GPR Profiles of Glacial Till and its Transition to Bedrock: Interpretation of Water Content, Depth and Signal Loss from Diffractions

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ABSTRACT

We discuss GPR reflection profiles that we recorded on glacial till and a colluvial diamict at several locations in New Hampshire, and from which we interpret water contents, depths and rates of signal loss. We used pulses centered from 150–200 MHz and 300–360 MHz. The boulder-rich sediments reside over granitic and metavolcanics, the horizons of which we recognize from the relative strengths and phase of their waveforms, underlying fractures, and well-developed diffraction asymptotes. The till produced an apparent dense distribution of diffractions with limited asymptotes and dispersion, and occasional minor stratification. We use these diffractions and moveout profiles to calculate relative dielectric permittivities between 17 and 27, values which suggest up to 30% volumetric water, and likely saturation within these over-consolidated sediments. The evidence for transitions from till to bedrock ranges from a simple horizon to complex horizon segments, all characterized by diffractions and amenable to single-layer migration. A gradational loss in diffraction strength with depth suggests gradational weathering or changes in grain size as the cause. Maximum profiled depths range from 4 m to at least 10 m, with estimated scattering attenuation rates of about 3.3 \(\text{dB m}^{-1}\). In contrast, one and possible two colluvial diamicts, which likely contained 3-m-size boulders, show short segments of stratification, rare diffraction asymptotes, allow more than 20-m penetration and provide scattering losses of about 0.5 \(\text{dB m}^{-1}\). We measured extremely low conductivity and calculated permittivities ranging from 9–12, which suggest high densities and volumetric water content of 4–12%. Low, single scattering loss and deep penetration in the till are consistent with evidence of ground waves traveling up to 40 m one way. The phase polarity of waveforms within till and colluvial events show they may originate from either high or low dielectric contrasts, likely related to water or large boulders, respectively.

Introduction

Glacial till likely covers more than 90% of New Hampshire (NH) and generally resides upon granitic and metamorphic bedrock; it sometimes lies on glacio-fluvial sediments (Thompson et al., 1999). Goldthwait (1951) estimated an average till thickness of 9 m, a value consistent with statistics gathered for over 10,000 wells each in the Winnepesaukee and Piscatqua basins (Neil Olson, NHGS, pers. comm., 2013). The primary source for estimating depth of bedrock is the inventory of over 100,000 well logs maintained by the state of New Hampshire. The use of ground-penetrating radar (GPR) can supplement this information, but to date the most common geologic use of GPR has been to investigate stratified sediments, whereas till is a mostly random medium. Necessary to determining till thickness within a GPR record is knowledge of the relative dielectric permittivity, \(\varepsilon\), which determines signal velocity and hence, allows conversion of time of signal return into depth. In turn, sediment values of \(\varepsilon\) have long been well known to be empirically related to volumetric water content (Topp et al., 1980). Consequently, if \(\varepsilon\) can be readily determined then both thickness and volumetric...
water content can be estimated for profiled sediment. Here we mainly discuss 150–200 MHz GPR profiles of till, a colluvium type diamict, bedrock, and their interfaces, from which we use volumetric backscatter, in the form of coherent diffractions, as well as moveout profiles, to derive values of \( \varepsilon \) to interpret till thickness, water content and causes of signal loss.

The till of New Hampshire has amenable and adverse characteristics necessary for GPR penetration to at least 10-m depth. The lodgment, or basal till, is a low permeability (15-30% porosity), over-consolidated sediment with grain sizes mainly from fine silt to boulders greater than 3 m in dimension. The overriding ablation till is likely similar, but less dense. Preliminary 150 MHz GPR profiles for this study (Arcone and Pfeffer, 2012) found an example of till for which \( \varepsilon = 18 \) was determined from the hyperbolic signatures of profile diffractions, yet up to 10 m of signal penetration was achieved. Given the likely low porosity, this \( \varepsilon \) value suggested saturation. On the positive side then, the likely low conductivity of the till (Arcone and Delaney, 1980), general absence of clay-sized particles and mineralogy, low conductivity of the ground water, as evidenced by that of its lakes (Arcone et al., 2010), and the generally felsic mineralogy of the sediments given that of the parent bedrock might be factors that could allow more than 10-m penetration in some areas. In addition, thousands of examples of exposed bedrock throughout the state are smooth, which, coupled with their relatively lower permittivity (5–8), suggest good bedrock reflectance. On the negative side, the high permittivity contrasts between scatterers such as boulders and the nearly saturated till matrix, and the resulting in situ contrasts, from hyperbola matching of diffractions within and beyond the cost of this work.

We interpret the presence of till and the till-bedrock transition from the diffraction and reflection attributes of the profiles. We generally assume that till lay directly on bedrock; we have little well log ground truth. We interpret water content and till depth mainly from our indirect measurements of effective \( \varepsilon \) obtained from hyperbola matching of diffractions within and beneath the till. We interpret volumetric water content, \( \theta \), using the simple CRIM mixing formula (Shutko and Reutov, 1982; Arcone and Boitnott, 2012) for effective refractive index \( (n = \sqrt{\varepsilon} ) \) and assumed values for the mineral portion. We estimate volumetric scattering loss from differences between estimated dynamic range and the sum of losses from geometric beam spreading, sediment \( \sigma \), and free water relaxation, as have others (Grimm et al., 2006; Boisson et al., 2011; Harbi and McMechan, 2012). We assume that the wide size variety
within partially buried boulders at the surface indicates subsurface conditions.

Previous GPR studies of sediments within bandwidths centered from 50–150 MHz have recorded horizons less than about 20 m deep in unfrozen alluvium (Baker and Jol, 2007; Beres et al., 1995; Smith and Jol, 1995), while greater depths have been recorded in desert sands near 30 MHz (Francke, 2012) and in frozen formations at 40–50 MHz (Arcone et al., 1998; Arcone et al., 2002). In random media, GPR profiles have been discussed for low permittivity tuff (Grimm et al., 2006) and frozen aeolian silts (Boisson et al., 2011), but at frequencies below 100 MHz in which the pulse resolution was insufficient to discern more than a few diffractions. Here we have the advantage of many interpretable diffractions and in a few cases, bedrock diffraction horizons from which to determine depths.

**Till and Colluvial Diamict**

Till and its genesis have been the subject of conferences and symposia (Evenson et al., 1983; Goldthwait, 1971; Legget, 1976; van der Meer, 1987). Glacial till, or “drift,” implies an unstratified to partially stratified mixture of grain sizes and lithology. Stratification can be caused by post depositional working, such as basal freeze-on, post glacial flow, slumping or solifluxion. Grain sizes in till extend from clay to boulders more than 3 m in size. Commonly in New Hampshire, ablation till (looser sediment released during ice sheet ablation) resides over denser and harder basal, or lodgment till (Drake, 1971), the latter having been highly compacted beneath an ice sheet to less than about 30% porosity. Bedrock is generally beneath till, but glaciofluvial sediments may also be present (Thompson et al., 1999). In immature till with igneous lithology such as in New Hampshire, there is often a bimodal grain-size distribution (Dreimanis and Vagners, 1971); e.g., boulders embedded in a silt matrix. We show strong evidence for boulder-rich sediments beneath our profiles (Appendix Fig. A1). New Hampshire till may contain assemblages of close boulders in contact, zones of clays and silts, variable water content, and variable mineralogy, especially if feldspars and micas have weathered to clay minerals. Quartz and feldspar are predominant within the clay-sized fractions (Drake, 1971) and therefore, for the coarser sizes, as well. Based on studies in New York State (Gross and Moran, 1971; Holmes, 1952), the likely bedrock sources for the tills we profiled are the same granitic bedrock north of our transects because this rock type extends several kilometers in the northerly direction of up glacier flow, as is well documented for tills and moraines in the Bethlehem-Littleton, NH area (Thompson et al., 1999).

Colluvium is defined as loose sediment, meaning dry densities probably no more than 1,500 kg m$^{-3}$, and the product of downslope processes such as landslides. A diamict is poorly sorted sediment of any origin and so till is a glacial diamict. If the colluvial source is till, then the resulting formation may be described as a colluvial diamict or a flow till. Surface and near-surface (partial burial) evidence shows that the colluvium we discuss is likely till reworked by downslope processes and containing massive boulders (Appendix Fig. A1). We present evidence that the density we encountered is significantly higher than 1,500 kg m$^{-3}$.

In general, diamicts are not ergodic and stationary random media because the texture and water content of samples may vary in space and time. Scattering theories (Sato et al., 2012) and some forms of single-scatterer modeling (Takahashi et al., 2011) based on simplifying statistical assumptions (stationary; well-mixed; single correlation lengths; fixed scatterer sizes relative to a wavelength) may not apply. As found by Hackert and Parra (2003) for ultrasonic propagation in porous carbonates, theoretical predictions of the dependence of attenuation upon frequency may not occur. However, despite the meter-sized in situ wavelengths (0.2–0.5 m) we used in relation to the likely wide range of grain sizes (up to several meters) encountered, the penetration achieved in our preliminary studies (Arcone and Pfeffer, 2012) suggested that single-scattering in the Rayleigh to Mie regime (Takahashi et al., 2011; Liu et al., 2012) may be the case in our data.

**Methods**

We used a Geophysical Survey Systems, Inc. (GSSI) System SIR3000 with a Model 5106A (known as “200 MHz” antennas) and model 5103 (“400 MHz”) antenna units, and GSSI’s RADAN software for processing. We polarized the antennas perpendicular to the transect directions, towed them behind a vehicle that moved about 2 m s$^{-1}$, and marked our profiles every 50 m using hand-held GPS with 2–3 meter accuracy. We hand-towed the antenna unit along the trails over the colluvium, the distances of which were also marked with hand-held GPS.

The spectra of our received 1½ wavelength pulses were centered near 150–220 MHz and 300–350 MHz for the 5106A and 5103 units, respectively. Figure 1 shows several examples, the shape and frequency contents of which are initially slightly lowered by ground coupling, and then altered by reflection, diffraction or propagation. The modeled pulses in Fig. 1 show that waveforms reflected from electrically thin layers (e.g., lower $\varepsilon$ material embedded in higher $\varepsilon$ matrix) retain the phase polarity structure of a pulse reflected from a half space.
We recorded our profiles using a wide bandwidth IIR (infinite impulse response) filter. Our post-processing included an FIR (finite impulse response) band-pass filter (e.g., 100–250 MHz for the 5106A unit) to reduce background noise, automatic gain control (AGC), horizontal low-pass filtering (background removal) and amplification. We display our profiles mostly in a non-linear grey-scale intensity format to reveal the diffraction nature of till responses, which is important to our arguments regarding distinction of till from bedrock. We also demonstrate that high values of ε reasonably migrated diffractions. Regardless of material heterogeneity, not all diffractions can be expected to migrate well in a single-layer migration, because some will originate from out-of-plane, and some will actually be near-surface guided events (Arcone et al., 2003).

We calibrated depth from the recorded time using the simple equation:

$$ d = c t / \sqrt{\varepsilon}, \quad (1) $$

where $c = 3 \times 10^8 \text{ m s}^{-1}$. The values for ε in till were determined by matching diffractions with model hyperbolae using RADAN software, and which we corroborated with moveout profiles. The diffractions we chose were the steepest and for which the peak was obvious; diffractions originating outside the transect plane give falsely low values of ε. The matching hyperbolae for the many diffractions within till gave $17 < \varepsilon < 27$, with $\varepsilon = 19–21$ being most common; we round our values to the nearest whole number. The accuracy within the matching procedure is about 14% for ε, but ε is based on the square of the velocity, the matching accuracy of which was no worse than 6.3%. In addition, we estimate our 50 m location marks to have been accurate to about 3%, which could add a 6% error to our velocity calculations within any one 50 m segment. Consequently, the maximum error in determining velocity could be about 12%, and about 20% for ε. Therefore, material characterized by $\varepsilon = 19$ could have ε range from 15 to 23.

We supplemented the reflection profiles with moveout profiles and dipole-dipole resistivity surveys. The moveout profiles used the transmitter antenna of one “200 MHz” antenna unit and the receiver antenna of another, with the latter being moved away to record direct and indirect ground waves (Arcone and Liu, 2012), from which ε values for the subsurface material can be derived from their phase speeds. We used an AGI model SuperSting 8R/IP control unit and 84 electrodes spaced either 1 or 2 m apart for our resistivity surveys. Software supplied by the manufacturer processed the data to provide a general apparent resistivity section of the upper 10 or 20 m, for the 1- and 2-m spacings, respectively.

**Results: Till, Bedrock, and Transitions**

We discuss several examples of till, bedrock, and the transitions between them. We provide profile migrations to verify our calculations of ε and of the transitions. We do not provide elevation corrections because stratigraphic orientation is not relevant to this paper, and because the vertical compression required for display obliterates important features; the depth scales often correspond with the scale of elevation change along the profile lengths. We refer to the profiles recorded with the 200-MHz antenna unit as “160-MHz profiles” and those with the 400-MHz unit as “330-MHz profiles” because these frequencies are close to the center of most pulse spectra. We use indirect evidence of surface photographs and previous observations to characterize the likely conditions of the subsurface sediments because there are no gravel pits near our profiles for observation. Most profile lengths are 130–200 m long, which facilitates comparisons between them.
Our till sites are between Lyme and Canaan, NH, and within Enfield and Randolph, NH (Fig. 2). The surficial geology at these sites is Wisconsin-age till (Goldthwaite et al., 1951; Fowler, 2010). The Grafton Turnpike gravel road transect runs for 12.6 km from the Dartmouth Skiway in Lyme Center, NH, to Codfish Hill Road in Canaan, NH. The bedrock is mostly a fine to medium-grained late Ordovician biotite granite to granodiorite (Og) except within the dashed enclosure where it is Ordovician metamorphosed volcanics (Ov; mainly amphibolites). The bedrock beneath Randolph Hill Road is Devonian granite (Dg).

The transect along May St. in Enfield, NH, originates near an abandoned quarry and ends in downtown Enfield. The bedrock is the same granodiorite. The Randolph transect was along the lower 1 km of the newly paved, Randolph Hill Road. The segment we discuss travels north to south and ends at state Highway 2. The bedrock is mapped as a medium to coarse-grained Devonian two-mica granite (Lyons et al., 1997; Dykstra, 2010). Three well logs near this lower section obtained from the Town of Randolph, NH, show no bedrock within 50-m depth. Consequently, we have no way of verifying if till actually was in contact with bedrock.

**Locations**

Goldthwaite et al.: GPR Profiles of Glacial Till

**Figure 2.** Till transects along a) Grafton Turnpike Road in Canaan, NH, b) May St. in nearby Enfield, NH, and c) Randolph Hill Road in Randolph, NH, superimposed on Google Earth images. The black arrows locate segments discussed. The white arrows are the entire transects. The bedrock beneath the traverses in (a, b) is Ordovician biotite granite to granodiorite (Og) except within the dashed enclosure where it is Ordovician metamorphosed volcanics (Ov; mainly amphibolites). The bedrock beneath Randolph Hill Road is Devonian granite (Dg).
Arcone (1984) recorded GPR reflection and moveout profiles over a nearby granodiorite exposure in Enfield, and from which he calculated $e = 6.1$. Parkhomenko (1967) gives $e = 4.9–5.8$ for hornblende and $e = 7.9–8.9$ for amphibolites. Below we find $7 < e < 11$ for the volcanics. An $e$ value for the Devonian granite is not known, but likely between 5 and 7 because it is light colored and acidic. We calculated $17 < e < 27$ for the till from diffractions within the profiles, with most values at 19.

**Bedrock**

The profiles we discuss provide reference features to help distinguish bedrock because there was minimal interference from an overburden. We recorded the unmigrated profiles in Figs. 3 and 4 where bedrock was near the surface and sometimes visible within or along the side of the road. Figure 3 shows 160- and 330-MHz profiles of a segment over the granodiorite along May St. The depth scale is calibrated using $e = 6.1$. Both profiles show a nearly continuous upper surface of the granite, but between 1,125 and 1,140 m distance this horizon degrades into diffractions at 330 MHz. The maximum depth of events, seen at greater depths than shown here, indicates 8 dB difference between 148 and 296 MHz signals. Consistently, the manufacturer-rated 8 W of 200-MHz unit radiated power is 9 dB greater than the 1 W of the 400-MHz unit.

Both profiles in Fig. 3 show well-developed and near horizontal sheet-fracture horizons as long as 40 m. Similar, but less extensive fractures were recorded in the two-mica granite on upper Randolph Road (Arcone and Pfeffer, 2012). Most of the fractures between 1,140 and 1,180 m are similar to each other in form, which, obviously, cannot be caused by local changes in velocity. The 330-MHz profile shows at least 11 horizons beneath the 1,170-m mark. The accompanying traces, extracted from the 1,144 m distance, show the $+ - +$ wavelet polarity sequence (likely caused by water), as discussed for Fig. 1. Although not apparent in the trace because of the amplification, the granite surface horizon has a $- + -$ structure. Also present are dipping sections of the sheet-fracture horizons (below 100 m at 15-m depth), and horizons that cross the sheet fractures (from 45 to 60 m).
Both profiles in Fig. 3 also show distinct diffractions with well-developed asymptotes, such as from 1,070 to 1,100 m and from 1,150 to 1,190 m. Those that originate near the surface do not necessarily provide an $\varepsilon = 6.1$ because they indicate near-surface propagation within the till. For example, the diffraction indicated by the broken arrow in Fig. 3(a) gives $\varepsilon = 18$. Close examination of the asymptotes reveals that they are shingled (leading half-cycles continually fade with distance), which means these events are dispersing within a thin (less than an in situ half wavelength thick; about 0.4 m at 160 MHz), slow velocity layer (Arcone et al., 2003; van der Kruk et al., 2007). This $\varepsilon$ value gives about 1.4 m for the thickest till, near the 1,125-m distance.

Figure 4 shows an unmigrated profile segment recorded along Grafton Turnpike where volcanics were near the surface. The depth calibration is based on subtle, but well-developed diffractions centered near 7,990-m distance that give $\varepsilon = 8.4$. There are many reflection horizons, but none have the repetitive sheet-fracture response of the granite, but seen later (Fig. 11(b)). As in the granodiorite, the horizons are mainly thin layer responses to fractures. The penetration depth of at least 25 meters shows that this rock type is a low loss medium similar to the granodiorite.

**Till**

Figures 5 and 6 give 160-MHz profiles of till without any apparent bedrock horizon. Consequently, the till may reside on other types of sediments or grade into a more weathered regime with smaller heterogeneities. Figures 5(a)–(b) shows unmigrated and migrated versions, respectively, of a 150-m long segment recorded over the Grafton Turnpike volcanics. The till is characterized by a dense distribution of diffractions with limited asymptotes; we count about 20 to 25 diffraction peaks over a depth interval of 2 m and a distance of 10 m. The likely cause of these diffractions are boulders (Appendix Fig. A1(a)) because there are many wavelets with the proper phase polarity sequence, as seen in the 6,523-m distance trace of Fig. 5(a), but high water content pockets are also a likely cause, as seen in the inserted trace from 6,549-m distance. Many diffractions correspond with an $\varepsilon = 19$, which collapsed them well (compare images within the dashed boxes), reveals some stratification within the till, and a minimum 4 m for till depth. A very high rate of stacking (201 fold) found a noise floor occurred at 5-m depth (discussed later), which shows that the till extinguished the signals, and not any underlying sediments. A moveout profile (Fig. A2(a)) confirms this value of $\varepsilon$. The migration is not perfect because many short steep asymptotes remain. This limited till depth and appearance of dense diffractions continued for 1.5 km (5.32–6.72 km) along a gentle slope, which argues for the dielectric uniformity of till composition within this depth at this site. A dipole-dipole resistivity survey (Appendix Fig. A4(a)) performed with electrodes spaced 1 m from 6.490 to 6.574 km found $\sigma$ no greater than 0.005 S m$^{-1}$ to a depth of 5 m.

Figures 6(a)–(b) shows unmigrated and migrated versions, respectively, of our 160-MHz profile in Randolph, NH, previously discussed by Arcone and
In contrast with Grafton Turnpike, the unmigrated section does not show a uniform distribution of dense diffractions with limited asymptotes, but clusters of diffractions, and some with long enough asymptotes to calculate a value of \( e \). The vertically aligned clusters near 845, 867, 880, 895 and 990 m suggest resonance within large objects. Such resonance is false evidence of penetration, but deeper and isolated events occur, such as within the circle. There is no indication of stratigraphy. The migration of Fig. 6(b) used \( e = 19 \), which was the lowest value before diffraction hyperbolas showed improper migration. We recorded a profile during the following February and found \( e = 19 \). For the migration we used AGC and a linear amplitude line intensity format to avoid showing the faint air waves that remain after migration. The lack of strong events within the top 2–2.5 m is not an artifact of the AGC, but instead may indicate a layer of fine-grained till above boulder till.

The waveforms of many events in Fig. 6, such as the isolated deep event in the circles, show a characteristic \(- + -\) polarity signature, which is consistent with a relatively lower \( e \) (e.g., 5–8 for granite) target. The insets show its signal waveform before and after migration, the center frequency of which is near 150 MHz. A large granite boulder, such as the ones seen in Appendix Fig. A1(b), are the likely cause. This isolated, 10-m deep event appears to be an abbreviated half of a diffraction hyperbola. In Fig. 6(b), the tilted slopes of this and other migrated events suggest they were caused by a facet of a scatterer that plunges to the north (upglacier), in keeping with known predominant clast orientations in sheared till (Evenson, 1971). The event lasts about 3 m laterally from its peak, so that it was detected over an angular width of about 17°. The migrated trace shows a 13 dB signal-to-noise ratio for this deep event. Later we discuss the diagrammatic inset in Fig. 6(b) that depicts enhanced backscatter, a possible cause of such isolated events.

### Till-Bedrock Transition

Figures 7–11 show three examples of a till to bedrock transition. The unmigrated 160-MHz profile in Fig. 7(a) was recorded along the northerly granodiorite section of Grafton Turnpike. The profile shows the typical till response of dense diffractions with abbrevi-
ated asymptotes. We interpret the bounding horizon, defined by closely spaced diffractions, to be generated by bedrock contact because of the general waveform polarity, its intersection with the surface near 2,950 m, the well-developed asymptotes of its diffractions (revealed by AGC), and the internal horizons at 2,910–2,950 m. The diffraction asymptotes of the bedrock horizon are long enough to allow hyperbola matching to determine \( \varepsilon = 19 \), which produced the reasonable migration in Fig. 7(b). Some diffractions that originate beneath the bedrock horizon in Fig. 7(a) are multiples of the diffractions that appear at the bedrock horizon. The migration did not include AGC, and performed best for the diffractions on the right side of the profile.

Figure 8(a) shows an unmigrated 160-MHz profile recorded along Grafton Turnpike above a discontinuous granite horizon; Figs. 8(b) and 9 show details of the till and of the bedrock contact, respectively. Bedrock is near the surface at 2,310 m. Both profiles of Fig. 8 reveal some stratification in the till; the horizons less than 0.5-m depth are likely the result of road construction and maintenance. Figure 8(b) shows 330-MHz till penetration was limited to 3 m, which implies strong scattering loss, which is discussed later. Given these many horizons, we interpret the brightest (labeled with numbers) to be bedrock because dense diffractions occur above them and only a few below them, the wavelet phase is correct (e.g., waveform at left in Fig. 8(a)) and the \#4 segment horizon leads to the surface. The diffractions along the bedrock horizons give \( \varepsilon = 19 \), and therefore, a thickest till of 7 m at 2,190-m distance. The bedrock transition from segment 1 to segment 2 is clearer in Fig. 9, where the migration and decrease in vertical exaggeration reveal a bifurcation in the bedrock horizon and continuity between bedrock horizon segments \#1 and \#2.

Figure 10 shows a 160-MHz profile in which diffractions make it difficult to interpret any bedrock interface. The profile was recorded over the volcanics along Grafton Turnpike, and the transition is not clear.

Figure 6. a) Unmigrated 160-MHz profile segment from lower Randolph Hill Road, showing diffractions, no stratigraphy, and no bedrock, and b) migration with \( \varepsilon = 18 \), obtained from the diffractions within the boxed area. Within a depth interval of 5 m (dashed box), there are about 45–50 visible diffractions per 40 meter length. The waveform inserts were extracted from the circled, deep event. The diagrammatic insert depicts enhanced backscatter caused by constructive interference along two equal, but opposite ray paths, and which may explain this event.
from 6,700–6,750 m and from 6,800–6,850 m. The bedrock fracture horizons are the deepest we recorded in terms of time delay; we low-pass filtered the detail in the boxed portion to make them more visible. The depth scale is calibrated for the bedrock, which appears to reach the surface at right, as seen more clearly in Fig. 11. The fracture wavelet structure is generally $+ - +$ (black-white-black), but it varies so the fractures may be partly empty.

The detail in Fig. 11(a) reveals the confusing diffraction nature of the bedrock horizon, and Fig. 11(b) shows its migration using $\epsilon = 19$, after low-pass filtering (100 MHz, 2nd order FIR) to alleviate migration noise. The migration shows that the till is no more than about 3-m thick. The white arrows indicate the horizons we interpret to be the bedrock surface because they appear over sequential subbottom horizons at 6,720 m and after 6,830 m (within the ovals), and so are likely sheet fractures.

**Results: Colluvial Diamict and/or Till**

**King Ravine**

Our main colluvial site (Fig. 12) is near state Rte. 2 at the base of King Ravine in Randolph, NH, on the north side of the Presidential Range. Transect KR1 is along a power line access trail and KR2 is on the start of the Air Line Trail. They are above Ammonoosuc volcanics and biotite quartz monzonite (Dykstra, 2010). The colluvial diamict (Fowler, 2010) is likely reworked till (Bradley, 1981, 1982; Waitt and Thompson, 1988; Fowler, 2010) of mostly metamorphic rock origin, with some stratification observed near the start of our profile (B. Fowler, pers. comm., 2012). Fowler’s mapping, translated to the Google Earth image in Fig. 12, suggests that it is the result of a landslide. The partially buried boulders that litter the surface along the transect (Appendix Fig. A1(c)) are the quartz-mica schist of the Presidential Range to the south; hence they are evidence that the sediments are from landslides or slower flow. We assume that these boulders persist to at least 20-m depth, based on our profiles. There is no evidence here of a terminal moraine, as there is in the Bethlehem-Littleton, NH area to the west (Thompson et al., 1999), and so the many surface boulders seen in the area are not likely to have been dumped by a receding ice sheet.

Figures 13(a)–(b) show unmigrated profile segments from KR1 and KR2, respectively. The profiles begin within 20 m of each other and at the point where
we began the moveout profile seen in Fig. A3(a). The moveout profile along KR2 began at the 180-m distance. The slopes of the direct ground waves within these moveout profiles gives $\varepsilon = 10$ and $9$, for KR1 and KR2, respectively, and which we used for the depth calibrations of the reflection profiles. Both profiles show distinct, intermittent stratification consisting of horizons up to 10-m long. There are only a few visible diffractions and no apparent diffraction asymptotes that originate within the sediment. However, in KR1 faint diffraction asymptotes that originate from events near the surface give $\varepsilon = 10$, as found from the moveout profile. These events are therefore, ground waves. The signals fade after 20-m depth, and the deepest event is at about 24-m depth. The resistivity profile of Fig. A4(c) shows values of $\sigma < 0.0001 \text{ S m}^{-1}$.

Jefferson Notch Road: Till and Possible Colluvial Diamict

Our second northern site was along Jefferson Notch Road (Fig. 14), which runs for 13 km from Rte. 2 in the north to the Cog Railway access road to the south. We discuss 750 m of this road along which we crossed Jefferson Brook from 200–210 m, and then turned sharply to the southwest and traveled along a flat straight section that parallels the brook. The bedrock is mapped as the same medium to coarse-grained Devo-
nian two-mica granite (Dykstra, 2010) beneath the Randolph Hill Road transect. Large granite boulders are in Jefferson Brook (Appendix Fig. A1(d)). Fowler (2010) mapped the surficial geology of this area as late Wisconsin till, as he does beneath Randolph Hill Road. The transect starts 1-km downslope from the well-known Ridge of the Caps (Fig. 14), the sediments of which are mapped as colluvial diamict (Fowler, 2010).

In Fig. 15(a), we first show a greatly condensed (stacked) and contrast-enhanced version of the 750-m profile, which reveals the change in depth penetration after crossing the brook. Above the brook, diffractions within the first 140 m give $15 < \varepsilon < 26$ (Fig. 15b). The depth scales in (a) and (b) are calibrated for $\varepsilon = 26$, which generates hyperbolas that match the clustered diffractions within the oval in Fig. 15(b), and the profiled depth is less than 6 m. Generally, the profile in Fig. 15(b) appears similar to that for the till beneath Randolph Hill Road in Fig. 6(a). The vertical alignment of diffractions above the arrow in Fig. 15(b) may indicate multiple reflections within a single object, as also seen in Fig. 6(a).

Below the brook, after 220-m distance, the unmigrated 130-m-long segment (Fig. 15(c)) also shows diffractions with brief asymptotes, many of which can be matched with model diffraction hyperbolas generated using $\varepsilon = 12$, as do two moveout profiles (one of which we show in Appendix Fig. A1(b)). However, the short reflection horizons lasting a few meters, the highly resistive sediments (Appendix Fig. A4(b)), the profiled depth of greater than 20 m, and the evidence for large subsurface boulders are so similar to our findings in King Ravine that this till may also be a colluvial diamict. The inset trace segments in Fig. 15(c) show coherent events with both type of phase polarity sequences at 20–21 m depth.

**Discussion**

**Water Content**

The $17 < \varepsilon < 27$ values obtained for the till allow the volumetric water content to be estimated by using the complex refractive index method (CRIM, Shutko and Reutov, 1982; Arcone and Boitnott, 2012), which relates the volumetric percentages, $\theta$, and $\varepsilon$ values of air, mineral and water to their effective value, $n_e$. Using only the real part of the generally complex quantity, $\varepsilon$, the formula is simply:

$$n_e = \theta_m n_m + \theta_w n_w + \theta_a n_a,$$

where $n = \sqrt{\varepsilon}$ for the individual components and $m$, $w$ and $a$ stand for mineral matter, water and air, respectively.

For the till, we assume a minimum $\theta_m = 0.7$, an $\varepsilon_w = 84$ for cold water at depth, and negligible adsorbed water in these likely overconsolidated, silty and quartz-rich (Haldorsen, 1983) tills; $\theta_m$ likely varies from 0.72 to

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**Figure 10.** 160-MHz profile of till over metamorphosed volcanics along Grafton Turnpike. The profile shows an unclear bedrock interface and a relatively deep fracture; the detail in the boxed portion was low-pass filtered to make the horizon more visible. The depth scale is for $\varepsilon = 8.4$, and may best apply to the right side where bedrock appears to reach the surface at right, as better seen in the next figure.
0.85 (e.g., Milligan, 1976). We use an effective $n_m \cong 2.3$ ($\varepsilon = 5.3$) for the dirt matrix of mostly quartz ($\varepsilon = 4.5$), feldspar ($5.7 < \varepsilon < 7.0$) and mica ($6.8 < \varepsilon < 9$) (Carmichael, 1989; Parkhomenko, 1967). This value of $n_m$ can be arrived at by assuming 60% quartz and median $\varepsilon$ values for 20% feldspar and 20% biotite to muscovite mica. Pure quartz would give a minimum $n_e = 2.1$, while an equal mix of biotite and muscovite, an extreme condition for schist, would give a maximum $n_e = 2.8$. For $n_e = 2.3$, $\theta_m = 0.3$, which means 100% saturation and an effective $\varepsilon_m = 19$, which agrees with most of our measurements and our moveout profile.

For the colluvial diamict, the range $9 < \varepsilon < 12$ is above that of granite (5–8) and likely of schist, as well, which means that water has contributed to its value. The extremely high resistivity values for the diamict (Fig. A3) suggest that there are insignificant conductive pathways through the sediments and that the water content is low and dispersed. There are two possible ways $\varepsilon$ could be this high: 1) moderate density and water content; and 2) high density and low water content. A possible moderate density of 1,500 kg m$^{-3}$ translates to a $\theta_m = 0.56$ and a porosity of 0.44 given an average mineral density of 2,700 kg m$^{-3}$. For case (1), an estimated $n_m = 2.5$ for the granite in Jefferson Notch and $n_m = 2.7$ for the quartz-mica schist mineralogy (J.E. Dykstra, personal communication, 2012) in King Ravine give $\theta_m = 0.21$ for $\varepsilon = 12$ and $\theta_m = 0.13$ for $\varepsilon = 9$, respectively. These $\theta_m$ values are unacceptably high for such resistive sediments. Consequently, the values of $\varepsilon$ must be caused by case (2), high sediment density. For example, $\theta_m = 0.85$ (not unusual for till) gives $\theta_m = 0.12$ at Jefferson Notch Road and only 0.04 at King Ravine.

### Scattering: General Considerations

The number of visible diffraction events within the till vary from 20–25 over a 20-m$^2$ depth interval (Fig. 5) to a less dense, but still significant 45–50 in an 200-m$^2$ interval (Fig. 6). In the former case, each event occupies about 1 m$^2$ of depth interval, while in the latter it is about 4.0 m$^2$. When visible within the traces, the scattered waveforms show both types of phase polarity sequences, so that heterogeneity likely originated from both high and low $\varepsilon$ perturbations relative to the bulk
values we derived. Consequently, the \( 17 < \varepsilon < 27 \) in till and the likely values of either boulders (\( \varepsilon = 6-8 \)) or pockets of saturated silts (\( \varepsilon = 36 \)), show that the till is characterized by a background \( \varepsilon \) with strong perturbations that are widely-spaced compared to the in situ 160-MHz wavelength of 0.4 m at a typical \( \varepsilon = 19 \).

The short asymptotes of the till diffractions and their virtual nonexistence in the colluvium profiles imply very little off-axis or out-of-plane backscatter, i.e., most scatter received was directed vertically forward and backward. For \( \varepsilon = 19 \) and using the procedures in Arcone (1995), we calculated 3-dB round-trip radar beamwidths of \( \pm 35^\circ \) in the line of transect (within the magnetic field plane) and \( \pm 25^\circ \) across the line of transect (within the electric field plane), which would have further confined any energy received to the vertical direction. The asymptotes seen at depth in the colluvium actually persist to the surface and are characteristic of surface propagation.

**Signal Loss and Volume Scattering: Grafton Turnpike Till**

We estimate volumetric scattering loss in the Grafton Turnpike till of Fig. 5 based on general considerations of dynamic range, and measurements of \( \varepsilon \) and \( \sigma \). The maximum possible available dynamic range within any one scan is 90 dB because of the 15-bit data (one bit for sign). Following Grimm *et al.* (2006) and Boisson *et al.* (2011), we used a long (201 traces, or, 25 m) horizontal low-pass filter to remove background...
clutter (in particular, the direct coupling), rectifying the signals, removing the random noise with a high rate of stacking (201-fold to give 23 dB noise suppression) and removing the applied range gain, to provide just a few traces from which to estimate the average total range of signal strength. From five remaining traces, this approach provided an average of 85 ± 2.5 dB from a peak value near 0.6 ± 0.1 m depth to the noise floor at 5.2 ± 0.1 m depth for five traces (reduced from 1,200). The depth of 1 m is near the far-field range (1.1 m) of these electrically short antennas (0.44 m dipoles), especially within this dielectric medium. We then subtracted losses from geometric spreading, and those estimated from dielectric and conductive processes to arrive at a volume-scattering amplitude decay rate.

Signal absorption in till and colluvium may be caused by Maxwell-Wagner and water relaxations, and induced conduction currents. Maxwell-Wagner relaxation is doubtful in the till because the near saturation conditions would limit the formation of spatially discrete and strong macro-dipole moments. For water relaxation, the Debye frequency occurs at 9–20 GHz from 0–25°C, respectively. Assuming a ground temperature of 10°C in summer, the relaxation frequency is about 13 GHz and the one-way attenuation rate at 160 MHz in pure water is only 1.5 dB m⁻¹. For θᵦ = 30%, we estimate that the one-way absorption rate caused by free water in saturated soil is about one third of this rate, which is 0.5 dB m⁻¹. Therefore, we estimate that water caused only 4 dB of round-trip signal absorption after the 4 m of penetration indicated by the deepest diffraction peak visible in the Grafton Turnpike till (Fig. 5(b)).

The loss caused by a maximum σ = 0.005 S m⁻¹ (Appendix Fig. A3(a)) can be calculated using the well known formula for two-way attenuation rate:

$$\beta (\text{dB m}^{-1}) = 8.686\sigma / (c/\sqrt{\varepsilon \varepsilon_o}),$$  \(3\)

where c is the speed of light and \(\varepsilon_0 = 8.854 \times 10^{-12}\) Farad/m, in a low loss-tangent dielectric. In this case...
Figure 14. Transect (arrow) along the southerly portion of Jefferson Notch Road (dirt) just west of the Presidential Range. The map and nomenclature are extracted from the larger, regional map of Fowler (2010). The road parallels Jefferson Brook below the bridge. Qt denotes till and the colluvium is within the unit labeled Qdl, within the topographic feature labeled “Ridge of the Caps.”

\[ \beta = 3.8 \text{ dB m}^{-1} \], giving 15 dB conductive round-trip loss at a range \( R = 4 \text{ m} \). Adding 4 dB for water relaxation loss and 24 dB (using the classic radar equation) of round-trip geometric spreading loss from a finite target at 4-m depth, based on the 1-m reference range, leaves 85–43 = 42 dB of estimated round-trip scattering loss in the Grafton Turnpike till and a rate of 5.3 dB m\(^{-1}\) for the 8-m round-trip. However, a maximum spherical target radius of 1 m, as observed for the granitic \((\varepsilon = 6)\) boulders on the surrounding terrain (and even less, as observed in stream cuts–Appendix Fig. A1), provides a radar cross section of \(-16 \text{ dB} (\pi a^2 \Gamma, \text{where } a \text{ is radius and } \Gamma \text{ is the power reflection coefficient})\) for the permittivity contrast between boulder and till, which leaves a round-trip scattering loss rate of at least 3.3 dB m\(^{-1}\). For \( \varepsilon = 19 \), the in situ 160-MHz wavelength \( \lambda \) (0.43 m) is \(<\ll\) than \( R \) and \( 2\pi a \).

In Fig. 8(a), we find 7-m penetration at 160 MHz in till, but barely 3-m penetration at 330 MHz (Fig. 8(b)). In Fig. 10, we find bedrock penetration for another 30 m (a resurvey found maximum penetration at 34 m) beneath 3 m of till, yet a 330-MHz profile (not shown) indicates no bedrock. This extra 30-m (from 3 m) penetration plus reflection from a water-filled fracture caused an extra 26 dB of round-trip loss. Even though the manufacturer-rated radiated power for the 330-MHz antenna unit is only 1 W, as opposed to the 8 W for the 200 MHz unit, the 9 dB difference is obviously not enough to account for this difference in performance and extra penetration to 34 m within the bedrock. Given that attenuation rates caused by conductive absorption at these pulse center frequencies are frequency independent (Eq. (3)), and the likely soil \( \sigma = 0.005 \text{ S m}^{-1} \), the extra loss at 330 MHz was caused by strong scattering. At \( \varepsilon = 19 \), the in situ 330-MHz wavelength is only 0.21 m, or half the length of the 160-MHz signals. Consequently, the smaller wavelengths may have been near the mean grain size and that Mie scattering occurred.

**Signal Loss and Volume Scattering: Colluvial Diamict**

In general, \( \sigma < 0.00017 \text{ S m}^{-1} \) for the Jefferson Notch Road and King Ravine sites (Fig. A3). These resistive sediments and the lack of conductive minerals (to make interstitial water more conductive–Arcone and Boitnott, 2012) such as carbonates and gypsum, preclude the likely existence of Maxwell-Wagner relaxations, and so attenuation is caused by scattering and water relaxation. At an estimated \( \theta_e = 0.12 \) along Jefferson Notch Road and following our above argument, a one-way attenuation rate of no more than 0.2 dB m\(^{-1}\) was likely caused by the water in the sediments. This provides a round-trip loss of 8 dB after 20 m penetration. Given 52 dB for two-way geometric spreading loss after scattering from a finite target at 20-m depth, and an estimated full dynamic range of 90 dB (signals were saturated), as determined using the procedures just mentioned, we estimate no more than 30 dB of scattering and target reflectivity two-way loss. A 1-m radius granite \((\varepsilon = 6)\) boulder (Appendix Fig. A1(d)) inside a \( \varepsilon = 12 \) colluvium matrix (giving an in situ 160 MHz \( \lambda = 0.5 \text{ m} \)-less than the target circumference and range) provides only a \(-11 \text{ dB} \) radar cross section because of the weak dielectric contrast. In this likely case, the two-way loss rate is 19 dB and the necessary one-way volumetric scattering loss rate to fill the dynamic range is then no less than 19 dB/40 m, or 0.5 dB m\(^{-1}\). This rate would be even less if our estimate of dynamic range is high.

If conductivity, relaxation and scattering had been significant across the pulse bandwidth, then they would likely have caused dispersion (spreading of the waveform caused by frequency dependent wave speed and attenuation). However, the dominant frequencies of almost all pulses received by the model 5106A antenna unit are centered from 160–180 MHz, which is mostly accounted for by transmitter antenna ground-loading (Arcone and Liu, 2012; Lampe and Holliger, 2005). Therefore, any significant local waveform dispersion likely resulted from propagation through concentrations of water in the till.
Enhanced Backscatter

The evidence in Fig. 6(a) that penetration might exceed 10 m in till suggests that some responses may have resulted from a phenomenon known as enhanced backscatter (Ishimaru, 1991). In this process, rays that propagated in opposite directions along the same preferred, low loss (and not necessarily perfectly vertical) round-trip path constructively interfere, as diagrammed in Fig. 6(b). The equality of the two path lengths precludes off-nadir diffraction asymptotes, and does not necessarily place the target beneath the antennas. The paths differ because intermediate inhomogeneities along the way are approached from different directions. Therefore, for this high ε matrix case, most inhomogeneities along the round-trip path were likely less than a wavelength in dimension.

The deep event in Fig. 6(b) shows about a 13 dB signal-to-noise ratio. Another 6 m of penetration would provide 4 dB more of geometric spreading loss, and, at a relatively low σ = 0.002 S m\(^{-1}\), an additional two-way loss of 9 dB (from Eq. (3)) to give 13 dB and a barely detectable signal. A more reasonable σ = 0.005 S m\(^{-1}\), as along Grafton Turnpike where ε was similar, would extinguish the signal after only 2 m, without consideration of scattering losses.

Conclusions

The important New England till characteristics are the felsic mineralogy and boulders, to which we add volumetric water contents likely at or near 100% saturation, and persisting to the bedrock horizon. The results of these characteristics are GPR profiles filled with diffractions. We see no strong evidence of a water table nor convincing evidence of an intra-till transition (ablation to basal), although the onset of diffractions at

Figure 15. a) Condensed and unmigrated 750-m long profile segment recorded along Jefferson Notch Road, b) unmigrated detail between 100 m and 140 m, and c) unmigrated 130-m section showing diffractions and reflection horizons lasting a few meters (block arrows). At 200–210 the transect crossed Jefferson Brook and traveled along a level road for 550 m (Fig. 14). The depth scales in (a, b) are calibrated for ε = 26 based on model hyperbolas that match the diffractions within the oval in (b). Two moveout profiles along the section in (c) gave ε = 12 and the resistivity profile spanned the entire length. The vertically aligned diffractions above the arrow in (b) may indicate multiple reflections within a single object. The inset traces in (c) show two different phase polarity events at 20–21 m depth. Likely boulders beneath this transect are seen in Appendix Fig. A1(d).
2–3 m depth along Randolph Hill Road (Fig. 6) does suggest this possibility. Nor was it always certain that till was in direct contact with bedrock; the 4-m deep till along Grafton Turnpike in Fig. 5 could be sitting on glaciofluvial sediments. Thus for a statewide survey of water resources, GPR surveys could be used to at least assess water content, given the abundant occurrence of diffractions, whether from bedrock or from within the till itself.

Although single and strong forward scattering appear to be present in some till because of penetration to 10 m and, alternatively, the limited length of the diffraction asymptotes, multiple scattering could also have occurred because of the limited penetration of about 4 m seen in Fig. 5. Our resistivity profiles and loss calculations suggest that volume scattering losses were significant. Therefore, GPR would not be reliable to consistently find a bedrock horizon. The limited penetration seen in Fig. 5, which lasted for 1.5 km, shows that GPR may only give a minimum depth for till.

The limited lengths of diffraction asymptotes could also have resulted from masking by stronger signals, which imply close and strong targets. Within a given length and depth, the countable number of diffractions within the profiles relative to the likely number of possible targets suggests that the profiles are dominated by the stronger scatterers. Large boulders likely comprise many targets; those we frequently observed are much larger than an in situ till wavelength. Our examples of resonance within till (Figs. 6(a) and 15(b)) suggest multiple scattering might occur within these large dielectric objects.

The colluvial diamict in King Ravine, and likely along Jefferson Notch Road, is characterized by short reflection horizons and a much lower rate of signal loss caused by scattering. This rate, along with a lower value of $\varepsilon$, is the main reason that this material is electromagnetically different from the till. The partial stratification suggests rhythmic deposition, as might occur from an outburst flood (Russell and Knudsen, 1999). The high density implied by our relatively low values of $\varepsilon$ contradicts the characteristic coarse-grained and medium density of a colluvial deposit, and so the King Ravine profiles confirm the diamict description of Fowler (2010).

Diffraction horizons comprised of wavelets with a consistent half-cycle polarity sequence commonly characterized the transition from till to bedrock. Where there was no obvious diffraction or reflection bedrock horizon, then the appearance of fracture horizons and well-developed diffraction asymptotes characterized the bedrock.

A major shortcoming of this investigation was the lack of direct sediment observation. Of primary interest would be distributions of till grain size to assess likely scattering cross sections, and measurements of density to assess porosity. Unfortunately, drilling often encounters large boulders, which make this exercise difficult. However, the consistent values of $\varepsilon$ and the consistent profile appearance of till within the profiles recorded along Grafton Turnpike show that in this particular case, dielectric homogeneity was present when averaged over the 3–7 m of till depth imaged. This does not necessarily imply physical homogeneity, as well, because the general fading of diffractions with depth in Fig. 5 may have been caused by a gradation into smaller boulders or weathering. Consequently, GPR surveys might be used to generalize a limited number of grain size, density and porosity measurements.

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References


Arcone, S.A., and Pfeffer, W.T., 2012, GPR profiles of partially to completely unstratified geologic formations:
Arcone et al.: GPR Profiles of Glacial Till


**APPENDIX**

**SUPPLEMENTARY INFORMATION**

We present supplementary and corroborating evidence of our interpretation of subsurface conditions in Figs. A1–A4. Figure A1 provides indirect evidence of large boulders within the till and colluvium. Figure A1(a) shows a cluster of boulders revealed in a stream cut near Grafton Turnpike Road. Figure A1(b) shows boulders gathered during construction of upper Randolph Road. Similar boulders are found near lower Randolph Hill Road. Figure A1(c) shows the surface conditions along transect KR2 in King Ravine. All boulders are partially buried. Surprisingly, this rough surface did not produce any visible air wave diffractions. Arcone and Pfeffer (2012) discuss a GPR profile recorded along the nearby and smooth Amphibrach

![Figure A1. Indirect evidence of subsurface conditions. a) Boulder cluster in stream cut along Grafton Turnpike; largest (arrow) is approximately 1-m long. b) Granite boulders excavated during construction of the upper section of Randolph Hill Road. Conduits in photo (arrow) are 0.9 m in diameter. c) Trail conditions looking north along transect KR in King Ravine, and showing partially buried quartz-mica schist boulders; largest at left (arrow) is approximately 3 m in length. Similar large boulders distributed along KR1 are now pushed aside for the power line. d) Boulders in Jefferson Brook, right next to our transect. The large one at left (arrow) is approximately 1.5-m long.](image-url)
Trail (incorrectly referred to in the paper as the Air Line Trail) just 600 m to the west, along which many ground wave diffractions occurred. Along KR1 similar sized boulders have been pushed aside for the power line. Figure A1(d) shows large boulders within a stream cut right next to Jefferson Notch Road. The photograph was taken from the bridge that crosses Jefferson Brook.

Figures A2 and A3 show most of the moveout profiles. Arcone and Liu (2012) explain many of the events within them. All profiles began with an antenna separation of 1 m and were limited by cable lengths to a maximum separation of 40 m. Figure A2(a) was recorded along Grafton Turnpike, with its placement indicated in Fig. 5. The profile shows both the direct air and ground waves, for which the slope of the latter (0.071 m/ns) gives $\varepsilon = 18$, nearly that (19) determined from the diffractions in Fig. 5. The ground wave event appears discontinuous, with a slightly greater slope between 6,537 m and 6,549 m. In (b) there is a direct and an indirect (reflected) ground wave, the latter of which is slightly dispersive and has an average slope (0.087 m/ns) that gives $\varepsilon = 12$. The direct wave starts with a slope corresponding to $\varepsilon = 5$, which, at 285 m, becomes faint and changes slope to $\varepsilon = 12$.

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Figure A2(b) shows one of two nearly identical moveout profiles recorded along the Jefferson Notch Road transect (started at 280 m and 340 m), and in which there is a direct and an indirect (reflected) ground wave, the latter of which is slightly dispersive and has an average slope (0.087 m/ns) that gives $\varepsilon = 12$. The dispersion (shingling) is not severe, with most phase fronts having the same general slope as the general wave packet. The direct wave starts with a slope corresponding to $\varepsilon = 5$, which becomes faint and changes slope to $\varepsilon = 12$ at 285 m. Although the attenuation rate of direct waves, with broadside antenna polarization, is determined by $1/R^2$, the attenuation is rapid and likely caused by large surface inhomogeneities such as boulders visible along the surface. In contrast, the many indirect ground waves, generated by subsurface reflections, attenuate as
\( R \), and confirm that 20 m round-trip penetration was possible in these sediments.

Figures A3(a)–(b) shows the moveout profiles we recorded at the start of KR1 and starting at the 180-m distance along KR2. The slopes (velocities) of the ground waves \((0.093 \text{ m/ns})\) give \(v = 10\) and \(9\) for KR1 and KR2, respectively. The former velocity agrees with those of the diffractions in the reflection profile of Fig. 13(a). The non-dispersive nature (minor shingling) of the ground wave events indicates that these values are not that of a surface high velocity layer.

Figure A4 shows the results of the dipole-dipole surveys, in the form of 2-D calculated and simplified apparent conductivity sections for (a) the Grafton Turnpike profile in Fig. 5 (1-m electrode spacing), (b) the Jefferson Notch Road profile in Fig. 15 (2-m electrode spacing) starting at the 220-m distance, and (c) transect KR1 (2-m electrode spacing) starting at 0 m (Fig. 14(a)). In (a) the maximum value within the top 5 m is \(\sigma = 0.005 \text{ S m}^{-1}\). Contact resistances for (a) and (b) were acceptable, but very high for (c).