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GROUND PENETRATING RADAR IN A HYDROGEOLOGICAL INVESTIGATION OF THE OAK RIDGES MORAINE, ONTARIO

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ABSTRACT

This paper presents a summary of the results obtained with Ground Penetrating Radar at three of the eleven sites surveyed during the summers of 1992 and 1993 as part of the hydrogeological investigation of the Oak Ridge Moraine. After topographic correction of the data, we were able to accurately determine the location of the water table. Areal surveys at the St. John and Bolton Farm sites allowed comprehension of changes in water table topography. In addition, we obtained substantial subsurface structural information which improves our understanding of sediment architecture and genesis. The data from the Brighton and Bolton Farm sites were acquired near aggregate quarries which allowed direct correlation between the radar records and the sedimentary exposure. The results presented here highlight the level of geological details detected by the GPR surveys. Even though further studies will be conducted in 1994 and 1995, we are already able to demonstrate that GPR is an excellent geophysical technique for geologic (textural and structural), and hydrogeologic studies in appropriately resistive surficial sediments.

INTRODUCTION

In 1993, the Geological Survey of Canada began two complementary three year programs to map the surface and sub-surface Quaternary geology and study the hydrogeology of the Oak Ridges Moraine (ORM) and environs (Fig. 1). The ORM is recognized as a significant local natural resource and is exploited for its aggregate and groundwater resources. As a consequence of its regional extent, it is a resource shared by over 3 million residents of the Greater Toronto Area. Previous hydrogeological studies (e.g., Sibul et al., 1977) have relied on limited borehole coverage for subsurface data, regarding both the structure of the ORM and the stratigraphy below it. As a consequence, regional planners have limited information pertaining to the extent, thickness, internal structure and groundwater flow patterns of the ORM. The lack of subsurface information within the ORM make it essential that geophysical surveys form a key part of the new hydrogeological investigations.

Applicable geophysical techniques (Table 1) for hydrogeological investigations in the ORM have been outlined by Pullen et al. (in press). These techniques can identify textural and structural contrasts, delimit sedimentary geometries, and image the water table. However, these techniques vary in terms of cost, speed, data continuity, record depth, textural, structural and geometric detail, and the

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optimum conducting material. As the ORM is a resistive aggregate deposit with a water table below relatively dry aggregates, the near-surface part of the feature is an ideal target for ground penetrating radar (GPR) surveys, where it is not capped by till. Previous work has identified a variety of hydrogeologic applications for GPR, including identification of, depth to, and lateral character of, the water table, minor water table surface inflections, perched water tables, sediment texture variations, sediment geometry, and postdepositional deformation structures (Beres and Haeni, 1991; van Overmeeren, 1993).

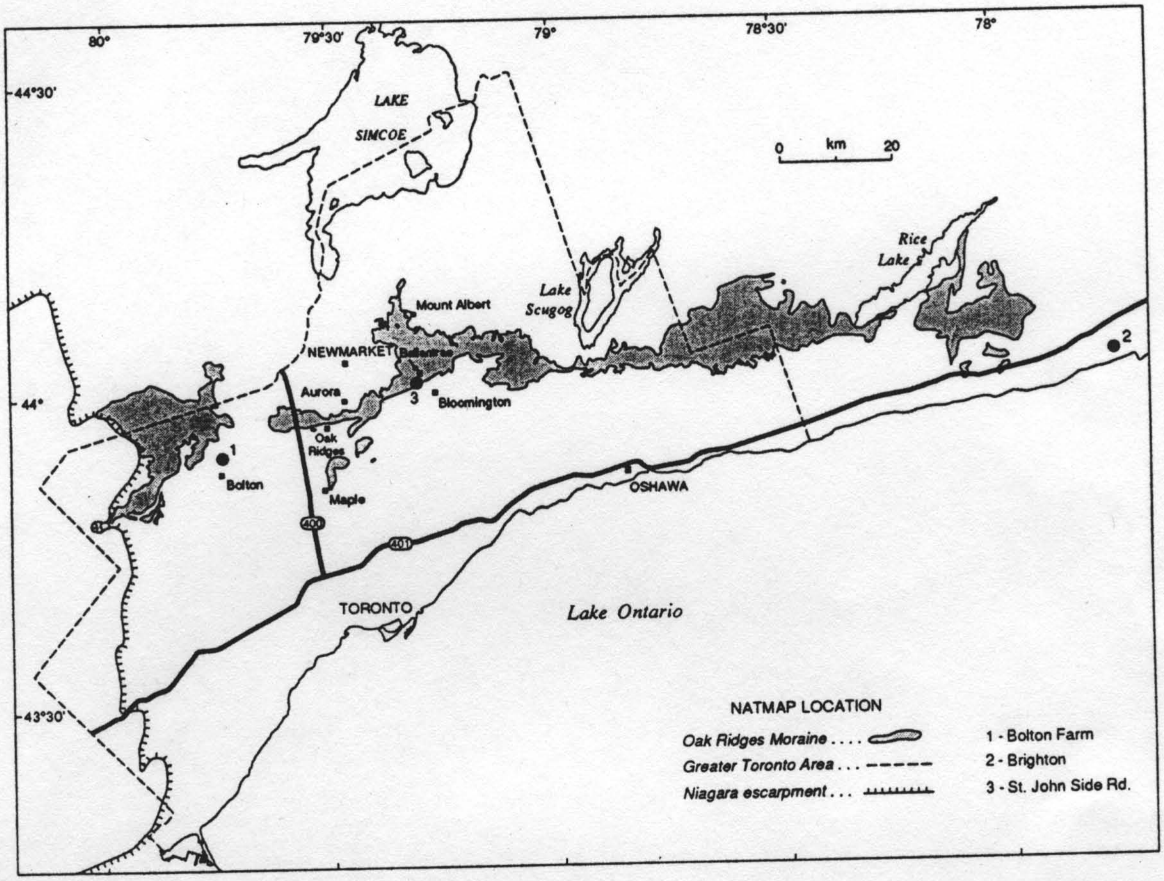

Figure 1. Location of three ground penetrating radar surveys in the Oak Ridges Moraine and environs.

Table 1. Attributes of geophysical techniques used for groundwater investigations

Technique	Survey Cost	Survey Time	Nature of Sediment	Continuity of Data	Depth Range (m)	Sediment Texture	Sediment Structure
GPR	Moderate	Fast	Resistive	Continuous	0.5-55	Yes	Yes
Shallow EM (EM-31-34)	Low	Fast	Resistive	Point	0-30	?	No
Deep TDEM (EM47)	Moderate	Moderate	Resistive	Point	20-200	?	No
Shallow Seismic Reflection Profiling	High	Slow	N/A	Continuous	20-200	No	Yes

In the summers of 1992 and 1993, GPR surveys were conducted at eleven sites in the ORM and environs. Here, we present a summary of the results obtained at three of those sites: Bolton Farm, Brighton, and St. John. Conducting GPR surveys adjacent to known sedimentary records allows verification of the reflectors, and their combination aids 3-D description of sedimentary structure and architecture. This paper highlights the geological detail detected by the GPR surveys and the identification and characterization of shallow (<50 m) water tables. Electromagnetic (EM) return facies descriptions follow the terminology of Beres and Haeni (1991).

GEOLOGICAL SETTING

The Oak Ridges Moraine (ORM; Fig. 1) forms the upper 100 m of a 200 m thick sedimentary sequence of Pleistocene age (Sharpe et al., in press). It comprises predominantly glaciofluvial and glaciolacustrine sand and gravel, capped locally by thin Halton drift along its southern flank.

Based on surface mapping, Ontario Geological Survey (OGS) borehole logs, and supported by new Geological Survey of Canada (GSC) geophysical data (Pullan et al., in press), the ORM appears to be floored by a stony, sandy to silty till, the Newmarket Till (Gwyn and DiLabio, 1973; Sharpe et al., in press). The character, extent and bulk properties of this till suggest that it is a regional aquitard significant to the hydrogeology of the ORM and environs. Geological investigations in the thick drift sequences, to the north, have revealed a network of southwest trending tunnel channels (e.g., Barnett, 1990) cut into the Newmarket till, and possibly underlying the ORM (Gorrell and Sharpe, in press; Barnett, 1993). Where the till is thin or absent due to channel erosion, enhanced or direct hydraulic connection of surface ORM aquifers to lower, older permeable beds may occur. Additional hydraulic connection may occur in this low-permeability till due to fractures (Howard, personal communication, 1993).

METHODOLOGY

Ground penetrating radar (GPR), as with other geophysical techniques, depends on contrasts between physical properties in the subsurface to generate a signal return. In the case of GPR, the dielectric constant and electrical resistivity of subsurface materials are particularly important.

The dielectric constant of the materials determines the propagation velocity and the reflection of the electromagnetic signal (Davis and Annan, 1989). Dry sand has a dielectric constant (K) of 3 to 5, and freshwater-saturated sand has a K of 20 to 30 (Pilon et al., 1992a; Davis and Annan, 1989). Therefore, for groundwater application, the contrast between unsaturated and saturated sediment results in a large dielectric contrast, and an imaging of the water table. For geological application (texture, structure, architecture), the EM signal responds to variation in moisture content in undersaturated sediment, reflecting variations in grain size (Sutinen et al., 1992).

The electrical resistivity of the material governs the attenuation of the EM signal and, thus, determines the depth that can be investigated with the GPR equipment (Davis and Annan, 1989). Ideally the resistivity should be at least 100 ohm m (van Overmeeren, 1993). In practice, this means that the overburden should be granular (sand and gravel) with a minimal amount of silt and clay. Trials on the ORM, for example, show signal loss below 1-3 m of silty to clayey Halton Till, where it caps thick sand and minor gravel.

The GPR profiles presented in this paper were obtained with a pulseEKKO IV GPR system using a 1000 volt transmitter and an antenna centre frequency of 50 MHz. The transmitter/receiver separation for the reflection surveys was 2 m with a station increment of 1 m. Experience has demonstrated that a stack of 64 pulses maximizes the signal to noise ratio and optimizes survey efficiency. The speed of propagation of the EM signal was measured at each location by conducting common mid point (CMP) surveys with station increments of 0.5 m. The calculated propagation speed was used to create the depth/elevation scales of the reflection profiles at each site. In places, depths were measured directly from adjacent pit exposures. Post-acquisition processing involved correction for relief (excluding Brighton) and application of an automatic gain control (AGC) factor with varying amount of high frequency filtering (point averaging of 5 to 8).

BOLTON FARM

This site is 3 km north of Bolton, at the Bolton sand and gravel pit, in an erosional depression within the Palgrave Moraine (White, 1973), on the southern flank of the Oak Ridges Moraine. Erosion of the surface Halton Till has exposed sands comprising the Oak Ridges and Palgrave Moraines. A total of 1650 m of GPR profiles, along five transects, were completed at three elevations: site I, a bench above the pit (~ 260 m asl), site II, the floor of an erosional gully (~ 235 m asl), site III, the pit floor (~ 220 m asl). The interpretation of these sections is based on pit exposures and field mapping.

Site I (Fig. 2) is situated 10 m back from a pit face exposing channelized and bedded medium sand to pebbly gravel. A good correlation was observed between the exposure and the topographically-corrected GPR record. This GPR profile records two EM return facies (Fig. 2). Near the surface a number of continuous, subhorizontal reflectors (F_1, Fig 2) are truncated by the bench floor. A second, deeper EM return facies is comprised of relatively continuous (~40 m), southerly-dipping reflectors with intervening, discontinuous, subhorizontal reflectors (F_2, Fig. 2). No water table was encountered in this transect, due to its proximity to a pit face and due to its elevated position.

At site II (Figs. 3 and 4A) three lines were completed at perpendicular and oblique angles, producing a three-dimensional perspective of the sediments. The depth of penetration in this area was limited by a strong signal return related to the water table (9.2 m depth, eastern part of Fig. 4A, verified by a water well sounding). The occurrence of a shallower reflector, parallel to the water table reflector (WT, Fig. 3B), may indicate a lateral textural transition and the development of a capillary fringe. The downward inflection (WT_i, Fig. 3B) may also indicate a textural change but is more ambiguous. Changes in water table topography which occur in concert with changes in surface relief (WT_i, Fig. 4A), probably illustrate the influence of hydraulic head on water table topography. In a number of areas the records are masked by cultural noise (e.g. culvert at 35 m, vehicule between 70-75 m; Fig. 3A).

Above the water table, the profiles illustrate a number of EM return facies (F_1-F_4, Fig. 3). At the

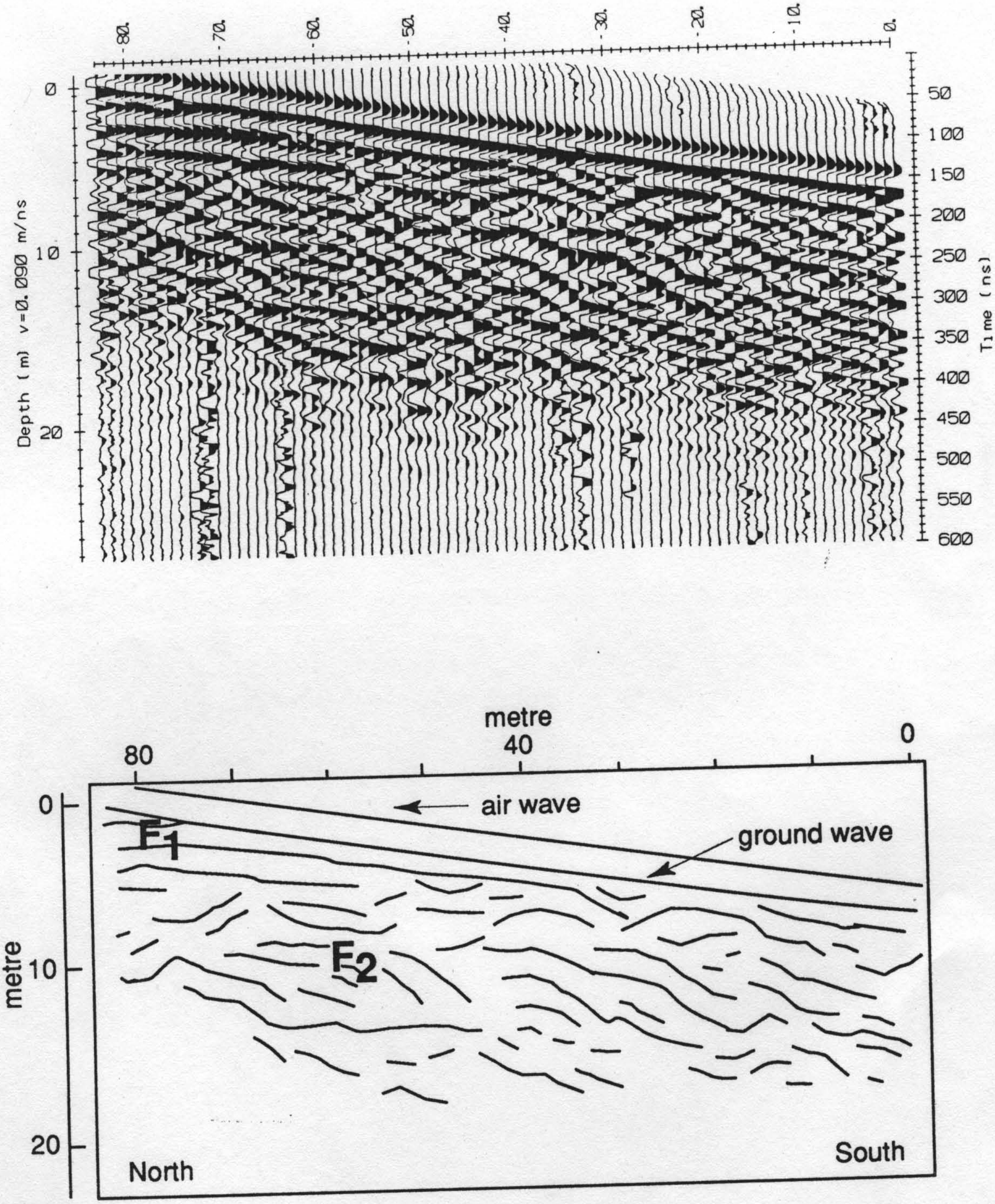

Figure 2. Bolton Farm site I: profile above a pit face, with interpretive drawing. F_1 and F_2 are EM return facies; see text for discussion

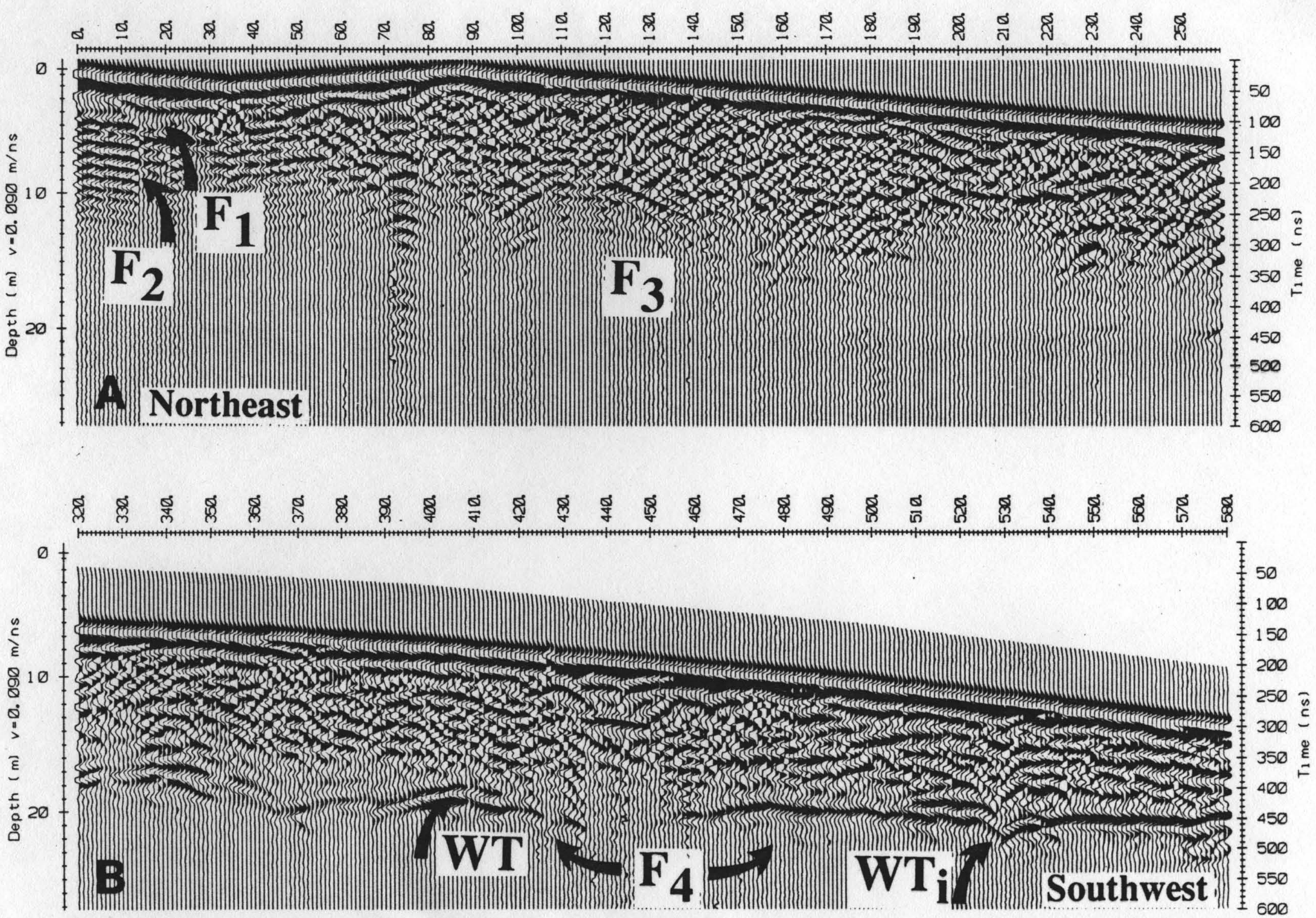

Figure 3. Bolton Site II: Two segments of a GPR profile within an erosional gully of the Palgrave Moraine. Arrows and letters refer to discussion in the text. WT and WT_i indicate the water table.

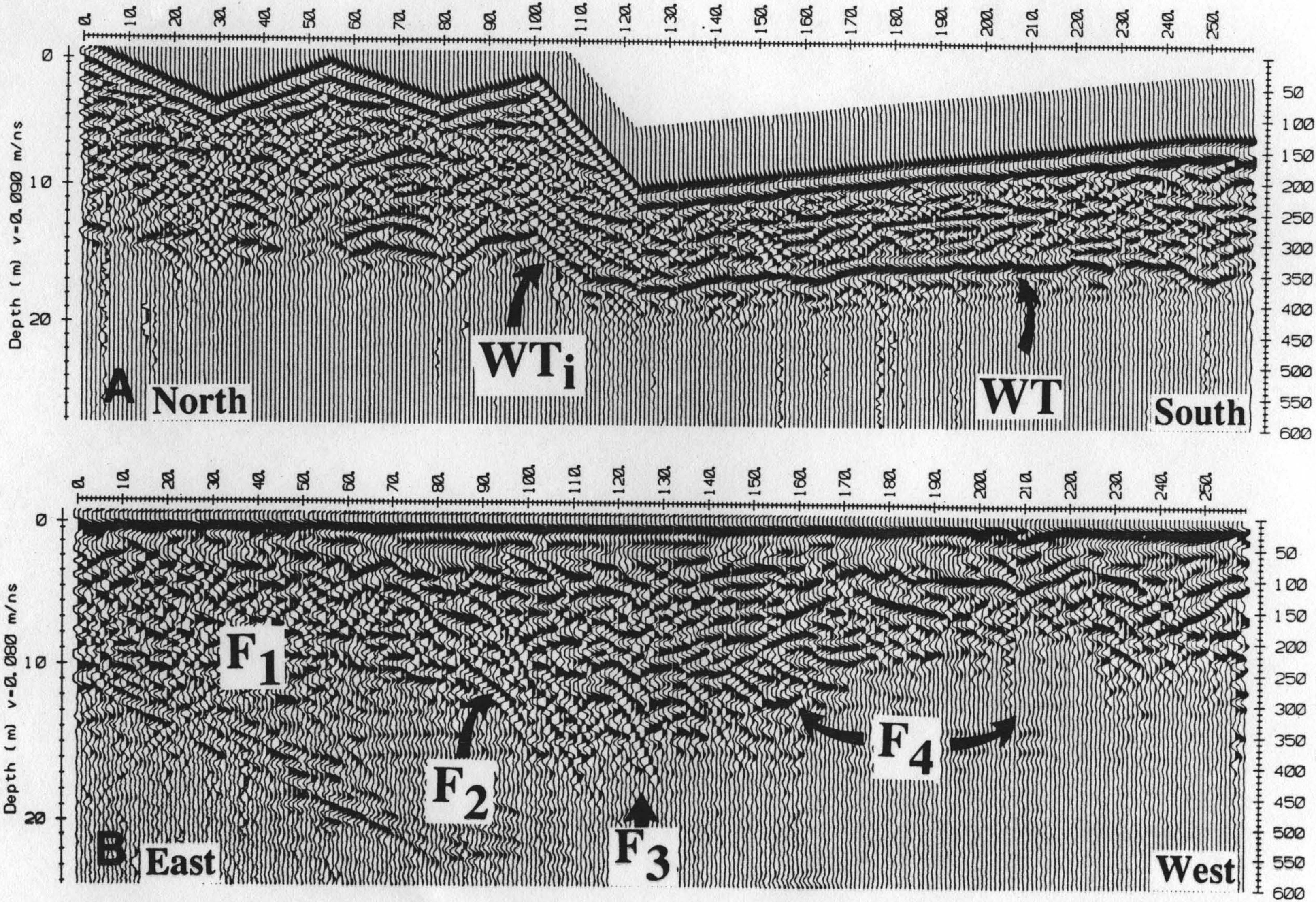

Figure 4. GPR profiles from Bolton site II (A) and site III (B): Arrows and letters refer to discussion in text. WT and WT_i indicate the water table.

northeastern end of the line (Fig. 3A) Halton Till is at the surface. The signal here has a broad negative amplitude with a weak positive amplitude reflection (F_1, Fig. 3A), interpreted as the lower boundary of the till. The series of close, evenly-spaced reflections below the till, exhibit progressively diminishing amplitude (F_2, Fig. 3A), and are inferred to be EM return artifacts. Similar signal responses are not found on any of the data from profiles run on sorted sediments. Moving laterally the profile is dominated by hummocky EM return facies (F_3, Fig. 3A). A final EM return facies (F_4, Fig. 3B) characterizes the southwestern end of the line and is comprised of subhorizontal, continuous reflectors. Progressing southwestwards, this facies develops stronger continuity and less variability with respect to reflector slopes.

At site III the water table was within one metre of the pit floor and plots within the wiggly trace of the ground wave (Fig. 4B). A strong coupling with the groundwater gave penetration of 12 m in the saturated medium (Fig. 4B), in contrast to the attenuation recorded at site II (Figs. 3B and 4A). The two dominant EM return facies (F_1 and F_4, Fig. 4B) are separated by a steep, westward-dipping reflector (F_2, Fig. 4B). At the base of facies F_2, asymmetric diffractions (F_3, Fig. 4B) obscure the record. EM return facies F_4 is comprised of continuous, inclined to subhorizontal reflectors.

With the exception of the EM return facies associated with the Halton Till (F_1, Fig. 3A), all three Bolton Farm sites have similar GPR signatures. The sequence of reflectors is suggestive of channelized and bedded sand and gravel, with isolated boulders (F_3, Fig. 4B). Variability in reflector geometry and continuity may reflect the scale of the depositional and/or erosional events. The water table was readily identified on the basis of strong reflector amplitude and lateral continuity.

BRIGHTON

The E-W Brighton GPR profile (Fig. 5) traverses a bench within a gravel pit owned by Trent Valley Sand and Gravel Company. Sedimentary exposures exhibit gravel cross beds, overlying horizontal sand and gravel beds (Shaw et al., in press). The GPR survey is oriented obliquely to the maximum dip of the gravel cross beds (SSW). This GPR record has not been topographically corrected; the transect was relatively flat.

The Brighton GPR profile shows four EM return facies (Fig. 5). Laterally continuous (up to 20 m), oblique and sub-parallel reflectors (F1, Fig. 5) are recorded to a depth of 7 m. Below 7 m depth, sigmoidal reflectors dominate the eastern part of the profile (F2, Fig. 5), subtle, discontinuous, concave reflectors are present in the middle portion (F3, Fig. 5), and wavy and subhorizontal reflectors (F4, Fig. 5) dominate the western part. Facies F1 and F2 record some of the gravel cross beds seen in exposure (Fig. 5). Facies F3 may record buried gravel trough cross beds. Facies F4 records horizontal sand and gravel beds, similar to those observed in exposure (Shaw et al., in press). There appears to be good correlation between dry and moist beds in the exposure and EM reflectors (Fig. 5). Strong reflector amplitude at 16 m depth (east), and attenuation of the GPR signal below, suggests a water table at this depth. However, discontinuity and dislocation of this reflector at position 23-42 m may be explained by the topographically uncorrected profile, textural or structural control, or the effect of a capillary fringe above the water table (Freeze and Cherry, 1979).

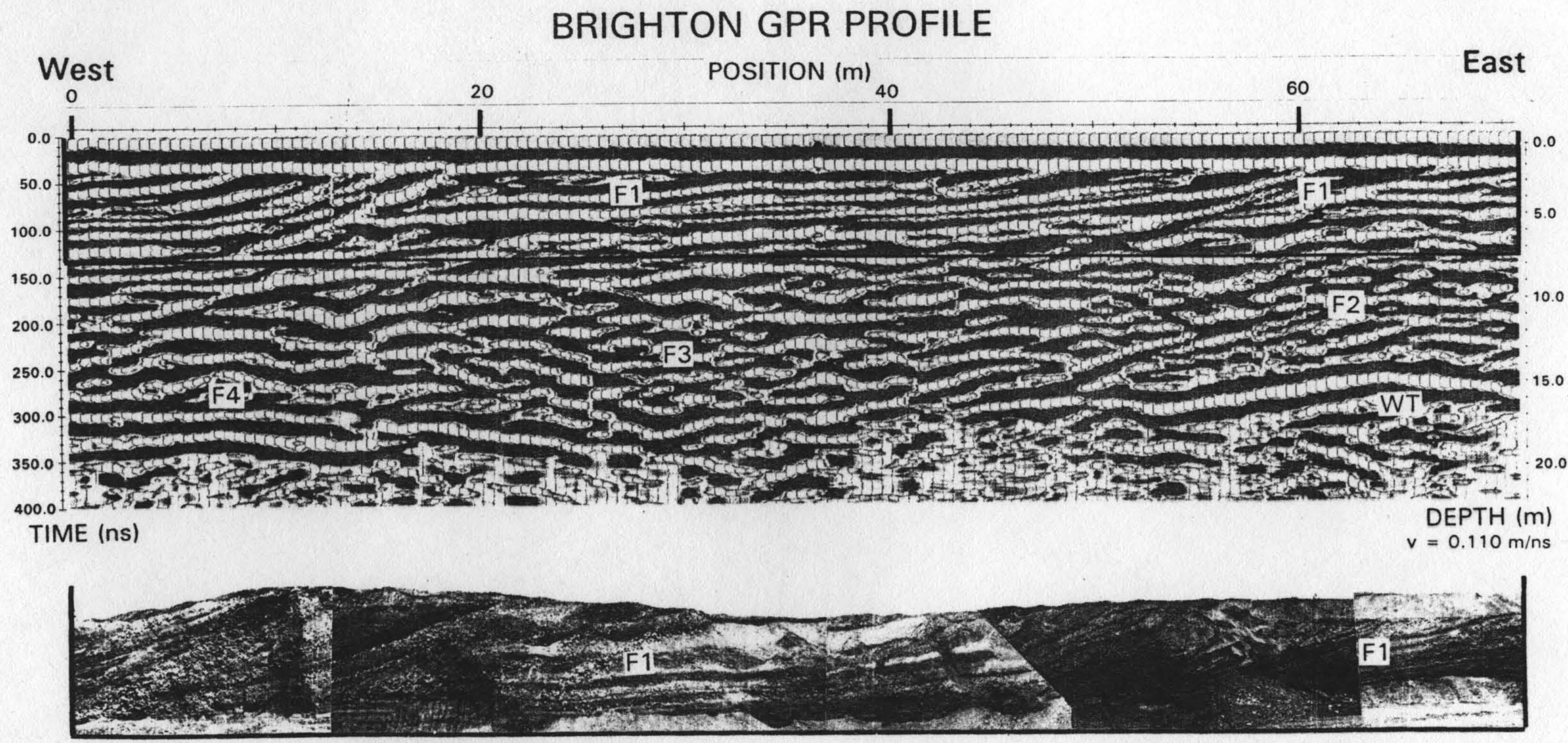

Figure 5. East-west oriented Brighton GPR profile and pit exposure. The exposure is located on the GPR profile (heavy line). F1-F4 are EM return facies; see text for discussion. WT is the strong amplitude reflector interpreted as the water table.

In summary, the Brighton GPR survey (Fig. 5) highlights sedimentary structures and shows the presence of the water table at depth.

ST. JOHN

This site is 2 km north of Ballantrae, in the hummocky terrain of the ORM. Sand and occasional cobbles and boulders are exposed at the surface. Approximately 1500 m of GPR profiling, in two transects oriented approximately E-W (1010 m) and N-S (450 m) were run adjacent to an Ontario Geological Survey borehole (OGS-93-15).

A portion of the E-W profile adjacent to borehole OGS-93-15 (Fig. 6) is shown. The EM signal is best recovered from the top ~10 m of this profile. Some of the records are masked by cultural noise. In the east, adjacent to the borehole, reflectors are mostly subhorizontal, with some discontinuous, concave reflectors. Subparallel reflectors likely record horizontal sand beds similar to those recorded in the borehole (Fig. 6), whereas discontinuous concave reflectors may record trough cross beds. Reflectors become more discontinuous and chaotic westward. The upper part of borehole OGS-93-15 (Fig. 6) shows fining and thinning packages of sand; this level of detail is not obviously recorded in the GPR profile.

A relatively continuous, high amplitude reflector at 5 m depth (west) below the surface, and sloping up towards the east, is interpreted as the water table. In the east, the EM signal is attenuated below this strong reflector. In the west, the water table is close to the ground surface, allowing good coupling with the groundwater, and EM signal penetration below the water table.

SUMMARY AND DISCUSSION

The sites investigated were all in glaciofluvial sand and gravel, where structure is often differentiated on the basis of changes in grain size. This is clearly illustrated at the Brighton site (Fig. 5), where reflectors show good correlation with wetter, finer-grained beds. The GPR technique has limited penetration in areas with fine-grained tills near the surface (northeast end of Fig. 3A), and must be replaced by more appropriate geophysical techniques (Table 1) in those areas.

A number of characteristics related to the water table can be seen on the GPR profiles:
(1) The water table is readily differentiated on the basis of strong reflector amplitude, lateral continuity of the reflector, and underlying signal attenuation.
(2) The relationship between the water table and signal attenuation is depth dependant. Shallow water tables (<1 m depth) provide good signal coupling, reduced signal attenuation, and permit structural imaging in saturated sediment (Figs. 4B, 6). In contrast, the presence of water tables at depth reflect a large proportion of the signal, preventing deeper imaging (Figs. 3B, 4A, 5, 6).
(3) Variations in the topography of the water table can be related to surface relief. This records the effect of controlling hydraulic head on groundwater flow. In contrast, isolated mounds do not influence water table topography as they are not major recharge areas. For example, Bolton Farm site II illustrates both conditions (Fig. 4A).

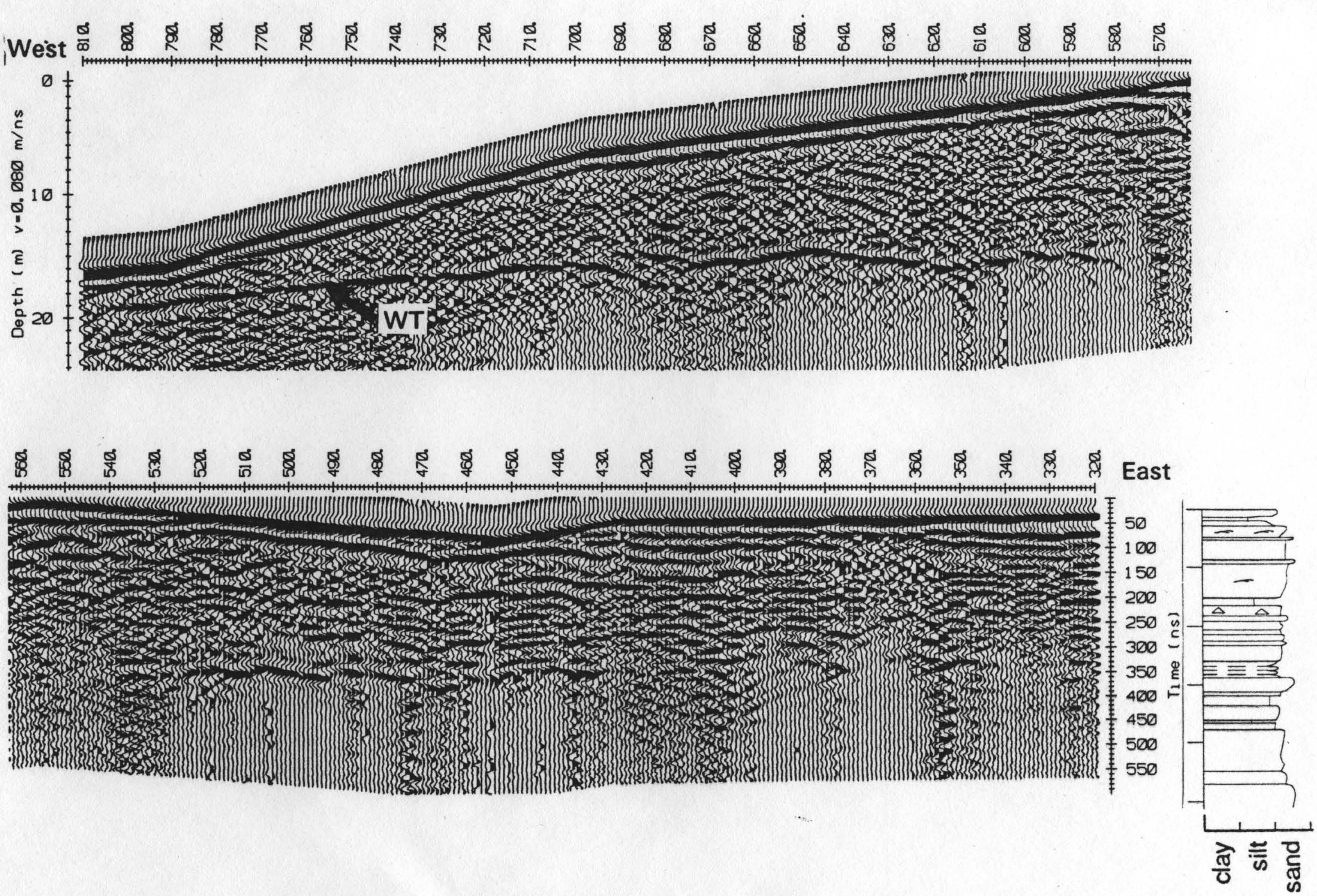

Figure 6. East-west oriented St. John GPR profile. WT is the strong amplitude reflector interpreted as the water table. Borehole OGS-93-15 (right) is located on the GPR profile at position 320 m.

(4) Some apparent dislocation and discontinuity in the water table may be related to textural and structural change (van Overmeeren, 1993), or to a capillary fringe above the water table blurring the saturated-unsaturated transition (Freeze and Cherry, 1979).

In this resistive sedimentary environment the GPR has proven to be an effective investigation tool for delineating the water table.The ORM water table is commonly within 20 m of the ground surface, and our surveys to date have had limited success in obtaining penetration below these depths. Evolving geologic understanding suggests buried channels cut into, or through, the Newmarket Till aquitard, underlying the ORM sand and gravel (Sharpe et al., in press). If water table draw-down cones are associated with tunnel channels or hydraulic windows in the Newmarket Till, GPR could be an invaluable tool to resolve them.

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