; electromagnetic induction; electrical resistivity tomography; seismics; turf building

Introduction

Geophysical methods can be successfully applied for archaeological prospection only if there is a contrast in physical parameters between the object of interest and the surrounding material, that is, mostly soil (Seren et al., 2013). Geophysical methods commonly applied for archaeological prospection are magnetics, ground-penetrating radar (GPR) and electrical resistivity tomography (ERT). These techniques are related to contrasts in magnetic susceptibility, dielectric permittivity and electrical resistivity, respectively (Erkul et al., 2011; Rabbel et al., 2014). Regarding the application of seismic surface waves in archaeological prospection, only a few studies can be found in the literature. Castellaro et al. (2008), for example, used the horizontal to vertical (H/V) spectral ratio method to determine the subsoil stratigraphy of a Roman theatre. Woelz and Rabbel (2005) applied a combination of magnetics and surface waves for investigating an ancient Greek harbour. A small number of other studies have applied seismic surface-waves for the detection of cavities (e.g. Grandjean and Leparoux, 2004; Nasseri-Moghaddam et al., 2007).

Geophysical surveys for archaeological prospection have not been widely conducted in Iceland, but have found a measure of success.
(2002) and Horsley (2004) carried out magnetic and Earth resistance measurements on sites in western and northern Iceland. At Gásir in Eyjafjörður (cf. Harrison et al., 2008), for example, a magnetometer survey detected a church inside a circular structure. Turf booths closer to the shoreline at Gásir were only slightly visible in the magnetic results, but Earth resistance measurements clearly showed a contrast between the turf walls and the surrounding soil. Damia and colleagues (2013) imaged skeletal remains with GPR in a churchyard in northern Iceland. The churchyard was surrounded by a turf and stone enclosure, with the stones of the enclosure visible as diffraction hyperbolas in the radargrams.

Further geophysical surveys have been conducted using mainly magnetic, GPR and Earth resistance surveys (see Horsley, 2004), but most of them remain unpublished. The Skagafjörður Archaeological Settlement Survey project has been conducting yearly geophysics surveys for archaeological remains in northern Iceland. They have successfully used mainly electromagnetics and GPR to image turf walls (Damiata et al., 2008).

The objective of the present article is to investigate which geophysical prospection method or combination of methods is most suitable for discovering and non-destructively investigating the remains of ancient turf buildings. The special challenge lies in the fact that turf buildings can be expected to show only slight physical contrast to the surrounding soil because both consist of basically the same material. Another challenge posed by Icelandic sites is the underlying volcanic geology, which may heavily influence magnetic signals.

In this article, we first introduce key aspects of Icelandic geology, some general observations concerning Icelandic turf architecture, and the archaeological site of Skæggiastadir in the Mosfell Valley of northwestern Iceland. We then provide an overview of our project goals and an introduction to the geophysical methods and instruments used to investigate the ruins of a turf building at Skæggiastadir. Among the methods applied is seismic Rayleigh wave resonance (Wilken et al., 2015), which is used here for the first time to map soft soil over bedrock. Finally, we present the results and compare the efficiency of each method for archaeological prospection in Iceland.

Geology

Iceland is a volcanic island situated at the northern end of the Mid-Atlantic Ridge. The geology of Iceland is dominated by recent volcanic activity and the bedrock is composed of young volcanic basalt. Volcanic ejecta develop unique soil characteristics that are known as andic soil properties and most Icelandic soils are classified as Andisols (Strachan et al., 1998; Guicharnaud, 2002).

Generally, Icelandic soils can be divided into three groups on the basis of site characteristics: soil of poorly drained sites, typical andisols of freely drained sites, and soils of barren areas (Jóhannesson, 1960; Strachan et al., 1998). The barren soils that make up 40% of Icelandic soils are mainly found in the interior and are mostly absent from coastal valleys such as the present study area of the Mosfell Valley. The soil in Mosfell Valley consists mainly of poorly and freely drained Andisols, with the distributions varying depending on elevation and slope.

From a geophysical point of view, the geology of Iceland is characterized by volcanic bedrock with high magnetic susceptibility \( > 10^{-4} \) (SI units) (Schön, 1983), which may show significant portions of thermoremanent magnetization. Therefore magnetic surveys are strongly influenced by the bedrock.

In addition, remains of archaeological features in Iceland consist mainly of turf, earth and partly stones, but no solid foundation walls are present such as are known from the cultures of the Mediterranean region. The magnetic anomalies caused by archaeological objects are therefore expected to be small compared with the anomalies caused by the geological background.

Another important aspect for planning geophysical measurements in Iceland is that Andisols have a high ability to retain water and the ability to accumulate organic matter: the former influences mainly the electromagnetic methods, whereas the latter has an effect on magnetic measurements. It is therefore useful to combine geophysical methods that are sensitive to different physical parameters.

Turf buildings

Turf was a major component in traditional Icelandic farm buildings of all kinds (Byock, 2001; Ólafsson and Ágústsson, 2003; Urbanczyk, 1999). Turf used in construction was cut from local bogs or along the edge of cultivated fields (Loveday, 2007, p. 84). In Iceland, the preferred source for turf was a lowland bog where sedges (Carex), peat mosses (Sphagnum) and other bog plants grow deep roots, fed by organically rich and moist peat (Bathurst et al., 2010; Gestsson, 1982; Steinberg, 2004). The Icelandic turf used in building construction usually consists of the root mat and the sediment, including peat and peat mosses attached to this root mat.

Icelanders used turf of varying quality, but in general a denser root mat produces higher quality turf.
The highest quality turf for construction materials is cut from the top of peat bogs overgrown with sedge Carex goodenoughii, which has a well-matted root system (Gestsson, 1982, p. 163), and includes minimal amounts of sand and clay. Peat mosses (Sphagnum) form the majority of the volume of turf (Steinberg, 2004, p. 62). Although usually not desirable, clay inclusions can function to provide strength and stability to structural walls if used carefully and dried properly. In general sand makes the turf less stable and more likely to crumble and is therefore risky to build with. Sand and silt can settle in turf in undesirable quantities during floods, meaning that areas periodically covered in water potentially produce lower quality turf (Sigurðardóttir, 2008, p. 13).

Turf harvested for building and wall construction had a wide array of types and shapes that varied depending on their usage (Sigurðardóttir, 2008). The two major categories of turf shapes are strips (strengur) and blocks (klambra and hnausar). Turf strips are cut horizontally with a turf scythe and are longer and thinner than the blocks, which are cut vertically with a turf spade. Once cut, turf needs to be left to dry for at least two weeks before use, because blocks and strips shrink during the drying process (Sigurðardóttir, 2008, p. 8). Drying would take place close to the extraction site, as turfs become much lighter when dry. For the Skeggjastaðir site, turfs were probably cut from boggy areas to the north and east of the farm and transported to the well-drained slopes for building construction.

In turf walls, one or more courses of stones were often laid down underneath the turf to keep moisture from seeping into the walls and causing the turf to rot (Sigurðardóttir, 2008, p. 12). The amounts of stone used varied greatly depending upon availability of appropriate stone, but also upon the use of the structure. For example, buildings meant for animals often had walls built using stone at the bottom levels where animals could reach, because livestock destroyed turf walls by eating or rubbing against the turf. In general, archaeological work in Iceland suggests that the earliest Viking Age structures used less stone in the foundations than the later medieval and post-medieval buildings.

In archaeological excavations usually only the lowest layers of turf walls are found in situ. As the walls of abandoned turf structures collapse in various directions, however, collapsed turf is often found all around the archaeological structures and particularly inside the walls of buildings. Over time, as part of the post-depositional processes of turf, the organic material and air pockets in the turf compress, a factor that should have implications for geophysical identification of old turf structures. Moreover, severe erosion since the Viking Age has resulted in considerable aeolian soil deposition in the valleys and on the low mountain slopes, burying many of the old abandoned farms. Turf used for building and wall construction often contains remnants of volcanic ash or tephra layers. Many of the volcanic eruptions have been dated through stratigraphic relationships, historical sources, radiocarbon dating and ice cores (Thorarinsson, 1970; Grönvold et al., 1995; Haflidason et al., 2000). These layers are recognizable in structural turfs in archaeological excavations and subsurface coring. For modern researchers, the tephra provides the unique opportunity of supplying a terminus post quem for turf structures.

Measurement site

Through the cooperation of American, Icelandic and German research projects (cf. Kalmring 2013; Byock et al., 2015), geophysical measurements were carried out in Iceland in the Mosfell Valley. In this study we present results of five different methods applied to a medieval turf building. The measurement area, called Skeggjastaðir, is a dependent farm to the chiefly manor at Hríðbrú (Zori, 2010; Zori and Byock, 2014), located approximately 6 km inland from the Icelandic west coast (Figure 1). The farm was settled in the Viking Age with the colonization of the island and has been inhabited since then, with a few brief periods of abandonment. It is situated in a sloping landscape where strong winds have allowed little soil accumulation. As a result, the archaeological remains can be expected at very shallow depths.

In the lowlands in the centre of the Mosfell Valley the soils consist mainly of ‘peat on gravel and sand’ (Jóhannesson, 1960 p. 72). In the lower area of the valley where multiple streams flow together we can assume an increase in water saturation of the Andisols. The organic soils also stretch partially up the slopes of the surrounding mountains. Higher up on the slopes, where important sites such as Hríðbrú and Skeggjastaðir are located, the soils consist mostly of sandy soil that originates from erosion of the surrounding mountains and the adjacent highlands. Around these occupation sites, previous subsurface archaeological work has revealed basalt bedrock under soils with relatively high organic content, and the occasional sandier and less waterlogged soils higher up the slopes. The Skeggjastaðir site is located on a well-drained slope in the high eastern end of the valley and close to the more barren highlands. As a result Skeggjastaðir is characterized by very little organic soil development and well-drained sandy soils.
On the grassy slopes immediately east of the modern farmhouse at Skeggjastaðir, several old grass-covered ruins are visible as slight elevations protruding a few centimetres above the surface (Figure 1). The ruin chosen for focused geophysics investigation consists of turf walls and measures approximately 2 m × 6 m. Extensive coring in and around the turf building revealed that stones lined the inside of the turf walls and that no evidence of further structural remains existed under the visible ruin (Byock and Zori, 2009; Zori, 2014). Inside the building, the coring encountered layers of collapsed turf from the walls and roof mixed with aeolian soil (Byock and Zori, 2009). Cores taken from the turf walls revealed tephras from the Katla eruption of AD 1500 incorporated into the turfs used in the building’s walls, dating the construction of the building to sometime after AD 1500. Outside of the building, cultural material below the in situ Katla tephra shows human activity at the site before AD 1500.

**Methodology**

Due to the known subsurface information from corings and the visible ruins at the surface this building at Skeggjastaðir is a good location for testing different geophysical methods in the Icelandic context and comparing their ability to image turf buildings.

Turf building structures should in principle be detectable with geophysical methods if they show contrasts in the following soil and rock parameters compared with the surrounding soil: (i) the mechanical stiffness (shear modulus), (ii) the porosity and related bulk density and (iii) the magnetite content of the wall material and environment. The first can be accessed by seismic-wave velocity especially by the shear-wave velocity. Seismic velocity is also sensitive to density, which is influenced by porosity and the water saturation of pores. Porosity and water saturation, together with clay content, are also the soil parameters that mainly control electrical resistivity and dielectric permittivity. Electrical resistivity is measured through electromagnetic induction (EMI) measurements and DC ERT. Dielectric permittivity is the major factor influencing the velocity of radar waves (GPR). The magnetic soil characteristic mainly affects the results of magnetic and EMI (in-phase component) measurements.

This compilation shows that many soil parameters and related physical parameters are correlated to a certain extent. However, they usually differ in contrasts, and the geophysical methods show strong differences in lateral and vertical structural resolution. Therefore, we tested and compared all of these methods.

**Magnetics**

Magnetics measures the magnetic field of the Earth. As in archaeological prospection we are mainly interested in the upper few metres, fluxgate magnetometers are often used. These magnetometers measure the vertical difference of the vertical component of the magnetic field. The difference is independent of regional fields and therefore mainly measures the local magnetic field caused by bodies in the shallow part of the ground. The physical parameter that is important in causing anomalies is the magnetic susceptibility (κ). To cause an anomaly a body needs to have a susceptibility contrast with its surroundings.
For magnetic measurements a handcart with six Foerster fluxgate magnetometers was used. The distance between the sensors was 50 cm and the in-line sample rate 20 Hz. For an average measurement velocity of approximately 1 m s\(^{-1}\) this results in a spatial sampling interval of 5 cm. For each profile the mean of the measured values is subtracted from each sensor’s measurements and the resulting data are interpolated onto a 20 cm \(\times\) 20 cm grid. Accurate positioning was achieved by a DGPS (differential global positioning system) mounted on the handcart, which was set to collect a coordinate every second in the Icelandic coordinate system ISNET93.

**Ground-penetrating radar**

Ground-penetrating radar uses electromagnetic waves that are transmitted from an antenna into the ground. At boundaries and objects that have different dielectric permittivity the wave is reflected back and recorded by a receiving antenna. The dielectric permittivity of the medium also determines the propagation velocity of the electromagnetic wave.

The GPR survey was conducted on a rectangular 12 m \(\times\) 15 m grid with a profile spacing of 0.3 m using a SIR-3000 system by GSSI. A GSSI 400 MHz antenna was pulled along a measuring tape and a marker was set every metre. Later a coordinate was assigned to every marker and differences in pulling velocity were accounted for by interpolating between the markers to result in a trace distance of 0.02 m. Every trace of 100 ns length was digitized with 512 samples.

Further processing consists of time zero correction (using the first break), horizontal stripe removal by subtracting a mean trace, coordinate transformation from local to ISNET93 coordinates and direction ordering (because the profiles were collected in zigzag mode). The profiles were interpolated and cut into horizontal time slices by summing the absolute amplitudes. The propagation velocity was estimated by diffraction hyperbola fitting in several radargrams.

**Electromagnetic induction measurements**

For EMI measurements a transmitter coil emits an oscillating magnetic field that is diffused into the conductive ground, where it generates eddy currents. These currents in turn produce a secondary magnetic field, which is superimposed on the primary magnetic field. A receiver coil records their interference. Two physical parameters have an effect on the eddy currents and thus the magnetic field that is measured at the receiver: the electrical conductivity and the magnetic susceptibility. The electrical conductivity can be derived directly from the measured magnetic field, whereas the effect of the susceptibility is best described by the in-phase component of the magnetic field, but is not the magnetic susceptibility itself. In the following text it is referred to as the IP component.

We used a CMD Mini-Explorer (GF Instruments) with three coil spacings of 0.32 m, 0.71 m and 1.18 m and vertical coil orientation that results in effective depths of 0.5 m, 1.0 m and 1.8 m according to the user manual. It measures the electrical conductivity and the IP component of the three coil combinations simultaneously resulting in six measurement values per point. An area of 12 m \(\times\) 15 m was measured on a regular grid of 0.5 m point spacing in-line and cross-line. Each grid point was measured 10 times during 1 s. During later processing, values with standard deviation higher than 3% were removed. The data were interpolated on a 0.1 m \(\times\) 0.1 m grid and smoothed with a two-dimensional median filter over 0.5 m \(\times\) 0.5 m in order to reduce outliers.

**Electrical resistivity tomography**

The electrical resistivity of the ground can be measured by four steel electrodes placed in the soil. An electrical current is injected between two of them and the resulting potential difference is measured between the others. From the current, voltage and a geometrical factor, the apparent electrical conductivity of the ground is calculated. Using this measuring procedure automatically along a line of electrodes results in a so-called pseudosection that shows the distribution of the apparent electrical resistivity with depth along the profile. These values are then converted into a model of specific electrical resistivity by an inversion.

Two ERT profiles 15 m long were measured using 60 electrodes with 0.25 m electrode spacing each. The first profile was measured with dipole–dipole (DD) and Wenner alpha (WA) electrode configurations, whereas the second profile was measured only with DD configurations due to limited time. The data were acquired with RESECS II equipment. The inversion was carried out using the program Res2DInv (Loke, 2004) with finite-element model blocks having half the electrode spacing and with robust inversion constrained: the program automatically optimized the damping factor.

**Seismic Rayleigh wave resonance analysis**

The seismic method applied in this work uses the idea of seismic resonance to detect archaeological objects. A detailed description can be found in Wilken et al. (2015).
The basic concept is to process single vertical component recordings in order to determine Rayleigh wave resonance frequencies. The change of these resonance frequencies in the area or along a profile can be used to identify and map archaeological structures if they represent a volume within which the shear modulus or the shear-wave velocity differ strongly from the surrounding and underlying soil. Measurements comprise excitation and recording of ground oscillations (Figure 2a) on a grid of measurement points. Surface layer shear-wave velocity or thickness changes generate a variation in dominant frequency. This frequency variation can be understood by numerically modelling Rayleigh waves for varying velocity–depth models (Figure 2b).

For a subsurface model consisting of a low-velocity top and a higher velocity bottom layer, numerical modelling by Wilken et al. (2015) showed that observable effects in vertical component seismic recordings are as follows: (i) a shift in resonance frequency due to a change in topsoil layer thickness or velocity and (ii) a change in amplitude due to a change in polarization, which is caused by a change in topsoil velocity (see also Figure 2b). Furthermore, a broadening of the spectrum can be expected in the case of changes in layer thickness.

The seismic data were collected using a 4.5 Hz OYO vertical geophone mounted on a steel plate (Figure 2a). A small (100 g) hammer hitting a small anvil made of a steel screw was used as the wave source. Both source and receiver were used in a fixed set-up with 1 m offset. The whole set-up was used to make one shot every 0.5 m on 12 parallel profiles with a distance of 0.5 m. The coordinate of a measurement was assigned to the receiver. Acquisition was carried out using a Geometrix Geode seismograph. Record length was set to 1 s and the sampling frequency was chosen to be 8 kHz.

The processing follows the procedure described in Wilken et al. (2015). The data were first checked for unsuitable traces, which when found were muted. Then, all traces were transformed to frequency domain using fast Fourier transformation. All spectra were then bandwidth filtered, which means that the spectra were used as a time series on which a low-pass filter operator with a cut-off frequency of 50 Hz was applied. After spectra were smoothed, the amplitude spectrum was placed into an x-y-f data cube. Two parameters can be derived from this dataset: (i) the mean amplitude in a certain frequency range and (ii) the resonance frequency, which is the frequency where the amplitude is maximal. For the first parameter, the mean of the spectral amplitudes between 30 Hz and 40 Hz is calculated and displayed as a frequency slice. The second parameter, the resonance frequency, is also displayed in a map.

Results

The magnetic, seismic, EMI and GPR measurement results of the investigated area around the turf building are shown in Figure 3. The dashed thin line indicates the location of the turf building. It outlines a slight topographic elevation that represents the remaining parts of the turf walls. The magnetic map shows some strong and intermediate anomalies in the area of the building, mainly in the northern and southern walls and southeastern corner (Figure 3a); however, the background magnetization is highly variable due to the underlying geology. Anomalies from the turf walls are hardly distinguishable through this background magnetization. The EMI IP signals (Figure 3c) integrate
over an effective depth of 1 m and correlate well with
the magnetic anomalies. At the southern edge of the
building and at the eastern and northern walls, in-
creased IP values form lines, which correspond to a
smoothed version of anomalies in the magnetic map.
The anomalies of the EMI IP component are smoother
compared with the magnetics because the coil spacing
of about 70 cm leads to an integrational effect over a
larger soil volume compared with a punctual measure-
ment of the magnetic sensor. The southern line of
anomalies is also found in the GPR timeslice between
8 ns and 14 ns (Figure 3e), which corresponds to an
approximate depth of 20 to 35 cm (calculated with a
velocity of 5 cm ns\(^{-1}\)). In the radargrams (Figure 4) they
are visible as diffraction hyperbolae. Similar reflections
can be seen along the western and southern inner walls
of the building and beneath the eastern wall. Another
location of strong anomalies is found in the northeastern
corner, where they are caused by stones, one of which
was found by coring at 20 cm depth (Figure 4: C2).
The deeper GPR time slice (Figure 3f) between 30 ns
and 35 ns (75–88 cm depth) shows re-
fl
ecti
ons in an
oval form in the same orientation as the visible turf
walls, but about 3 m larger in north–south diameter.
Comparison with the radargrams shows mainly a
layer interface, which forms a sort of bowl under the

Figure 3. Maps of (a) magnetic, (b) seismic, (c and d) EMI and (e and f) GPR measurements of an area surrounding the turf building at Skeggjastaðir
(indicated by dotted lines).
remaining walls. This interface is partly associated with strong reflection hyperbolae (Figure 4).

Figure 5 shows the seismograms and frequency spectra of all traces along profile S1 from the seismic measurements. The seismogram (Figure 5a) shows a decrease in amplitude between about 2 m to 7 m and between 12 m to 14 m profile distance. In addition, between 4 m and 7 m the arrival time of the Rayleigh wave (grey line) is earlier than in the rest of the profile. Figure 5b shows that the frequencies range from about 20 Hz to 60 Hz. Here, the previously mentioned amplitude decrease is also visible. The solid line shows the resonance frequency of the Rayleigh waves, that is, the frequency with maximum amplitude. In most of the profile it is between 30 Hz and 40 Hz, but at the end it increases to about 50 Hz. This change is caused by a rise in the layer interface, which is also observed in GPR (Figure 5c): its meaning will be discussed later. The amplitude mean from 30 Hz to 40 Hz for all shots is mapped in Figure 3b. In the middle part a decrease in amplitude corresponding to the ruin can be clearly seen. The effect of the rising layer interface at the northeastern side is also visible here.

The electrical conductivity map measured by EMI (Figure 3d) shows a rectangular anomaly of low values ≤ 1 mS m⁻¹. The surrounding area has values only
slightly larger (around 2 mS m⁻¹), but the anomaly is clearly visible. Some point anomalies of higher conductivity ≥ 4 mS m⁻¹ can also be seen. At the southeastern side of the measurement area, the conductivities increase sharply to > 4 mS m⁻¹.

The ‘inverted’ ERT profiles show very clear anomalies of higher electrical resistivity around 2000 Ωm (Figure 6). On profile E1, which crosses the northwestern corner of the turf building, the anomalies of high electrical resistivity are closer together, with some high resistive material in between. On the second profile, which perpendicularly crosses the western and eastern walls, the anomalies are clearly separated. The depth of the anomalies derived by ERT is between 20 and 50 cm. The surrounding soil has resistivities between 250 and 600 Ωm. Below a depth of approximately 1 m the resistivity increases sharply to values larger than 3000 Ωm.
Discussion

Comparison of methods

An overview of the turf structures visible in the magnetic, seismic, EMI and GPR measurements is shown in Figure 7. The EMI IP anomalies correlate well with the magnetic results. The strong magnetic anomalies in the area of the building mainly in the northern wall and southeastern corner can be interpreted as strongly magnetized stones (Figure 7a and c). The intermediate anomalies in the southern wall and in the middle of the building can be produced by stones of weaker magnetization, or by stones at greater depth. Other possible interpretations of the magnetic anomalies are: (i) fire places or kilns with thermoremnant magnetization or (ii) iron stains in tumbled turfs, which were identified in the subsurface archaeological cores. This form of bog iron is typical for Icelandic marshy soils (van Hoof and van Dijken, 2008). This finding would imply that magnetics or EMI (IP) could be used to detect a turf building built without stones if enough bog iron is incorporated into the turf blocks.

The line of anomalies at the southern border of the building, which is probably caused by stones, can also be seen in the GPR time slice between 8 and 14 ns (Figure 7e). In the radargrams (Figure 4) they are visible as diffraction hyperbolae, which support the interpretation as stones. In the northeastern corner of the building, core C2 confirms the presence of a stone at about 20 cm depth.

In principle, both tumbled turf blocks and stones can produce diffraction hyperbolae such as those associated with the layer interface occurring in the deeper time slice (Figure 7f). In our case, stones are the more likely explanation because a known turf block found in core C3 is visible in the radargrams only as a weaker reflection compared with stones. The layer interface corresponds well with the sudden increase of electric resistivity at 1 m depth in the ERT depth sections and can be interpreted as the top of bedrock.

The seismic resonance analysis is successful in imaging the outline of the turf building. The dominant effect of the lateral structural change of the subsurface in the Rayleigh wave spectra is a strong decrease of amplitude correlating with the outline of the building. Wilken et al. (2015) showed in a modelling study that a decrease in amplitude in the vertical component of the Rayleigh wave can be evidence for an increase in topsoil velocity, leading to a change in the polarization of the surface wave. The decrease of first-break travel times in the area of the turf building (Figure 5a) shows that the building’s area has a higher velocity than the surrounding soil.

Changes in layer thickness of the topsoil that influence the dominant frequency can be observed at the right-hand side of the profile in Figure 5b, as well as in the northeastern part of the frequency slice in Figure 3b, correlating with a rise of the bedrock GPR reflector (Figure 3c).

The field example shows that the Rayleigh resonance method is able to detect the shear-wave velocity contrast between the turf building and its surroundings. The comparison with the other methods shows that the resonance amplitude effect seems to correlate spatially well with the turf walls, also identified in EMI. The strength of the resonance method is that it does not require much instrumentation and that it is
based on mechanical, that is, non-electromagnetic, subsurface parameters, but the interpretation of the records remains qualitative. This could be improved by recording not only the vertical but also horizontal Rayleigh wave components and by performing seismic refraction profiling in order to determine the seismic velocity structure of the geological background for reference.

The ERT and the EMI conductivity component are the only measurements that detect the turf walls directly. With these methods, the turf walls are visible as anomalies of higher resistivity, that is, lower conductivity, compared with the surrounding soil. The turf walls in the ERT have electrical resistivities around 2000 Ωm corresponding to 0.5 mS m\(^{-1}\) conductivity. The anomaly in the EMI mapping result has electrical conductivity values of around 1 mS m\(^{-1}\). This slight difference can be explained by the integral composition of the EMI signal originating not only from the turf wall alone but also from the surrounding soil having higher conductivity.

All other methods basically indicate the walls indirectly through the stone foundations. Some point anomalies of the EMI conductivity map of ≥ 4 mS m\(^{-1}\) indicate either small metal objects or lenses of more clayey or wet soil (Figure 7d). The larger area of higher...
conductivity in the southeast could also be explained by either increased clay or water content occurring in the natural geology. In the ERT profiles the area of resistivity $\geq 3000 \, \Omega \cdot m$ below 1 m depth is interpreted as the bedrock.

The increased resistivity of the turf building remains can be explained by the good insulation properties of the turf blocks as a result of air trapped in the mats of roots (van Hoof and van Dijken, 2008). Steinberg (2003) also observed increased resistivity of turf walls, although Horsley (1999) showed examples of turf walls having higher and lower resistivity. The decreased resistivity of the underlying soil could be explained by the higher amount of water retained by the organic-rich material compared with the surrounding soil (Horsley, 2004). This suggests that the resistivity contrast between turf and soil is due to different porosities, and that the contrast can be either positive or negative, so the nature and causes of the contrast have to be investigated at each site individually.

A direct comparison between GPR and ERT on profile E1 is shown in Figure 8. Areas of higher resistivity coincide with strong reflections, and the depth of the bedrock is seen with both methods. In the radargrams the bedrock is seen as a bowl-shaped reflection in the non-topography corrected radargrams (Figure 4). In the area of the building the soil overlying the bedrock is thicker compared with the surrounding grasslands. The thicker soil causes an increase in travel time of the reflection in and around the building. As the time slices in Figure 3 show the reflection amplitudes at a certain depth below the surface, the rounded anomaly seen in the time slice between 30 and 35 ns represents the intersection of overlying soil and bedrock.

The ERT resolution analysis

Between 10 cm and 30 cm depth turf blocks were detected by coring, but the ERT profiles show corresponding highly resistive anomalies only between 20 cm and 50 cm depth. To explain this discrepancy and to analyse the resolution of the ERT profiles, we conducted numerical modelling and checkerboard tests, which are commonly used in seismological tomography.

First, a model was built with a similar structure to the field example, namely a bedrock depth of about 1 m below surface and two high resistive turf blocks (2000 $\Omega \cdot m$) between 10 and 40 cm depth (Figure 9a). The zone of intermediate resistivity (700 $\Omega \cdot m$) of the model starts at a depth of 30 cm. Then synthetic apparent resistivity values in DD and WA configurations were calculated using the Res2dInv software (Loke, 2002). These synthetic data were inverted again using the Res2dInv software, both with and without 5% added noise and the same settings used for the data measured in the field (Figure 9b and c). The model was then iteratively updated so that the inversion result of the synthetic data fits the inversion result of the measured data (Figure 9d). The final model shows two high resistive turf walls (2000 $\Omega \cdot m$) and material of medium resistivity (700 $\Omega \cdot m$) between them and to the eastern side of the building. These anomalies could represent the tumbled turf and soil also found in the corings (Byock and Zori, 2009), although the stones lining the inside of the walls could also increase the resistivity. The GPR time slice indicated an accumulation of stones outside the northeastern corner of the building. They lie directly next to the ERT profile and thus might cause an increase in resistivities.

To the west a 30 cm thick layer of medium resistivity (700 $\Omega \cdot m$) starting at 30 cm below the surface causes not only a defined anomaly in this depth range, but also affects the specific resistivity values below it. If 5% noise is added to the apparent resistivities before the inversion, the layer seems to be composed of several distinct anomalies, as is also observed in the inversion result of field data. This could be an effect of insufficient resolution of the inversion in this part of the data. When comparing the model and the inversion results of the synthetic data it also becomes clear that the areas of very low resistivity values (dark blue) are artefacts of the inversion. Some small-scale anomalies in the uppermost 30 cm observed in the inversion results of both the synthetic and the field data can now also be addressed as artefacts.

The modelling has shown that the resolution of thin layers is problematic and that these anomalies might also affect deeper levels. To further evaluate the
For better resolution we conducted checkerboard tests for blocks of alternating high and low resistivity values in two sizes: (i) 50 cm width and 30 cm depth; (ii) 100 cm width and 30 cm depth. Electrical resistivity values of 300 and 2000 $\Omega$ m were chosen, because the field data showed this contrast between turf walls and the surrounding soil. Synthetic apparent resistivity values were then calculated for WA and DD configurations and inverted with the same settings as for the measured profiles. The results are shown in Figure 10. In both cases the first row of blocks (0–30 cm depth) is well resolved, both in amplitude and size. For the smaller blocks of 50 cm width the quality of the second row is decreased (Figure 10a). The correct resistivity values are not achieved and the depth extent is too deep, reaching down to almost 1 m below the surface. Below this second row no further anomalies can be resolved. For the wider blocks (Figure 10b) the second row of blocks is still satisfactorily resolved, but again below 1 m depth a reliable resolution is not possible.

The results from the checkerboard tests indicate that turf walls about 30 cm thick can be reliably inverted only if they begin directly at the surface. When they are situated deeper, under the topsoil in our case, they appear to reach deeper than they are in reality. Another find from the tests is that the inversion results cannot resolve structures below about 1 m depth.
Conclusion

To investigate the extent to which remains of Icelandic turf buildings can be detected by geophysical measurements we applied several geophysical techniques to a known turf ruin at Skeggjaðaðir in southwestern Iceland. We used magnetics, GPR, EMI, ERT and seismic RRM. Table 1 shows an overview of the advantages and disadvantages of the different methods. Magnetics showed an accumulation of stones inside and beside the ruin. As it is the fastest method for covering large areas in a short time, magnetics is ideal for selection of smaller areas of interest that warrant further investigation with other methods. Another method that maps mainly magnetic stones is the in-phase component of EMI measurements, which can be related to the magnetic susceptibility. A very precise image of the stones lining the inside of the former turf walls is generated by GPR. At some points archaeological coring confirmed the presence of stones and compared well with the GPR results. The use of higher frequency antennae and closer profile spacing would even increase the resolution of turf and stones. Nevertheless, less depth penetration has to be taken into account when using high frequencies.

In contrast to the detection of the stones, EMI conductivity and ERT imaged the turf in the turf walls. The turf has a higher electrical resistivity than the surrounding soil, a fact that is probably explained by differences in the porosities of turf versus soil. The mapping of Rayleigh wave resonance clearly revealed the location of the ruin by weaker amplitudes compared to the surrounding area. This amplitude effect is explained by an increase in the upper-layer velocity in places were turf walls are present. A rise of the bedrock at one side of the measurement area, which is supported by GPR, resulted in an increase of the Rayleigh wave resonance frequency and a decrease in amplitude. Therefore, the effects of velocity change or thickness change can be differentiated in seismic Rayleigh wave resonance analysis. The method thus enables an investigation of turf structures without reliance on stone foundations or linings. It furthermore addresses the seismic shear-wave velocity, enabling a qualitative investigation of changes of stiffness in the subsoil. The increased velocity observed in our example may thus indicate more compacted turf blocks – a scenario that fit well with our explanation for the increased electrical resistivity.

As a best-practice approach for detecting and investigating turf buildings we suggest the following procedure. Although magnetics did not uniquely detect the location of turf buildings it is the fastest method to cover large areas. If the turf buildings also contain some amount of stones or bog iron, delineated positive anomalies in the magnetic map could point to locations of archaeological interest. These smaller areas could then be surveyed with GPR and EMI to take advantage of the combined detection of stones (GPR) and turf walls (EMI). Finally, ERT profiles could help understand the resistivity-depth distribution as well as the spatial mapping of electrical conductivities by EMI.

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Table 1. Advantages and disadvantages of all methods used and the main target related to the turf building.

| Method                      | Advantages                                           | Disadvantages                                               | Target                                      |
|-----------------------------|------------------------------------------------------|-------------------------------------------------------------|---------------------------------------------|
| Magnetics                   | Fast, large areas                                    | No clear outline of building, disturbance by geology, no     | Stone settings (and bog iron in turf blocks) |
|                             |                                                      | depth resolution                                            |                                             |
| GPR                         | Depth resolution, high resolution                    | No penetration if electrical conductivity too high           | Stone settings (and turf walls)             |
| EMI Conductivity            | Fast mapping of electrical conductivity (compared with ERT) | No real depth resolution (integral effect)                  | Turf walls                                  |
| In-phase                    | Accumulation of stones visible                      | No real depth resolution (integral effect)                  | Stone settings (and bog iron in turf blocks) |
| ERT                         | Electrical resistivity distribution with depth resolution | Slow, single profiles                                       | Turf walls                                  |
| Seismic resonance analysis  | Even possible if no contrast in electrical parameters| Slow, lower resolution                                     | Turf walls                                  |

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