Surficial and bedrock geology mapping with ground-penetrating radar in New England: general results and a case study from Mount Adams, New Hampshire

Seth Campbell, U.S. Army Cold Regions Research and Engineering Laboratory and University of Maine*
Steven A Arcone, U.S. Army Cold Regions Research and Engineering Laboratory

Summary

We collected ~200 km of ground-penetrating radar (GPR) data at center frequencies between 80-400 MHz within New Hampshire and western Maine. Lower frequency profiles revealed maximum penetration depths over 30 m with greater penetration over solid bedrock and shallower penetration generally occurring over till. Attenuation rates vary considerably depending on water content, till cover, and bedrock type. However, wet till sequences generally exhibit the highest losses with meta-volcanic bedrock also exhibiting higher attenuation rates than granites. Relative permittivity contrasts between till, granite, and fractures within granite allow for easy delineation of till over bedrock (aiding estimates of till volume) and constituents within granite fractures (i.e. water or air). In some instances, a contrast in reflection characteristics between bedrock type is evident (e.g. granite versus metamorphic-volcanic bedrock) allowing the potential sub-surface delineation of bedrock type. These results suggest that GPR is useful for delineating some rock types at depth, till depth and associated till volume, aquifer dimensions, and potentially water volume. Herein, we present a case study from these results with data collected from Mount Adams, New Hampshire. This case study also shows significant promise of GPR as a remote geological exploration tool.

Introduction

New England has a rich geological and glacial history resulting in complex surficial and bedrock geology. Much of New England has been successfully mapped on the surface through the federally funded STATEMAP program. However, due to vegetation cover, challenging terrain, and many geological complexities, some ambiguities, simplifications, and unknowns exist within geology interpretations. Likewise, reliance on boreholes and the rare surface outcrops to identify geologic structures and economic deposits within New England result in significant quantitative uncertainties.

Surficial and bedrock geology mapping with GPR provides vast opportunities for improving quantitative estimates of economic deposits (e.g. sand, gravel, and till), delineation of potential aquifer boundaries or bedrock and till boundaries, and estimates of ground water potential. Likewise, the use of radar to locate veins and fractures within bedrock provide a potential method for locating appropriate water or mineral extraction locations at near surface (≤35 m) depths. Here we show a case study that exhibits the potential of GPR as a tool for aiding surficial or bedrock geology mapping or for economic geologic resource extraction efforts in New England or other challenging locations.

Methods

For data collection in this study a Geophysical Survey Systems Incorporated (GSSI) SIR-3000 control unit was used with a range of GSSI antennas at center frequencies between 80-400 MHz. Specific antennas included the GSSI MLF 15-80 MHz, 100 MHz, 200 MHz, and 400 MHz. Profiles were collected on class II-VI roads, hiking trails, and off-trail, during the months of February, 2012 to March, 2013. Data were collected with stacking and band-pass filtering to reduce noise, at rates between 16-48 scans s^{-1} and with two way travel time (TWTT) ranges to 1000 ns. Profiles were collected via towing antennas by hand at ~2 km hr^{-1} or by vehicle at ~4-8 km hr^{-1}. Each profile was geo-referenced by simultaneously recording GPS marks on a hand held GPS (accuracy ~3 m) and marks on each GPR profile within the SIR-3000 at 20-50 meter increments. Post processing included single layer migration of diffraction hyperbolas to estimate relative permittivity values. We estimated depth (d) via the relationship between relative permittivity (ε) and wave velocity:

$$d = c\, t/\sqrt{\varepsilon}$$

where t is TWTT and c is the radio wave velocity in air (3×10^8 m s^{-1}).

Mount Adams GPR Example

A 2 km GPR profile was collected using a 400 MHz antenna in February of 2013 near the summit plateau of Mount Adams in the Presidential Mountains of New Hampshire. The transect ranges in elevation from 1580 to 1680 m a.s.l. Snow cover minimized rough terrain and provided the opportunity to collect the profile via ski while towing the antenna in a sled over the smooth snow surface. The local geology is currently mapped as boulder dimict residing over meta-sedimentary schist, quartzite, or two-mica granite (e.g. Fowler, 2011; Eusden 2010; Allen and others, 2001). Several exposed outcrops are mapped showing estimated contacts between the meta-sedimentary schist and granite. However, the boulder-dimict cover makes it impossible to estimate contact locations over much of the terrain. This GPR profile was also collected across a controversial elevation boundary. Current research supports the hypothesis that elevations above 1600 m a.s.l. were ice free during the last glaciation. This interpretation suggests that minimal till should exist over the basement rock above 1600 m because ice flow would not be available to pluck or redeposit till or debris above these elevations. However, depth of till or dimict is currently unknown in this region.

Results from the 400 MHz profile revealed relative permittivity values between 6-14 and penetration depths to 15 m. The near surface (0-5 m) consists primarily of random hyperbolic diffractions likely caused by the boulder dimict. Below 5 m (and in some places at shallower depths) multiple parallel sets of continuous horizons occur with apparent dips oriented to the Northeast (Figure 1) or Southwest (Figure 2). These dipping horizons are generally oriented in-line with locally mapped bedding planes and fractures within the two-mica granite. Therefore we interpret these horizons as bedrock fractures within the two-mica granite. We note that the fracture pattern is also classic of exfoliation joints within other regional igneous plutonic rocks. True fracture dip estimates may help directly compare surface mapped features to horizons imaged with GPR at depth. However, a 3-D grid of profiles would be required to estimate true dip orientations.

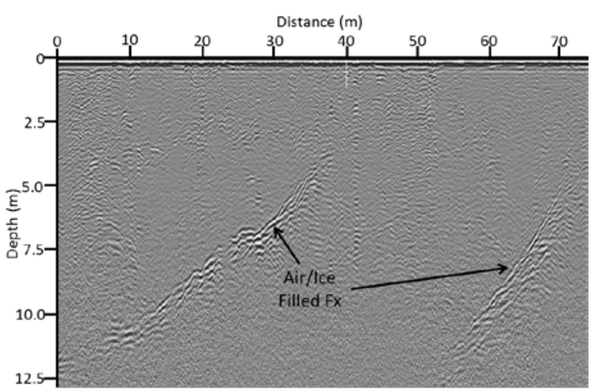

Figure 1: 400 MHz GPR profile showing parallel bedrock fractures (Fx) within a zone of Mount Adams, NH.

The relative permittivity of the dimict calculated using hyperbolic diffractions in the GPR profile from Mount Adams is far lower than most values calculated using GPR profiles from lower elevations in New Hampshire (ε~18 to 27). Maximum penetration depths of GPR profiles collected at lower elevations over till and till-bedrock mixtures is only 9 m using 400 MHz antenna, for comparison to the 15 m penetration depth on Mount Adams. We attribute high losses in saturated till to scattering, conductivity, and relaxation processes. Lower water content within the dimict of Mount Adams, therefore likely decreases attenuation rates.

Finally, we adopt the interpretation scheme outlined by Arcone and others (1995) regarding waveform polarity of triplet sequences to estimate contents within the interpreted bedrock fractures. That is, the polarity of the first three half-cycles of a response from a horizon dictates the ε contrast. The significant differences in ε of water (~80), ice (~3), air (=1) and bedrock (~5–9) provides enough contrast to interpret changing dielectric properties at horizons or discrete events. For example, we interpret some fracture horizons with a negative triplet sequence (suggesting a change from higher to lower ε) to represent an air or ice filled fracture (Figure 1). In contrast, a positive triplet sequence (suggesting a change from lower to higher ε) likely represents water filled fractures (Figure 2).

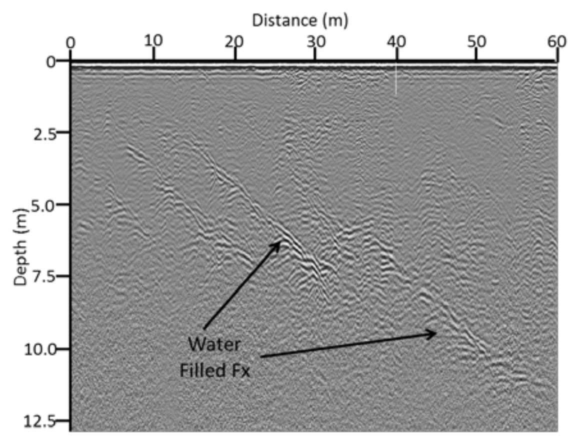

Figure 2: 400 MHz GPR profile showing parallel water filled bedrock fractures (Fx) on Mount Adams, NH.

Conclusions

We conclude that roughly 2-5 m of dimict overlay two-mica granite in a region which previously was interpreted as predominantly meta-sedimentary schist. The fractures mapped on the surface in the granite seem to support this argument. On a broader scale, this example shows the potential value of GPR use in remote regions where interest in a 2-D or even 3-D bedrock or surficial geology view will help delineate geological history, geometry, or geologic features of economic value.

Acknowledgements

I would like to thank Jeff Spaulding and Curtis Marston for assistance in the field collecting GPR data on Mount Adams.

Allen T, Creasy J, Davis PT, Eusden JD, Fowler BK, Thompson WB (2001) The Notches: Bedrock and Surficial Geology of New Hampshire's White Mountains. West DP and Bailey RH, editors, *Guidebook for Geological Field Trips in New England,* Geological Society of America, 2001 Annual Meeting. pp. C1-C33.

Arcone SA, Lawson DE, Delaney AJ (1995) Short-pulse radar wavelet recovery and resolution of dielectric contrasts within englacial and basal ice of Matanuska Glacier, Alaska, U.S.A. *J. Glaciol.*, **44**(137), 68-86.

Eusden JD (2010) The Presidential Range; its geologic history and plate tectonics. Lyme, NH, Durand Press, 62 p (with colored map).

Fowler BK (2011) Surficial Geology of Mt. Washington & The Presidential Range, New Hampshire (Derivative Annotated Map, 1 Sheet). Durand Press, Lyme, NH.