Journal of Cultural Heritage 63 (2023) 187–193

Contents lists available at ScienceDirect

Journal of Cultural Heritage

journal homepage: www.elsevier.com/locate/culher

Case study

First geophysical investigations to study a fragile Pomor cultural heritage site at Russekeila – Kapp Linné), Svalbard

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ARTICLE INFO

Article history:
Received 4 May 2023
Accepted 4 August 2023

Keywords:
GPR
Arctic
Permafrost
Cultural heritage
Pomor
Svalbard

ABSTRACT

With climate warming, the cultural heritage sites of the Arctic are in great danger. Extensive research is needed to study such sites. The archaeological site at Russekeila – Kapp Linné, Svalbard was selected for the survey as previous research had highlighted its vulnerability to cryospheric hazards. The main objectives of the survey were (i) to register the precise surface and subsurface locations of cultural heritage (CH) (remains of an 18th century Russian Pomor trapper's hut) objects within the study area, (ii) to determine the impact of coastal erosion on the CH objects and (iii) to understand the near-surface stratigraphy of the site. The geophysical surveys were carried out using a Ground Penetrating Radar (GPR) instrument with two shielded antennas of 500 MHz and 800 MHz centre frequencies. Only weak anomalies were observed at the intersections with wooden drifts, which can be explained by the low contrast between the relative dielectric constant values of the driftwood and the background soil. The depth extent of the driftwood within the soil was understood from the processed GPR data to a depth of approximately 25 cm. A near-surface stratigraphy of the site morphology, including thaw depth, saturated and unsaturated sediments and soil cover, was established based on multiple reflectors observed to 2 m depth. Loose sediments are indicated by reflectors to a depth of approximately 20 cm. Unsaturated fine sediments, which show a stronger signal compared to the underlying saturated sand layers, can be observed from about 1.2 m depth. No reflectors are shown below the thaw depth.

Introduction

The cold and dry conditions of the Arctic are ideal for the long-term preservation of archaeological remains. However, with weather patterns – leading to higher temperatures and more precipitation – the nearly 180.000 archaeological sites registered in the Arctic are at great risk [1]. Over the past 43 years, the Arctic has warmed four times faster than the global average [2]. Climate warming has devastating effects in the polar regions, such as the rapid shrinking of sea ice, leading to an increase in the number of icebergs, accelerated erosion of permafrost-dominated coastlines, increased intensity of coastal erosion, thaw slumps or thermo-erosion gullying [3–5]. Conducting archaeological fieldwork in the Arctic is particularly challenging due to short field seasons, high costs, and rapidly changing weather that can make remote sites difficult to reach. Geophysics has proven to be an effective tool for exploring the Arctic region and understanding its cultural heritage [6]. The Arctic region is of great interest to geophysicists because of its unique geological features, including permafrost, sea ice, and glaciers, and its cultural history [7]. Geophysical methods, especially GPR, provide valuable information about the composition and condition of the site [8–10], allowing for informed adaptation and conservation efforts [11,12].

Cultural heritage on Svalbard

Supplementary Material 1.

Earlier studies and geophysical investigations

Geophysical surveys at high latitudes, focusing on mapping the subsurface of cultural heritage are rather scarce, compared to those in mid-latitudes. Amongst those identified is Hodgetts et al. 2011 [7], which used magnetometry to locate buried archaeological features and to identify activity areas within some dwellings at

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https://doi.org/10.1016/j.culher.2023.08.005

Maguse Lake (Nunavut, Canada). Following by Viberg et al. (2013) [6], who used magnetic susceptibility to locate settlement remains associated with a Middle Neolithic tool production site in northern Sweden. Subsequently, Landry et al. (2015) [13] used a combined geophysical approach (magnetic and electromagnetic) on a 3000 year old Palaeo-Inuit site on Southern Baffin Island, Nunavut, Canada.

Hodgetts & Eastaugh (2017) [14] used magnetometry to map both archaeological and permafrost features on Banks Island (Northwest Territories, Canada), allowing them to investigate site structure and assess the level of threat to the CH sites from climate change. Another study evaluated the applicability of remote sensing and geophysical techniques (Terrestrial Laser Scanning, GPR, electromagnetic survey) to investigate a Paleo-Inuit lithic quarry site in the interior of southern Baffin Island, Nunavut, Canada [15,16].

To our knowledge, there have been considerably fewer geophysical surveys for archaeological purposes in Svalbard. This can be explained by, for example, the lack of ground truthing data, the lack of or very limited previous survey results from many sites (including Russekeila), the complexity of obtaining survey permission, which depends on the specific instruments to be used, the limited number of days per year available for fieldwork, the harsh weather conditions, and the sensitivity of excavations due to the protection of the CH. Some exceptions are the work of Koster & Kruse (2016) [17], who applied GPR to investigate a historic quarry abandonment in Kongsfjorden, and by Davis et al. (2000) [18] who used GPR surveys to locate the 1918 Spanish flu victims in the permafrost in Longyearbyen.

Due to the slow and limited soil development and formation in the Arctic, the vast majority of archaeological sites are highly visible in the landscape in the form of surface artifacts, surface features made of stone, whale bone(s), etc. Sometimes they may be covered by a thin layer of ground cover, either by processes of solifluction, or by rock-encrusting lichens that camouflage surface features [19]. The challenges of conducting geophysical surveys in the Arctic are related to the thin soils (represented mainly by exposed glacial till without soil cover) and the periglacial environment. Namely, the seasonal thawing of the active layer of permafrost, which moves soils both vertically and horizontally [7].

Research aims

The present study aims to i) use GPR to locate and register the exact position of surface and buried CH objects; ii) investigate the applicability of GPR as an optimal geophysical tool for detecting specific objects of interest, i.e., wooden house remains and graves; iii) provide a basis for studying temporal variations in the condition of the CH objects caused by coastal erosion and cryospheric hazards effects (thaw slumping, solifluction) by repeating measurements in subsequent years. In addition, the results from the GPR data should contribute to a better understanding of the morphology and stratigraphy of the shallow subsurface to a depth of about 2 m.

Study site

The focus of this study is the Russekeila area, an almost 2 km wide bay near the mouth of Isfjorden (Nordenskiöld Land, Svalbard) (Fig. 1a). Russekeila Bay is located approximately halfway between Isfjord Radio and Kapp Starostin. Due to the presence of remarkable geological and Quaternary geological features, the area is part of the Fortress Geotop Protection Area. The Linnéelva river divides the bay into a (smaller) western part and a (larger) eastern part. According to the periglacial geomorphology map [20], the low-lying area (2–6 m a.s.l.) is represented by an active beach system, followed by uplifted beach and marine deposits into which various thermokarst processes (thermo-erosional gullies and thaw slumps) cut easily (6–16 m). Ice-wedge polygons are present above 16 m. The maximum depth of the active layer within the study area is estimated by [20,21] to be between 0.3 m in the bog areas and 2.2 m in the exposed raised beach ridges at Kapp Linné and Isfjord Radio in the western Spitsbergen.

Background and cultural heritage at Russekeila

Russekeila is one of the largest archaeological sites of its kind in Svalbard (78° N, 14° E) and is famous for hosting its Pomor Russian huts. The Pomors are an ethnographic group descended from Russian settlers [22]. Russekeila hosts the remains of a Russian wintering station – Russekeila West (RW), which is subject to intense coastal and river erosion (Fig. 1b). There is also an important Russian Pomor trapper's hut in the centre of Russekeila (Russekeila – East, RE), dating from the 18th century (Fig. 1c). There are also two other houses, a restored grave and a Russian tree cross from the same period can also be found in the area. The inhabitants of Russekeila were hunters of polar bears, Svalbard reindeer, various birds, arctic foxes, white whales, and walruses [23]. The main cultural remains are the exposed decayed wooden ruins of a multi-roomed building, the hunting hut and several huts covering an area of about 200 m^2 [24].

Previous archaeological excavations at Russekeila took place in the summers of 1955 and 1960 during the inter-Nordic archaeological-ethnographic research expeditions. The main purpose of these expeditions was to investigate whether Stone Age and Medieval settlements existed on Svalbard before 1596 [23]. During the excavations, many hunting and skiing tools were found, as well as chess men, lamps, clay vessels, barrel-making equipment and handicrafts in the form of carvings [24]. Russekeila was specifically chosen for investigation because previous studies have identified it as being at risk from thaw slumps [25], thermo-erosion gullies [26] and coastal erosion [27], and also because it is included in the Catalogue of high priority cultural heritage sites in Svalbard (entry 61) [28].

Methodological approach

In August 2022, to further investigate the Russekeila sites, a geophysical field campaign was initiated to locate the cultural heritage objects described above using data acquired from GPR surveys. The field survey was conducted on both sides of the Linnéelva river (Fig. 1a): Russekeila West (RW) and Russekeila East (RE). The surface of the sites is predominantly covered by large-grained sediments. The air temperature at the time of the survey was between 4 °C and 7 °C.

The original plan was to collect both GPR and magnetic data. However, due to poor weather conditions the latter could not be completed. Interpretations in this study are based on the results of the one-day GPR survey combined with field observations.

GPR survey

GPR survey

The GPR survey was carried out with a Malå ProEX instrument. Two shielded antennas with frequencies of 500 MHz and 800 MHz were used to find the optimal choice, i.e. a suitable balance between resolution and penetration depth. An external GPS device was connected to the instrument. A total of 19 profiles were located east of the river Linnéelva (site RE), and five profiles were located on the west side (site RW) (Figs. 1, 2a and 4a).

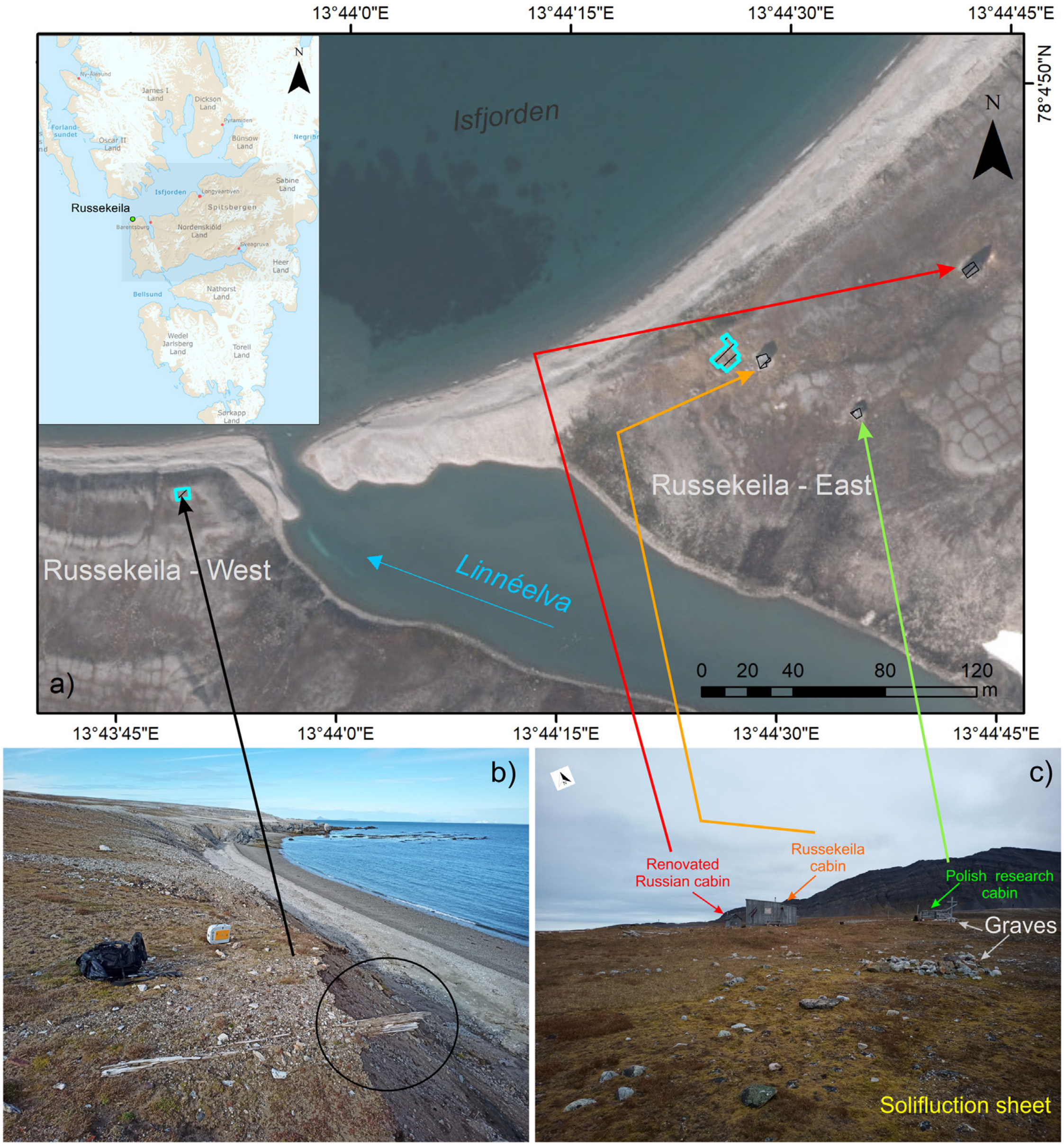

Fig. 1. Geographical location of the Russekeila site; a) Linnéelva river separates the eastern and the western parts of the bay (investigated cultural heritage in blue rectangles) (base map from Norwegian Polar Institute, 2023) [34]; b) Exposed house beams due to coastal erosion at study site Russekeila West; c) Overview of RE, with details over the cultural heritage sites (Renovated Russian Cabin, Russekeila cabin, Polish research cabin). Grave in the foreground is located on a solifluction sheet.

The 500 MHz or 800 MHz antenna was chosen depending on (i) the intensity and roughness of the topography, (ii) the geometry and size of the antenna, (iii) the desired penetration depth, and (iv) the conditions and vulnerability of the cultural heritage objects to be surveyed. The antenna offset was set to 0.18 m for the 500 MHz antenna and 0.14 m for the 800 MHz antenna. The sampling intervals was set to 0.1791 ns and 0.1231 ns for the 500 MHz and 800 MHz antenna, respectively. The lower frequency antenna, i.e. the 500 MHz antenna, provides greater penetration depth at the cost of lower resolution compared to the 800 MHz antenna. After measuring several test profiles, it was concluded that the 500 MHz antenna was better suited to the site conditions and was subsequently used as the primary antenna. All GPR data was collected and stored in. rd3 format.

GPR data processing

Initial processing of the GPR data was performed using the Reflex2Dquick-V4.0 (Sandmeier Geophysical research). Global background removal, running average and dewow (subtract mean with filter length of 25 ns to eliminate very low frequency components) filters were applied to the data. A linear gain function was applied to the data to account for signal attenuation in deeper parts of the section and to emphasize the continuity of the observed reflectors. Further processing using the Automatic Gain Control (AGC) filter in MATGPR [29] was applied to several profiles.

Results and discussions

Overall, the geological conditions at the site did not favour any of the geophysical surveys due to the low contrast between the petrophysical properties of the targets being surveyed and those of the background. GPR measurements were preferred over other methods because the method is relatively quick and easy to use (which is crucial in an Arctic context) and provides high-resolution results from shallow depths. Several challenges made data collection and processing difficult, namely high soil moisture, the domi-

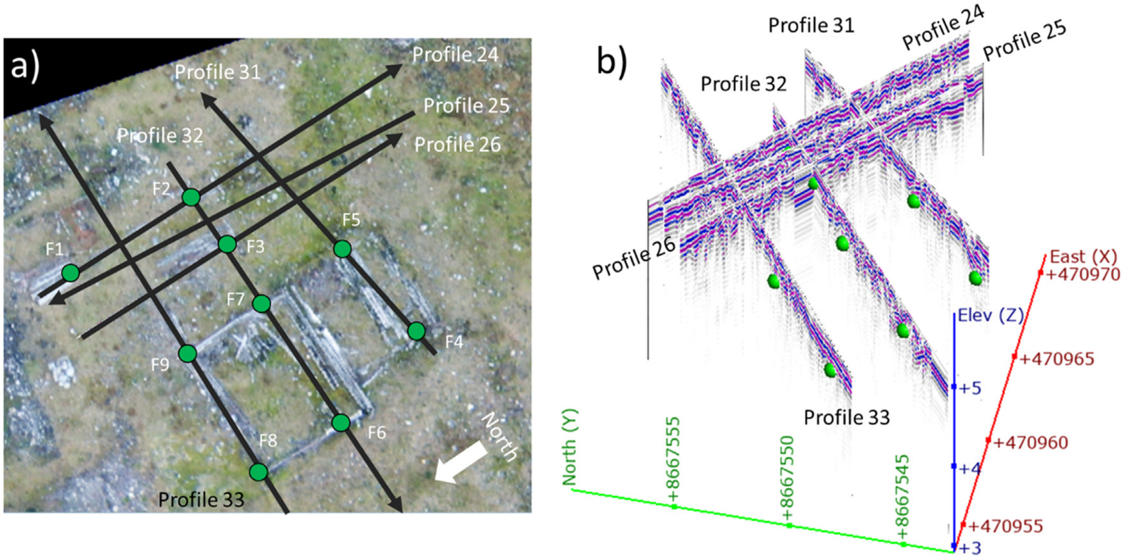

Fig. 2. Overview of the measured GPR data from Russekeila East (RE): a) 2D view; b) 3D view. from profiles 24, 25, 26, 31, 32 and 33. Conversion to depth was based on $V = 0.1$ (m/ns). All profiles in this figure were measured using the 500 MHz antenna.

nance of large boulders, an uneven survey area due to the exposure of parts of the surveyed heritage features above the ground surface, rough terrain and the aforementioned relatively low contrast between the relative dielectric constant (eR) values of the background geology and the archaeological remains.

Russekeila East (RE)

The main objects of study at the RE site include (i) wooden remains of huts, such as the Pomor hunting hut, (ii) graves consisting mainly of human skeletons covered by large stones (Fig. 1c, right), and (iii) hunting tools, mainly made of various types of metal. Only drifts from wooden huts produced signals strong enough and/or dimensions large enough to be detected by the GPR survey. Therefore, other CH objects are not discussed further in this study. The corresponding profiles that intersected the remains of the wooden drift are represented by profile groups 24, 25, 26 and 31, 32, 33 (Fig. 2a and 2b). The S-N trending profiles 24, 25 and 26 intersect with three main parts of the wood drifts (green dots; Fig. 2a and 2b). These intersections are associated with a signal attenuation due to a lower relative dielectric constant of the driftwood compared to the surrounding unconsolidated sediment. These areas are labelled F1, F2 and F3 in the respective profiles (Fig. 3). The E-W trending profiles 31, 32 and 33 indicate eight intersects with the wooden drifts (Fig. 3).

Russekeila West (RW)

West of the Linnéelva river (RW), coastal and river erosion develops faster than in the East (RE). At the RW site there are fewer cultural heritage features, consisting mainly of wooden remains from a largely destroyed hut (Fig. 1b). The mouth of the Linnéelva river shifted with about 30 m to the west between 2012 and 2020, which has devastating effects on the wooden remains in the following years. This estimate was possible due to very detailed drone photos taken in August 2020 (visible in Fig. 2a and 4a). This shift will result in a significant loss of the RW site. With the current development of coastal and river erosion at the site, this could lead to its complete disappearance in the future. It is therefore important to document the sites while they still exist. No prominent anomaly is observed at the intersection part of profile 47 (green dot; Fig. 4a, 4b and 4c).

General subsurface stratigraphy of the site based on GPR results

An overview of a representative depth section of profile 27 after processing can be used to illustrate the dominant near-surface stratigraphy of the site (Fig. 5a, see Supplementary Material 2). The following strata can be identified after applying the filters discussed above to profile 27, which can be considered a high-quality average of all measured profiles in the area (Fig. 5b, see Supplementary Material 2):

(i) *Beach sand – gravel*: unconsolidated sediments covering the top few centimetres of the subsurface stratigraphy. Stronger reflectors within this part are partly due to the high signal resolution near the surface, but also due to the dry nature of these surficial layers compared to those at lower depths.
(ii) *Fine-grained sediments*: unsaturated, fine sediments which consequently show a stronger signal compared to their underlying layers. The contrast between the reflectivity of this layer and its overlying parts, which decreases with depth, can be primarily be described by variations in grain size.
(iii) *Hyperbola – large-grained objects*: several scattered and weak hyperbolas can be observed across the study area at various depths. These hyperbolas most likely represent larger stones within a fine-grained composition. Alternatively, they may represent unexplored CH objects. Further investigation is required to better understand their origin.
(iv) *Saturated sand*: at approximately 1.2 m depth (Fig. 5, see Supplementary Material 2), the signal degrades dramatically, most likely due to a shift from the upper, unsaturated layers to the lower, saturated layers.
(v) *Thaw depth*: the weakest reflector in the section is related to the parts of the stratigraphy located below the thaw depth. Frozen ground transmits almost all the energy through itself and therefore no strong reflectors can be observed below the thaw depth.

Overall, the study had a mixed “contribution” of good and less good successes. The fact that it was not possible to carry out magnetic surveys due to the challenges of the Arctic fieldwork was outweighed by the results of the GPR survey. Identifying the depth of permafrost thaw beneath fragile cultural heritage sites could be a productive direction for future work aimed at assessing the threat to sites from permafrost thaw. This study has highlighted the gaps

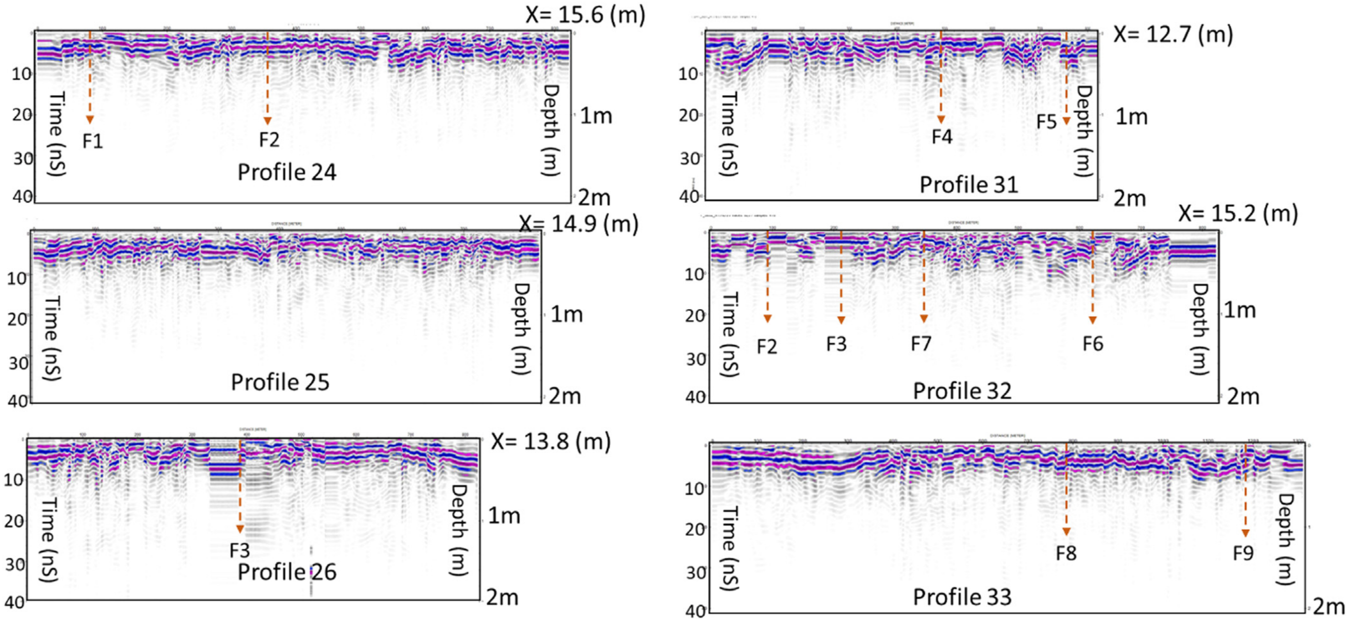

Fig. 3. Processed GPR profiles from Russekeila East (RE): intersects of the CH objects with GPR profiles are marked with orange arrows and indicated as F#. For location of the profiles see Fig. 2a. Conversion to depth was based on $V = 0.1$ (m/ns). Profiles were measured using the 500 MHz antenna. Arrows indicate the intersection between GPR profiles with remains from wooden drifts.

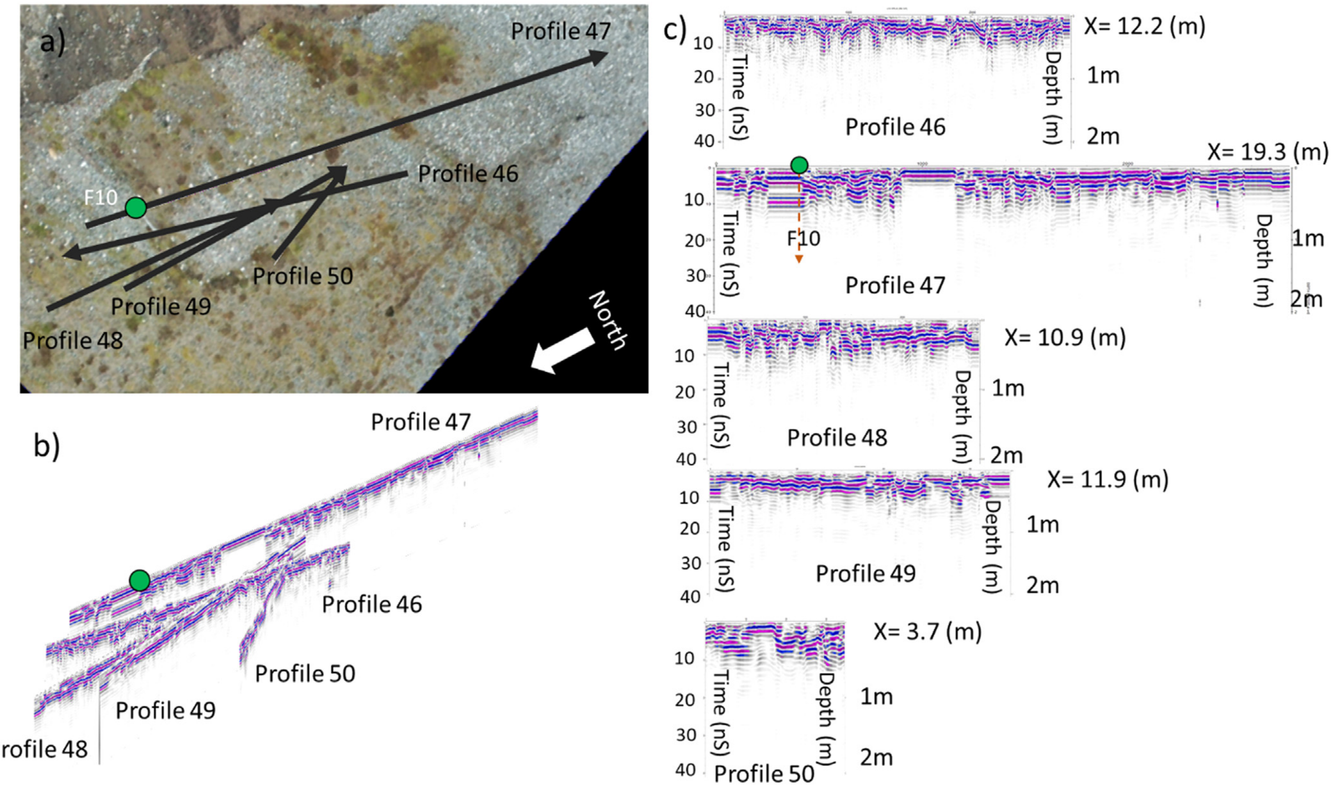

Fig. 4. Overview of the measured GPR data from Russekeila West (RW): a) 2D view; b) 3D view; c) GPR results from profiles 46, 47, 48, 49 and 50. Conversion to depth was based on $V = 0.1$ (m/ns). All profiles in this Figure were measured using the 500 MHz antenna.

identified in Arctic research with regard to the potential use of existing multidisciplinary methodologies to address the impacts of climate change on cultural heritage in the Arctic [30].

The use of the fragile landscapes and cultural heritage sites of the Arctic is crucial to send a broader message about the challenges of climate change and to inform future mitigation and adaptation efforts. Overall, the use of GPR in the Arctic has great potential to advance our understanding of the region's environment, history and culture. As a non-destructive method, GPR provides fast results with high resolution. It is sensitive to, to different degrees, most of the archaeological objects which makes the methodology attractive for many archaeological studies with different site conditions. In particular, for studies such as the present work, which due to remote site location or/and vulnerability of

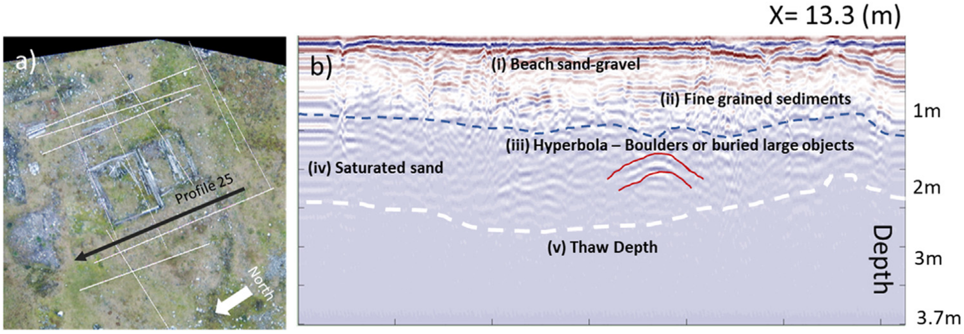

Fig. 5. Inferring the dominant near-surface stratigraphy of the study area at the time of measurement (August 2022) based on the GPR measurements. The presented depth section denotes the processed GPR results from profile 27. For details of the processing refer to Section 3. A standard AGC filter with 15 ns time window is applied. Processing is conducting in MATGPR. Conversion to depth was based on $V = 0.1$ (m/nS). Profile 27 was measured using the 500 MHz antenna. (Supplementary Material 2).

the site use of the more sophisticated geophysical instruments is not possible. However, it is important to consider the limitations of GPR, such as depth of penetration and resolution, and to use it in conjunction with other geophysical and field-based techniques for a comprehensive understanding of the subsurface. Future work should consider combining more remote sensing methods (e.g. repeated drone photography, drone-based geophysical surveys [31]), along with detailed geological and geomorphological mapping, and detailed topographical surveys. Integrated combination of non-invasive methods (such as magnetometry and electrical resistivity tomography [32]) would help in offering a better image of buried artefacts and graves, and managing the fragile Arctic cultural heritage sites. Digitisation of Arctic CH is needed to inspire creation and innovation for cultural dissemination to specialists in the field and to the general public. This will also contribute to the preservation of Arctic CH, ensuring that it is fully embedded in the Digital Era, while providing a more immersive experience for people [33].

Conclusions

The results of the GPR measurements did not show any significant contrast between the investigated CH features and their surroundings. Nevertheless, the methods proved to be an efficient tool for mapping the wooden remains of the huts at Russekeila. The preferred antenna frequency proved to be 500 MHz, which provided the best balance between the required penetration depth and the desired resolution. GPR data processing helped to improve the S/N ratio and eliminate the background signal and noise, which resulted in highlighting the reflectors that represented the features of interest. The following conclusions can be drawn from our interpretation of the collected GPR data: i) strong signals can be observed down to a depth of approximately 0.5 m. After processing, several reflectors can be observed down to a depth of 2 m, but the amplification of the signal is associated with additional noise; ii) the signal deteriorates where the radar pulses hit the wooden drifts of the huts (lower dielectric constant for the wood compared to the sediments). This is the most significant indicative feature of all the cultural heritage features surveyed; iii) understanding the extent of the depth of the graves was challenging due to: the precautions necessary to protect the fragile cultural heritage, signal attenuation due to low S/N ratio over the uneven surfaces of the graves at the site.

Acknowledgements

This study was funded by the Norwegian Research Council, through an Arctic Field Grant (AFG) ARCHEPHYSICS (Mapping of vulnerable cultural heritage sites in Russekeila, Svalbard using geophysical tools) project [grant number 333192]; and base funding from the Norwegian Geotechnical Institute (NGI). ICN also acknowledges the support from the Norwegian Research Council, within the framework of CULTCOAST project [grant number 294314]. The authors would like to thank polar bear safety guard Marcel Schütz, Sara Mollie Cohen from UNIS for help with the instruments and Hotel Isfjord Radio for all the help during our stay in Kapp Linné.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.culher.2023.08.005.

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