AN EVALUATION OF GROUND PENETRATING RADAR FOR INVESTIGATION OF PALSA EVOLUTION, MACMILLAN PASS, NWT, CANADA

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Abstract
The utility of ground penetrating radar (GPR) for investigation of perennally frozen peatlands is examined. GPR data from two sites in the Macmillan Pass area, Northwest Territories, supplemented with conventional data, are used to infer palsa evolution. Data processing techniques adapted from seismic applications were tested. Resolution of peatland stratigraphy was improved through deconvolution and coherency filtering processes. However, migration processing was less effective. GPR consistently imaged sub-peat topography in palsas and unfrozen fen, and detailed fen stratigraphy. Orientation of strata within palsas, inferred from GPR data, may assist genetic interpretation. Domed strata and frost penetration into underlying mineral sediment are correlated with palsa genesis by ice segregation. Stratigraphic discontinuities in unfrozen peat are correlated with a known palsa collapse scar; this signature may contribute to reconstructions of peatland history. Thaw degradation at depth was imaged by GPR as a subvertical frozen - unfrozen interface, and corroborated by field and historical evidence.

Introduction
Ground penetrating radar (GPR) provides subsurface stratigraphic and structural information through transmission of high frequency electromagnetic pulses into the ground and detection of signal energy reflected back to the surface from interfaces with electrical contrast. This contrast may be caused by a change in moisture content, density, composition, or temperature (Annan, 1992). Interfaces within and between organic and mineral sediment, and between frozen and unfrozen material are amenable to detection by GPR. Few studies applying GPR to investigations of perennally frozen peatlands have been undertaken to date (Doolittle et. al., 1992; Pilon et. al., 1992; Kettles and Robinson, 1996), and there has been little attempt to enhance the GPR data through processing techniques.

Palsas are permafrost mounds, occurring in wetlands, comprising a core of segregated ice and peat and/or mineral soil (NRCC, 1988); they are formed by ice segregation of a frozen core in peat which progressively penetrates deeper over time until it anchors in mineral sediment as a mature palsa (Seppälä, 1988). During this process, peat and mineral sediment layers are domed due to upward volume expansion upon freezing. Other similar-appearing frost mounds exist, and may form by degradation of an extensive peaty deposit comprising segregated (i.e., peat plateau) or intrusive ice (cf. Washburn, 1983), or by ice aggradation involving hydraulic or hydrostatic processes (Nelson et al., 1992).

This paper examines the utility of GPR for investigation of perennally frozen peatlands, and tests the effectiveness of seismic data processing techniques in enhancing image quality to facilitate interpretation. The data are used to infer palsa evolution, in conjunction with aerial photograph interpretation, historical records, and field observations.

Study area
Data were collected from two sites in the Macmillan Pass area of the Selwyn Mountains, Northwest Territories. The Porsild’s Field site is located in Macmillan Pass at approximately 1390 m asl (63°15’15”N, 130°01’05”W); four palsa mounds were surveyed at this site (cf. Kershaw and Gill, 1979). The Dale Creek study site (63°16’15”N, 130°06’00”W) is located in a valley north of the Porsild’s Field study site, at approximately 1470 m asl. At this site, five palsa mounds were surveyed.

Methods
GPR data are imaged as a continuous profile of subsurface interfaces with electrical contrast. The profile is generated by recording the two-way travel time of signal energy at evenly spaced points along a survey transect. Inferences are made regarding what each interface represents, based on the amplitude, frequency, lateral continuity, orientation, and attenuation of the reflected
signal, and are supported by coring. The GPR data presented in this paper were collected as single-channel, constant-offset radar reflection profiles using a pulseEKKO IV GPR system with 50 MHz antennae, developed by Sensors & Software Inc.. A constant antenna offset of 2 m and a constant 0.5 m station interval were used.

GPR is analogous to seismic exploration techniques, transmitting electromagnetic instead of acoustic waves. Data processing was performed at the Department of Geology and Geophysics at the University of Calgary, using the ProMAX 2-D seismic data processing package developed by Advance Geophysical Corporation (version 5.1). Processing steps performed included gain recovery, spectral analysis, spectral shaping, bandpass filtering, velocity analysis, deconvolution, normal moveout correction, time-depth conversion, migration, and coherency filtering (F-X deconvolution) (cf. Coffeen, 1984).

Coring was undertaken at several points along the GPR transects in both the fens and on the palsas to record major changes in ice content and character, peat characteristics, and occurrence of sediment for correlation with GPR.

Aerial photographs encompassing both sites were examined for the years 1949, 1972, and 1981. Enhanced photographic enlargements of stereopairs from each of the two sites were made to facilitate mapping of the areal extent of the features.

## Results

**Interpretation of Aerial Photographs**

The palsas at Porsild’s Field showed a greater percentage decline in areal extent (total areal decline of 36.4%) over the 33 year period between 1949 and 1981 than did those at Dale Creek (total areal decline of 19.7%), although the actual decline in areal extent of palsas at Dale Creek (ca. 1250 m²) was slightly greater than at Porsild’s Field (ca. 1210 m²). At both sites, the palsas showed greater average annual decline in areal extent over the 24 year period between 1949 to 1972, than over the 10 year period from 1972 to 1981. There is a lack of climate data for the study area itself over the study period. No clear warming trend or increased precipitation is apparent from regional records, to which the observed areal decline can be correlated.

**Ground Penetrating Radar**

Three transects were surveyed at the Porsild’s Field site, crossing four palsas. Two transects were surveyed at the Dale Creek site, crossing five palsas. Topographic corrections have been applied to the data. Depths are calculated using signal propagation velocities (derived from Common Mid Point surveys) of 0.038 m•ns⁻¹ in unfrozen peat, and 0.095 m•ns⁻¹ and 0.097 m•ns⁻¹ in frozen peat at the Porsild’s Field and Dale Creek sites, respectively. The radar profiles presented in the following sections are plotted with only time on the vertical scale. This is because the conversion of data from the time domain to depth is prone to error (Coffeen, 1984): vertical and lateral velocity variations caused by subsurface anomalies, and the horizontal component of the signal path in the subsurface (particularly at shallow depths) compromise the accuracy of depth conversion.

**Peat - Mineral Sediment Interface**

In unfrozen peat, the peat - mineral sediment interface represents the greatest subsurface change in water content (and therefore dielectric permittivity; cf. Davis et al., 1977) in peatlands, and thus yields the strongest amplitude subsurface reflection event on GPR profiles (Theimer et al., 1994:199). Where frozen, the dielectric contrast at the peat - mineral sediment interface is reduced, and therefore, this interface may be difficult to distinguish (Kettles and Robinson, 1996); this may be exacerbated by signal scattering from pinch-out of ice lenses and disseminated ice. On the basis of relative signal amplitude, the peat - mineral sediment interface could be consistently and reliably identified in both fen (ca. 3.9 to 5.2 m depth) and palsas (ca. 0.9 to 5.8 m depth).

**Fen Stratigraphy**

Coring (up to 5 m depth) showed fen peat stratigraphy at both sites was complex, with irregular variation in density and moisture content with depth. Peat decomposition increased with depth.

When displayed with a time variable gain control, the radar profiles show detailed stratigraphy in the unfrozen peat at the Porsild’s Field site (Figure 1). Wavy, subparallel, laterally continuous reflections can be traced across the profile. However, reliable correlation of a given radar event with a change in any given peat property, such as moisture content, density, peat type, and degree of decomposition, is problematic, due to the inaccuracy of available peat sampling techniques relative to the sensitivity of GPR.

Deconvolution of the radar data improved vertical resolution and lateral continuity of reflections. Lateral continuity was also improved in the fens by application of a coherency filter.

**Palsa Collapse Scar Stratigraphy**

One GPR transect crossed the edge of the collapse scar of palsa # 9, which collapsed some time between 1949 and 1972. The radar profile shows an apparent decrease in the lateral continuity of reflections at this location. A coherency filter was applied to test for and enhance...
Figure 1. Detailed fen stratigraphy is visible between 0 and 38 m, to 500 ns (ca. 8 m depth). Strong dipping reflection below the palsa, extending from 105 ns at 40 m, to 320 ns at 55 m, is inferred to represent frozen - unfrozen interface. Reflections dipping away from the palsa core at depth between 38 m and 45 m are inferred to represent unfrozen peat strata below the permafrost core.

Figure 2. Apparent decrease in lateral continuity of reflections between 45 m and 65 m on the transect, between 130 ns to 300 ns, compared to stratigraphy between 65 m and 90 m, is inferred to represent the stratigraphic signature of the collapsed palsa # 9.
continuity in reflections across this area of the profile; the observed discontinuity persisted through this processing step (Figure 2). However, a similar discontinuity in strata was not observed adjacent to the collapse scar of palsa # 6, which collapsed some time after 1981 (Figure 2).

No other stratigraphic discontinuities were observed adjacent to extant palsas to suggest that the current mound morphology of the palsas is a product of collapse or thaw degradation from a pre-existing plateau feature.

Palsa Stratigraphy
Coring at Porsild’s Field showed that the palsa cores comprised predominantly icy peat, with pore ice and ice lenses. The 50 MHz GPR largely failed to effectively image the internal stratigraphy of palsas at Porsild’s Field. Despite this lack of structural imaging, the chaotic, laterally discontinuous nature of radar returns from the palsas is consistent with signal scatter and reflection in ice-rich sediment. However, internal reflections below palsa # 5 suggest that peat, and possibly also mineral strata within the palsa core, are domed (Figure 3). This structure may be related to ice segregation (Seppälä, 1988).

The palsas at Dale Creek comprise a thin peat layer (ca. 0.9 to 2.0 m) over mineral sediment. The peat layer was too thin for internal stratigraphy to be imaged by the 50 MHz antennae used in this study. Individual reflections from within the mineral sediment were poorly resolved, even after processing; radar returns were chaotic and laterally discontinuous. Coring revealed a concentration of pore ice and ice lenses in the peat immediately above the peat - mineral interface. This structure, and external, domed palsa morphology, are consistent with an ice segregation model of palsa development.

Scattering of radar signal energy by pore ice and ice lenses, scattering and absorption in near-surface thawed and partially thawed layers (Doolittle et al., 1992; Arcone, 1984), and increased signal propagation velocity through frozen material impair resolution of internal peat stratigraphy and structure, particularly where peat is ice-rich. Deconvolution and coherency filtering did not improve resolution or lateral continuity in palsas, except for the inferred peat - mineral sediment interface; this is likely due to the lack of signal continuity pre-processing.

Frozen - Unfrozen Interfaces
Coring near the edge of palsa # 1 at Porsild’s Field encountered unfrozen material below 4.9 m of frozen peat; this frozen - unfrozen interface appears to correlate with a strong dipping reflection on radar transects intersecting this palsa (Figure 1). This radar pattern may be indicative of narrowing of the permafrost core with depth in palsas (cf. Zoltai and Tarnocai, 1971:119), and may be a result of thaw degradation.

Below the dipping reflection in Figure 1, a number of reflections dipping in the opposite direction, away from the palsa, are visible. This radar pattern may be related to velocity pull-up, where laterally continuous reflections appear shallower where they are overlain by frozen material, due to faster signal propagation velocity through frozen media (cf. Coffeen, 1984; Saarenketo et al., 1992; Kettles and Robinson, 1996). Looking from left to right on the profile, reflections arrive progressively earlier as the inferred permafrost core thickens.

Time migration to correctly position dipping radar events could not be reliably applied to the data due to the strong lateral velocity contrast across the frozen - unfrozen interface. Nevertheless, time migration was applied using a simple time- and space-variant velocity structure, assuming the strong dipping reflection represented the frozen - unfrozen interface. The multiples of this reflection were collapsed, and poorly resolved dipping reflections remain, dipping towards the palsa core; these may be true reflections from the frozen - unfrozen interface, which has been shown by coring to be a non-
vertical boundary extending from the palsa margin towards the centre.

Conclusions

Palsa Evolution

Conventional and GPR-derived data from both sites indicate palsa genesis by ice segregation. Coring revealed segregated pore ice and ice lenses in peat and mineral sediment. Stratigraphic doming within peat, inferred to be associated with ice segregation, was imaged by GPR in one palsa. Doming of mineral sediment below the palsas was also indicated by GPR. Ice segregation could be inferred from the chaotic nature of radar returns from ice-rich sediment.

Radar imaging did not reveal stratigraphic discontinuities adjacent to extant palsas that would suggest that the mounds were produced by thaw degradation or collapse from a previously more extensive plateau. Historical data indicate reduction in areal extent of palsas at both sites since 1949, although the rate of decline is not consistent between the sites or over the period of record. Thaw degradation at depth in palsas at Porsild’s Field was imaged by GPR and confirmed by coring.

Utility of GPR for Investigation of Palsa Evolution

The primary advantages of GPR include its ability to quickly and easily image structural information, in particular lateral and vertical continuity, as well as its ability to detect gross stratigraphic features, such as interfaces between peat and mineral sediment, and peat and gyttja. The GPR showed promise in imaging the frozen - unfrozen interface at depth below the palsa margin, which, if validated, could facilitate long-term monitoring of subsurface permafrost conditions. These data suggest that GPR may allow identification of stratigraphic signatures of pre-existing permafrost landforms. This may facilitate reconstructions of peatland history, particularly where collapsed permafrost features are not associated with persistent, identifiable surface features. Seismic data processing techniques led to improvements in vertical resolution and lateral continuity of reflections in fens. However, these processes were not effective in improving resolution of data from palsas cores.

With respect to genetic processes, GPR substantiated evidence regarding ice segregation gathered using conventional techniques, but, with the exception of imaging structure (e.g., doming in palsas), did not provide new kinds of information or go beyond facilitating compilation of data regarding peat thickness, stratigraphy, and ice content and character. GPR generally did not provide clear stratigraphic imaging of peat-cored palsas. Irregular and strong signal velocity contrasts in the frozen - unfrozen transition at palsa margins can generate complicated time structures on radar profiles which may not be indicative of actual physical structure at depth; care must be taken in interpreting such zones. Moreover, corrective data processing functions, such as migration, cannot be reliably applied to the data in the absence of detailed signal velocity information. The relationship between radar events and causative peat properties remains poorly defined. Improved peat sample retrieval methods (e.g., reduced water loss and compaction), in conjunction with more detailed coring and sample analyses, would be required to enable reliable correlation of observed strata with radar reflections, to support detailed stratigraphic studies.

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References


