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An Application of Ground-Penetrating Radar at a Greater Yellowstone Area Ice Patch

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Ice patches are an irreplaceable archive of past events. With atypical melting now occurring around the world, it is important to be able to quantify and interpret the potential of what remains in areas of archaeological interest. A ground-penetrating radar (GPR) survey was conducted at an archaeologically productive ice patch in the Greater Yellowstone Area to identify sediment layers in which archaeological materials may be present. Numerous reflective surfaces were observed and interpreted as being organic-rich layers called lags. GPR did not reveal all lag surfaces that were easily identifiable in an ice core that was collected concurrently at the same ice patch. 400 MHz and 900 MHz antennas were used in the survey, but neither fully revealed the basal profile of the ice patch. This is likely the result of the short time-window in which the data were collected, as opposed to attenuation of the radar waves deep in the ice. Future applications of the technology are explored.

Introduction

Archaeological and paleobiological materials are continuing to be exposed by melting ice around the world (e.g., Lee and Puseman 2017; Pilø *et al.* 2021; Steiner and Gietl 2020; Taylor *et al.* 2019). As these frozen archives shrink, a logical question arises: How much ice remains at archaeologically and paleobiologically productive sites? This paper details the application of ground-penetrating radar (GPR) as a non-inva-

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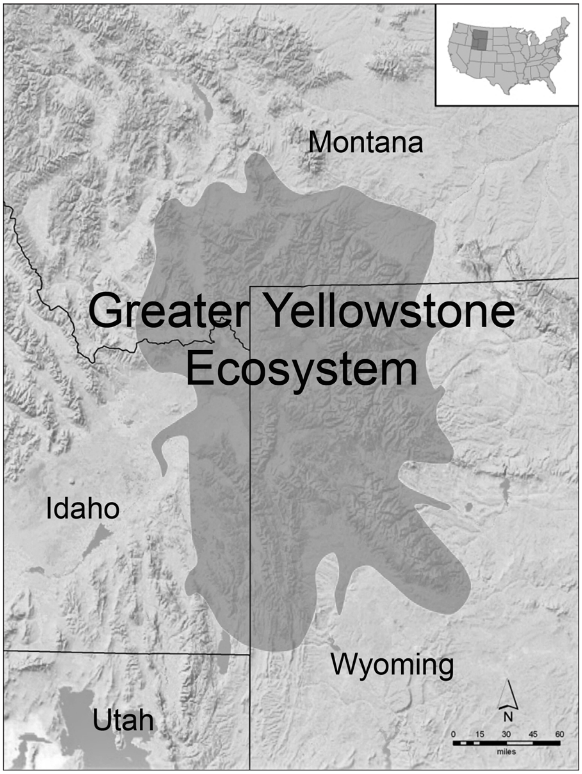

Figure 1 Overview of the Greater Yellowstone Ecosystem. Map: Joshua M. Robino.

sive method to assess the amount of ice remaining at an ice patch identified as TLIP-1 on the eastern flank of the Rocky Mountains in the Greater Yellowstone Area (GYA) (Figure 1). The objectives of the study were twofold: 1) to assess the utility of GPR relative to a direct measurement of ice depth obtained by coring, and 2) to develop and deploy a technology amenable for use in areas where other, more invasive (e.g., mechanized) equipment is restricted.

The location of archaeologically productive ice patches has been successfully modeled in the GYA since 2005. Some of these locations have undergone additional study including comparison of their aerial extents through time using remotely sensed images (Lee *et al.* 2009; Reckin 2017; Seifert *et al.* 2009), as well as through direct observation of their depth as revealed by coring (Lee 2018; Lee *et al.* 2015). Lee *et al.* (2018) summarized the 2016 coring effort at TLIP-1, and Chellman *et al.* (2021) reported on reconstructed climate variability for the 10,000-year long ice core sequence collected at that time.

Importantly, archaeological materials have not been identified at all locations where modeling suggests they might be expected. This can be a result of: 1) interannual variability in snow cover affecting survey conditions; 2) preservation bias; and/or 3) the simple fact that not all ice patches were likely used by ancient peoples. Because of the factors above, the absence of evidence in the form of observed materials melted out of the ice cannot necessarily be equated to clear evidence of human absence at a given ice patch. GPR is envisioned as a tool to further assess the archaeological and paleobiological potential of ice patches where no previous evidence of ancient human and animal use has been identified, but where modeling suggests that it might be present.

Greater Yellowstone Area Ice Patch TLIP-1

The GPR survey was conducted as part of a multifaceted, interdisciplinary project that included the first analysis of water isotopes from an ice patch ice core in the GYA (Chellman *et al.* 2021). The GPR survey and ice coring occurred in late-August and coincided with the period of maximum annual melt. The effort reported here

Figure 2 A representative Greater Yellowstone Area ice patch (TL12) with lags (stratified organic bands or layers) exposed by melting.

occurred at a location designated as TLIP-1, which is part of a cluster of four permanent ice patches (among many others) on the Beartooth Plateau of Montana and Wyoming in the northeastern portion of the GYA (Lee 2018).

The location was chosen because a 2013 ice coring effort at TLIP-2, which is 100 m south-southeast of TLIP-1, recovered stratified frozen layers of organic material (hereafter referred to as "lags") from within the ice patch. Eight lags were collected from the TLIP-2 ice core in 2013. The term "lag" emerged following field observations in the Yukon Territory of Canada (Farnell *et al.* 2004) and Alaska (Dixon *et al.* 2007) of stratified organic bands or layers visible in the destabilized/melting faces of some ice patches. These layers were presumed to be zones where organic material accumulated on old melt surfaces (Figure 2).

In 2016, a complete ice core sequence was recovered from TLIP-1 consisting of c. 5.7 meters of ice from the surface to the bottom of the ice patch (Figure 3) (see Chellman *et al.* 2021 for details regarding the isotopic analysis of the ice core). The GPR survey at TLIP-1 was designed to test the ability of the equipment to measure the overall depth of the ice and to potentially reveal the presence of lag deposits including one surface that was exposed along the lateral margin of the ice patch in 2007 (Figure 4). That surface contained organic artifacts dating in excess of 7,000 cal BP (Lee 2012).

Ground-penetrating radar survey

Ground-penetrating radar is a widely used geophysical method that images the subsurface through the transmission and subsequent reception of pulsed electromagnetic energy through a medium. The GPR method is particularly useful because it results in three-dimensional coordinates of subsurface features enabling the genera-

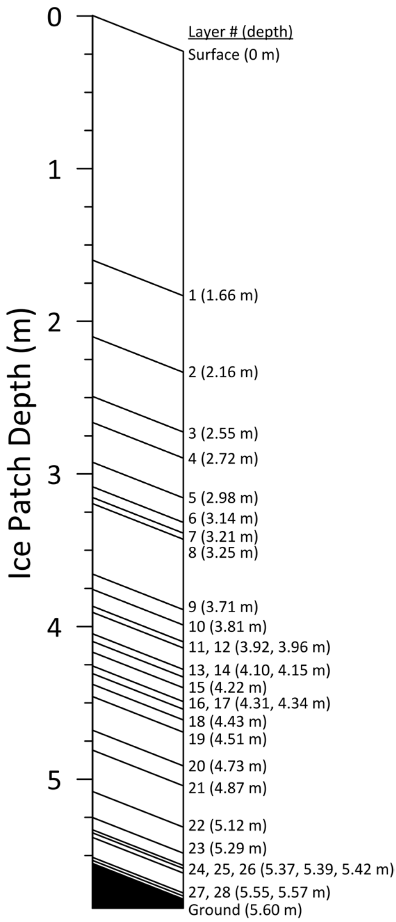

Figure 3 Schematic of ice core showing twenty-eight sediment horizons within the core body.

tion of depth measurements. Applications of GPR can be found in a variety of disciplines, including civil engineering (Alani *et al.* 2013; Klewe *et al.* 2021), geology (Chen and Jeng 2016; Xie *et al.* 2018), and glaciology (Egli *et al.* 2021; Monnier and Kinnard 2013). When utilized for archaeological research, GPR is often able to image subsurface phenomena of both natural and cultural origin (Conyers *et al.* 2013; Lowe and Wallis 2020). The ability to identify buried anthropogenic and natural landscapes makes GPR an ideal method for cross-disciplinary geoarchaeological studies that place ancient people within a broader environmental context (Conyers 2016).

Previous archaeological research at TLIP-1 and TLIP-2 revealed potential artifact-bearing organic sediment horizons or surfaces buried within the ice patches. Lags primarily consist of ancient organic (i.e., plant parts, pollen, charcoal) and inorganic (i.e., clay, sand, silt) material that can be useful in the reconstruction of paleoenvironments (Lee 2018; Lee *et al.* 2018). We hypothesized that GPR would be an effective tool for the non-invasive imaging of these sediment horizons within TLIP-1 where a concurrent ice coring operation would allow the direct comparison of a core to the GPR results.

An additional objective of this survey was to compare the utility of higher and lower frequency antennas to detect organic lags and the base of the ice patch. Previous applications of GPR at ice patches have focused on the use of 250 and 500 MHz frequency antennas (Meulendyk *et al.* 2012; Pilø *et al.*2021; Urban 2016). These studies successfully demonstrated the ability of GPR to produce low-resolution characterizations of ice patch interiors. Low-resolution datasets provide a greater overview of the internal structure of an ice patch but are unable to detail individual strata that are vertically in close association. Conversely, high-resolution datasets produced from higher-frequency antennas enable more-detailed imagery but are limited in depth. We deployed a 400 Mhz antenna, as well as a high-frequency 900 MHz antenna unit, which is more frequently used in archaeological, rather than geological applications to image shallow, near-surface deposits (Utsi 2017) (Figure 5).

The central frequency (a principal differentiator) of GPR units is a function of the distance between the transmitting and receiving antennas located within each GPR transducer. Higher frequency units have internal antennas spaced closer together

Figure 4 TLIP-1 as it appeared in October 2007. Arrows demarcate the approximate edge of a continuous lag surface that contained artifacts dating in excess of 7000 years BP. The surface the person is standing on is underlain by ancient ice. Through 2020, this ice patch has not melted back to the extent observed in 2007.

Figure 5 Lead author B. Ackermann belayed down the face of an ice patch in a toboggan while attending a GPR sled. We attempted to target a prism pole mounted on the sled with a total station to assess the position of the GPR, but the older-model total station failed. Photo credit: Matt Stirn.

and, therefore, generate energy with shorter wavelengths than their lower frequency counterparts.

The wavelength of propagating GPR energy is an important aspect defining the vertical resolution of stratigraphic horizons detectable within GPR datasets. This is because wavelengths that exceed the vertical distance between two horizons are too large to produce significant amplitude changes within a composite trace—the digitized version of electromagnetic waves that comprise GPR datasets (Conyers 2013). The maximum depth of penetration of a GPR unit is usually limited to a finite number of wavelengths (Utsi 2017). Therefore, higher frequency GPR units produce higher resolution datasets, but transmit energy to shallower depths than lower frequency antennas. We hypothesized that the highly penetrable qualities of ice and snow would overcome the depth limitations often encountered when using 900 MHz antennas while simultaneously producing a more detailed dataset.

Data collection

Ground-penetrating radar data were collected along a 36-meter transect on a transverse ice patch (following VanderHoek *et al.* 2012). In general, archaeologically productive ice patches in the GYA are "transverse," in that they lie horizontally on a slope below the crest of a ridge. The GPR transect was oriented parallel to the fall-line extending from the upslope edge (top) of the ice patch to the downslope edge (bottom) and terminating in the forefield. Data along the transect were collected twice, once with a 400 MHz antenna and once with a 900 MHz antenna. Both datasets were collected using a SIR-3000 GPR control unit manufactured by Geophysical Survey Systems, Inc. (GSSI), which generates 16-bit data. In both cases, an odometer-encoder survey wheel was utilized to record the distance of the transect and place GPR reflections into space. Data were recorded at 1024 samples per trace within a 55 ns time-window, with traces collected every 2.5 cm along the transect.

Data Processing and Analysis

Raw data were imported and processed in the GprViewer software package for visual analysis and interpretation (Conyers and Lucius 1996). Data were processed with a background noise removal filter and then manually gained to highlight horizontal reflections, which may indicate the presence of sediment horizons that could be artifact-bearing. Ground-penetrating radar systems record data in time, as opposed to depth. Data are recorded in two-way travel time within a specified time-window, capturing the properties of radar waves within that threshold. To convert time to depth, data must be assigned a relative dielectric permittivity (RDP) value. The RDP, also referred to as dielectric constant, is a measurement applied to a medium that models the velocity of propagating radar energy through it. In general, the greater the RDP of a medium, the slower the propagating energy will be in that medium (Conyers 2013). We used the hyperbola-fitting technique (Conyers and Lucius 1996) to estimate an RDP of 3.10 (17.03 cm/ns), enabling us to proceed with data interpretation.

The deepest upward sloping continuous planar reflections were interpreted as bedrock, which bound high-amplitude planar reflections interpreted as internal hori-

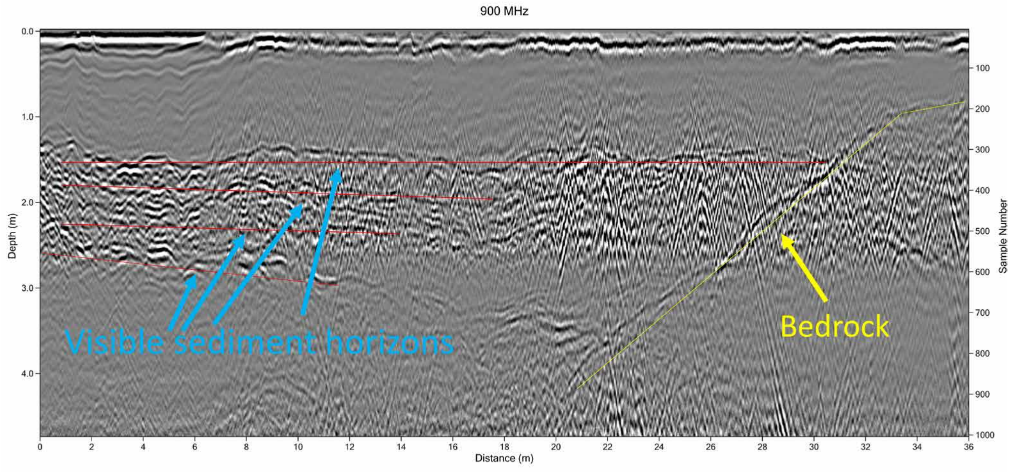

Figure 6 Annotated profile of data collected with 900 MHz antenna. Four sediment horizons and bedrock are visible.

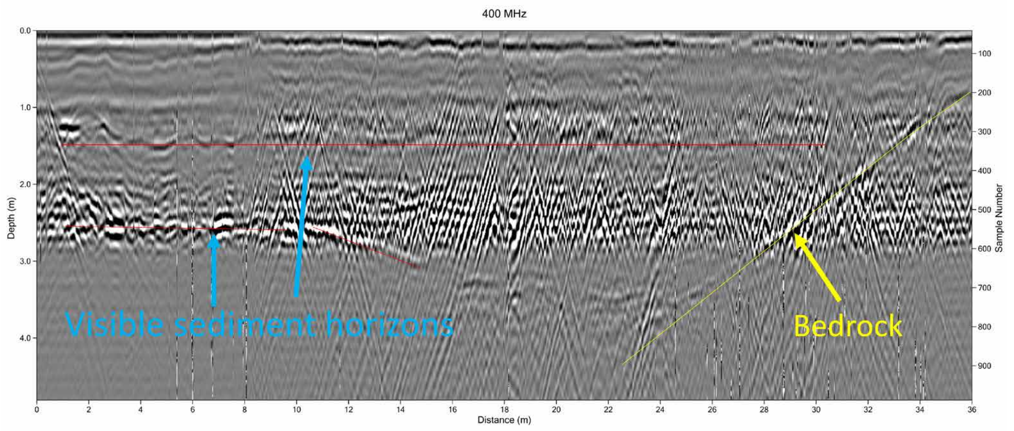

Figure 7 Annotated profile of data collected with 400 MHz antenna. Two sediment horizons and bedrock are visible.

zontal strata within the body of the ice patch. Internal stratigraphy is often defined within GPR datasets by continuous horizontal reflections, which indicate a shift in the physical and chemical properties of individual stratigraphic units within a medium (Conyers 2016). Figure 6 shows the annotated profile collected with the 900 MHz antenna. Figure 7 shows the annotated profile for the data collected with the 400 MHz antenna. Figure 3 is a schematic of the coring results (see Chellman *et al.* 2021 for details regarding the isotopic analysis of the ice core).

Discussion

Analysis of the GPR data reveal that data from both antennas identify distinct horizontal reflectors that correspond to sediment horizons observed in the core. These horizons are caused by shifting physical and chemical properties within the ice patch.

Neither the 400 nor 900 MHz antenna propagated energy deep enough to reach and identify the bed surface underlying the entire ice patch; however, they were able to capture the bed surface near the margins. This is more likely the result of the short time-window in which the data were collected, than the attenuation of the radar waves deep in the ice. A short time-window was used in this survey to maximize the resolution of the shallowest sediment deposits. Moreover, while neither antenna was able to resolve every sediment horizon within the visible depth range of the profiles, a comparison of the two data sets reveal important information about the use of GPR in ice patches.

As expected, the data collected with the 900 MHz antenna successfully images a greater quantity of sediment horizons than the 400 MHz dataset. The 900 MHz dataset shows the first four horizons, while the 400 MHz dataset is only able to image the first and fourth horizons. This is a result of each antenna's respective wavelength as they propagate through the ice patch. When calculated using Equation 1, the 400 MHz antenna produced wavelengths of .42 m, while the 900 MHz antenna produced wavelengths of .18 m. Therefore, those individual sediment horizons with vertical distances below these thresholds were unresolvable. Interestingly, both antennas "missed" horizons that should have been detectible to their wavelengths. This suggests that after the GPR energy encountered the first sediment horizon, the velocity of the propagating energy decreased, resulting in longer wavelengths that eventually exceeded the vertical thresholds as described above. That said, the higher frequency antenna was still able to better define the shallowest horizons, providing clear images of the sediment layers most likely to be exposed in the coming years.

$$\lambda = \frac{c}{v}$$

Equation 1 Where λ is wavelength, c is the velocity of the material in meters per second, and v is frequency of the antenna measured in hertz

To the best of our knowledge, this project represents the first use of a high-resolution GPR antenna unit above 500 MHz for ice patch archaeology. GPR is a method that is used across multiple domains for a variety of purposes. Importantly, not all GPR units are comprised of the same frequency antennas, and antenna selection should proceed from the research questions the GPR is tasked with addressing. Recognizing the trade-off between resolution and depth of penetration will enable researchers to fine-tune their approach and borrow GPR techniques from other disciplines. In addition, experimentation with different time-windows will allow a greater definition of the properties of different frequency wavelengths as they propagate deeper in the ice. Moving forward, a wide range of GPR approaches and methodologies should be applied iteratively and then integrated to identify important ice-patch features. Low frequency antennas, such as those used in geology and glaciology, will no doubt enable a gross picture of an archaeologically productive ice patch's internal architecture and provide a big-picture look at the geomorphological processes that underlie it. Conversely, recent advances in ultra-high frequency antennas, such as those used in concrete inspection, may be useful in the identification of lags with close vertical spacing. It is likely that higher frequency antennas could successfully image the lags "missed" by the 900 MHz antenna used here. When integrated, these datasets can provide a more holistic view of an ancient landscape and help to place ancient peoples (and their material remains) within that landscape.

Future Directions

GPR has advantages for the archaeological investigation of ice patches. Foremost, it is a highly portable method of detecting potential artifact-bearing sediment horizons buried within ice patches. This is particularly useful in backcountry studies in the United States which frequently occur in places managed as "wilderness, devoid of humans and their activities" (*sensu* the Wilderness Act, 16 U.S. C. 1131-1136, 78 Stat. 890) (see Lee 2012). In these instances, direct observation through coring is either impractical or not allowed. As noted above, seemingly promising ice patches identified by modeling efforts in the GYA have not yielded artifacts. GPR offers a tool to directly gauge the potential for ice patches to contain substantial lag surfaces and by extension the possibility of archaeological materials. Moreover, GPR studies can be flexible with different frequency antennas strategically employed depending on the questions and conditions.

High-resolution data sets coupled with regional models of ice melt may prove useful in modelling the rates at which known, as well as potential artifact-bearing surfaces will be exposed. These models can then be used to plan survey strategies to record and protect these unique, at-risk cultural resources. GPR for ice patch archaeology is in its infancy. As the computational technology at the core of GPR units advances, much promise lies ahead.

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