IMPROVING UNDERSTANDING OF PEATLAND HYDROGEOLOGY USING ELECTRICAL GEOPHYSICS

Dr. Lee D. Slater, Geosciences, U. Missouri-Kansas City, Kansas City, MO
Dr. Andrew Reeve, Geological Sciences, U. Maine, Orono, ME
Mr. Danney Glaser, Geosciences, U. Missouri-Kansas City, Kansas City, MO

Abstract

A geophysical survey was completed in Caribou Bog, a large peatland in Maine, to evaluate peatland stratigraphy and hydrology. Geophysical measurements were integrated with direct measurements of peat stratigraphy from probing and with measurements of fluid chemistry. Consistent with previous field studies, GPR was an excellent method for delineating peatland stratigraphy. Prominent reflectors from the peat-lake sediment and lake sediment-mineral soil contacts were precisely recorded up to 8 m deep. However, GPR provided no information below the mineral soil contact. 2D resistivity and induced polarization (IP) imaging was used to further investigate the stratigraphy of this peat basin. We observe that the peat is chargeable and that IP imaging is an alternative method for defining peat thickness. This chargeability is attributed to the high surface charge density on partially decomposed organic matter. The conductivity imaging resolved glaciomarine sediment thickness and its variability across the basin. Terrain conductivity measured with a Geonics EM31 correlated with glaciomarine sediment thickness and was effective in characterizing variability in layer thickness over approximately 18 km^2. The electrical imaging indicates that variations in glaciomarine sediment thickness may exert a key control on the hydrogeology and vegetation distribution within this peatland.

Introduction

Geophysical methods can assist understanding of peatland stratigraphy and hydrogeology. The ground penetrating radar (GPR) method has been most extensively used. Depending on the electrical conductivity of the peat, GPR can penetrate up to 10 m in peatlands, with a resolution of 10-15 cm (Lowe, 1985; Theimer et al., 1994). The method is effective as moisture content changes occur at important interfaces, causing measurable GPR reflections. Numerous studies illustrate the potential of the method for identifying the base of a peatland (Warner et al., 1990; Pelletier et al., 1991; Poole et al., 1997). Peat can contain up to about 95% water, with water content varying with degree of decomposition and the plant types that make up the peat (Hobbs, 1986). Moisture content typically drops to 30-40 % in the mineral soil, resulting in large-amplitude reflections at the peat-mineral soil contact (Theimer et al., 1994). Significant reflectors within peat have also been identified and associated with local changes in moisture content (Theimer et al., 1994). Reflections from boundaries between different types of peat and the interface between peat and organic-rich lake sediment are also identifiable (Hanninen, 1992). As the dielectric constant of peat is well known (50-70 depending on peat type, Theimer et al., 1994), reliable estimates of the depth to reflectors within and at the base of peat are obtainable.

Dc resistivity, EM and induced polarization (IP) methods may assist peatland studies, particularly for examining the relation between mineral soil stratigraphy and properties of peat. Unlike GPR, these methods are not typically limited to studies above the mineral soil. Bulk conductivity (σ_b) measured in the dc resistivity method depends upon fluid conductivity (σ_w), moisture content (θ) and surface conduction (σ_s). As peat is predominantly water, σ_b is particularly dependent on σ_w. The shallow pore waters in boreal peatlands are typically relatively dilute. The electrical conductivity of peat pore water usually increases with depth because the mineral soil underlying the peat is a source of inorganic solutes. As decomposed plant material within peat has a high surface charge, surface conduction is probably also significant in controlling bulk conductivity.

The IP method measures the magnitude of polarization of a material or, put simply, its ability to store charge. In nonmetallic mineral soil, polarization results from diffusion controlled polarization processes at the interface between the grain surfaces and the pore solution. The IP response thus depends on surface chemistry, which is controlled by charge density, surface area and fluid chemistry. The large surface area and cation exchange capacity (CEC) associated with clay minerals enhances the magnitude of polarization in clay-disseminated sediments and rocks (Vinegar and Waxman, 1984). The application of IP to the study of peatlands has never, to our knowledge, been reported and typical values of M in peat are not documented. The high surface charge density associated with poorly decomposed organic material results in a high CEC (Hobbs, 1986). As charge density is a major control on IP response, we expect the IP response of peat to be significantly different from the mineral soil.

In this paper, we report preliminary results of a field study to investigate the utility of electrical methods (resistivity imaging, IP imaging, GPR and terrain conductivity mapping) for understanding the stratigraphy and hydrogeologic setting of a large peatland in Maine. The full findings of the study will be presented in a later paper.

Caribou Bog

Caribou Bog is a large peatland extending 17 km south to north, from Bangor to Hudson, Maine (**Figure 1**). Peat thickness reaches 13 m, with as much as 5 m of underlying organic-rich lake sediment. Nine monitoring well clusters are installed across the southern complex. Hydraulic head measurements at these wells indicate that groundwater generally flows to the northwest, with a slight water table mound present near W3 and W4. Vertical groundwater flow changes seasonally; groundwater flows upward from the mineral soil in the spring and downward in the summer. The location of geophysical profiling lines within the study area is shown in **Figure 2**. Line 0 was established as the reference profile along the long axis of the basin. Six transects were established at monitoring well locations or at the approximate midpoint between them.

Samples of peat and mineral soil were obtained at four locations (**Figure 2**). Loosely compacted, peat forms the major unit within the basin, reaching 5.6 m thick at C2. It is underlain by organic-rich lake sediment, reaching 1.5 m thick at C2. A distinct silt band separates the peat and lake sediment at C1, C2 and C3. The mineral basement is a glaciomarine silt-clay, the Presumpscot formation. Penetration tests were performed along an 80 m section of Line 0 to determine small scale variability in peat thickness. A pointed steel rod was pushed into the peat until refusal, to identify the glaciomarine sediment contact.

Fluid conductivity (σ_w) in W1-W6 was measured at a depth of about 1 m, at one or two intermediate depths, and at the peat-mineral soil interface. Additional measurements in the upper 1.5 m were made at points along Line 0.. Conductivity within the peat varies from 40-77 μS/cm. Such low σ_w are indicative of surficial waters in northern raised peatlands that contain peat with little soluble material and are hydrologically isolated from external solute-rich sources of water (Siegel and Glaser, 1987). At Well 3 σ_w increases from 50-70 μS/cm in the peat to 150 μS/cm in the lake sediment, indicative of solute exchange from the mineral basement.

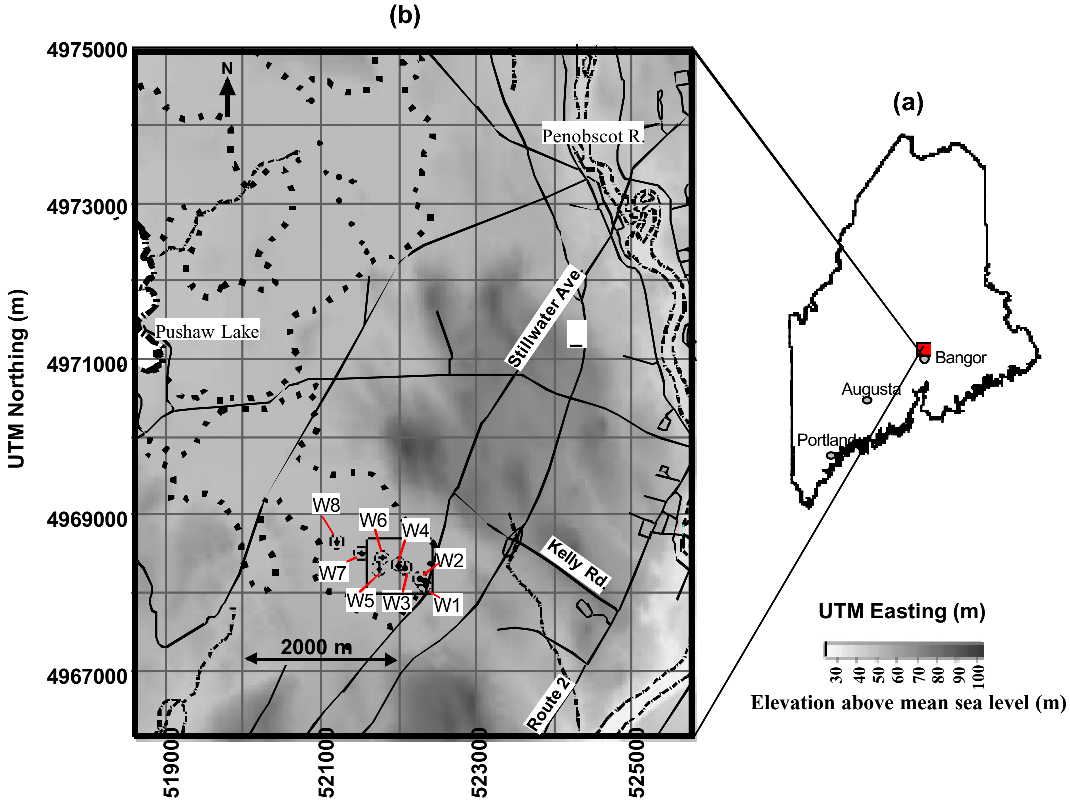

Figure 1. (a) Location of Caribou Bog in Maine (b) Position of monitoring wells and geophysical survey area in the southern unit of Caribou Bog, south-east of Pushaw Lake. Rectangle encompassing W1-W6 is extent of geophysical survey area shown in Fig. 2.

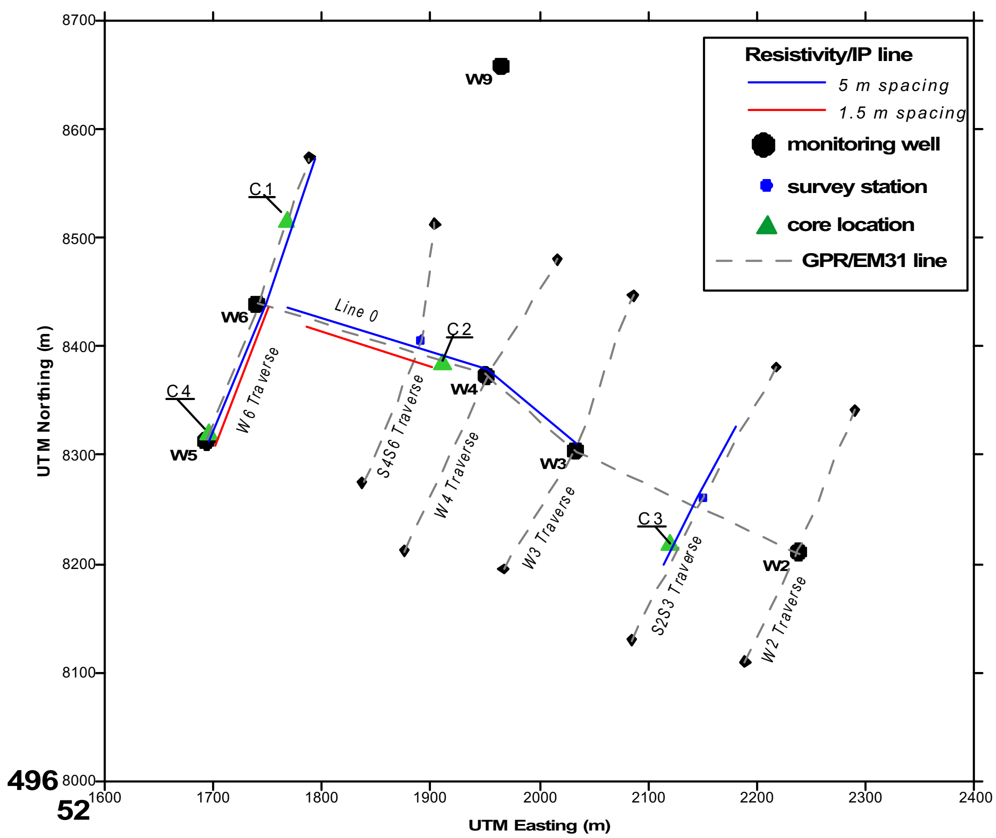

Figure 2. Location of geophysical survey lines. Peat core and monitoring well positions also shown

GPR Surveys

GPR surveys using a 100 MHz antenna were performed along lines shown in **Figure 2**. The relative dielectric constant (ε_r) of peat is known from laboratory and field measurements, ranging from 51.4 to 70.4, depending on the measurement method and specific peatland (Theimer et al, 1994). Using traveltime measurements to reflectors observed in peat cores, we calculated an average ε_r of 61 (velocity = 0.0385 m/ns) for the peat in Caribou Bog. CMP soundings applied to the reflector at the base of the peat gave a comparable value. Vertical resolution (res_v) for the 100 MHz radar pulse in this peatland was calculated as 0.1 m. GPR measurements were made using a RAMAC system. The sampling time window was 490 ns, providing a maximum investigation depth of 18.9 m, assuming constant ε_r with depth. Maximum lake-inorganic glaciomarine sediment interface depth observed in the cores was 6.1 m.

GPR profiles along Line 0 correlate with penetration tests (described above) and peat core data (**Figure 3**). We observe strong reflectors at the lake-glaciomarine sediment interface and at the peat-lake sediment interface. No reflectors were observed below the lake-glaciomarine sediment interface. GPR reflections in peat primarily occur where water content changes. The strong reflector at the base of the lake sediment presumably results from a change in water content at this boundary. Water content in the glaciomarine sediment is probably 30-40 % compared to 80-90 % in the peat. Reflections from this contact correlate with the point of refusal in the penetration tests. The weaker reflection from the peat-lake sediment boundary probably results from the higher water content in the peat, relative to the underlying lake sediment.

Electrical imaging

Measurements were made using a SYSCAL R1 resistivity-IP receiver interfaced with an automated data acquisition unit. A dipole-dipole array configuration was used. A 5 m electrode spacing was used to investigate the electrical structure to a depth of 18 m. A 1.5 m array was used to determine the near surface electrical structure of the peat and lake sediment. Resistivity and IP data were inverted using a smoothness-constrained, least squares algorithm developed by MacInnes and Zonge (1996). The location of resistivity-IP lines is shown in **Figure 2**. Conductivity and IP models along Line 0 using a 5 m electrode spacing are plotted in **Figure 4**. The peat-lake sediment and lake-glaciomarine sediment interfaces, as determined from GPR, are superimposed. The conductivity model contains a uniform upper resistive layer, underlain by a conductive unit of varying thickness, underlain by a resistive third layer. The GPR control data show that conductivity is not an accurate indicator of peat thickness. The base of the conductive layer is assumed to be the base of the glaciomarine sediment. In contrast, the top of the conductive layer occurs within the peat. Fluid conductivity profiles at W4 and W6 suggest that this is not a function of fluid chemistry. The increase in bulk conductivity with depth is likely a response to a change in the physical properties of the peat, primarily due to the transition from peat to lake sediment. However, models for the 1.5 m electrode spacing indicate that conductivity gradually increases with depth in the peat (**Figure 5**). It is apparent that the conductive unit resolved in the electrical imaging is an integrated response to the glaciomarine sediment, lake sediment and lower portion of the peat.

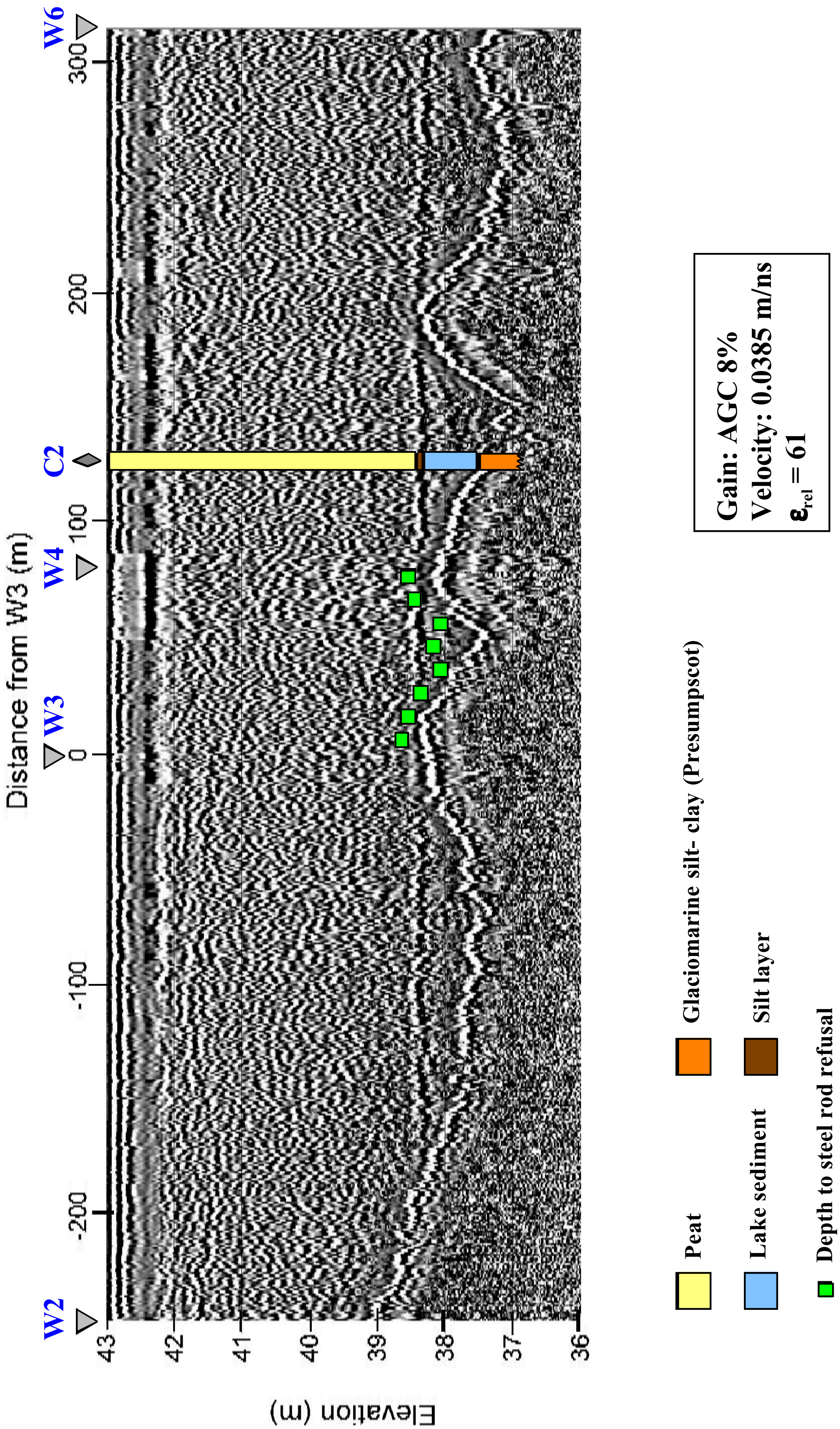

Figure 3. Radar profile along Line 0 correlated with peat cores and depth to refusal from penetration tests

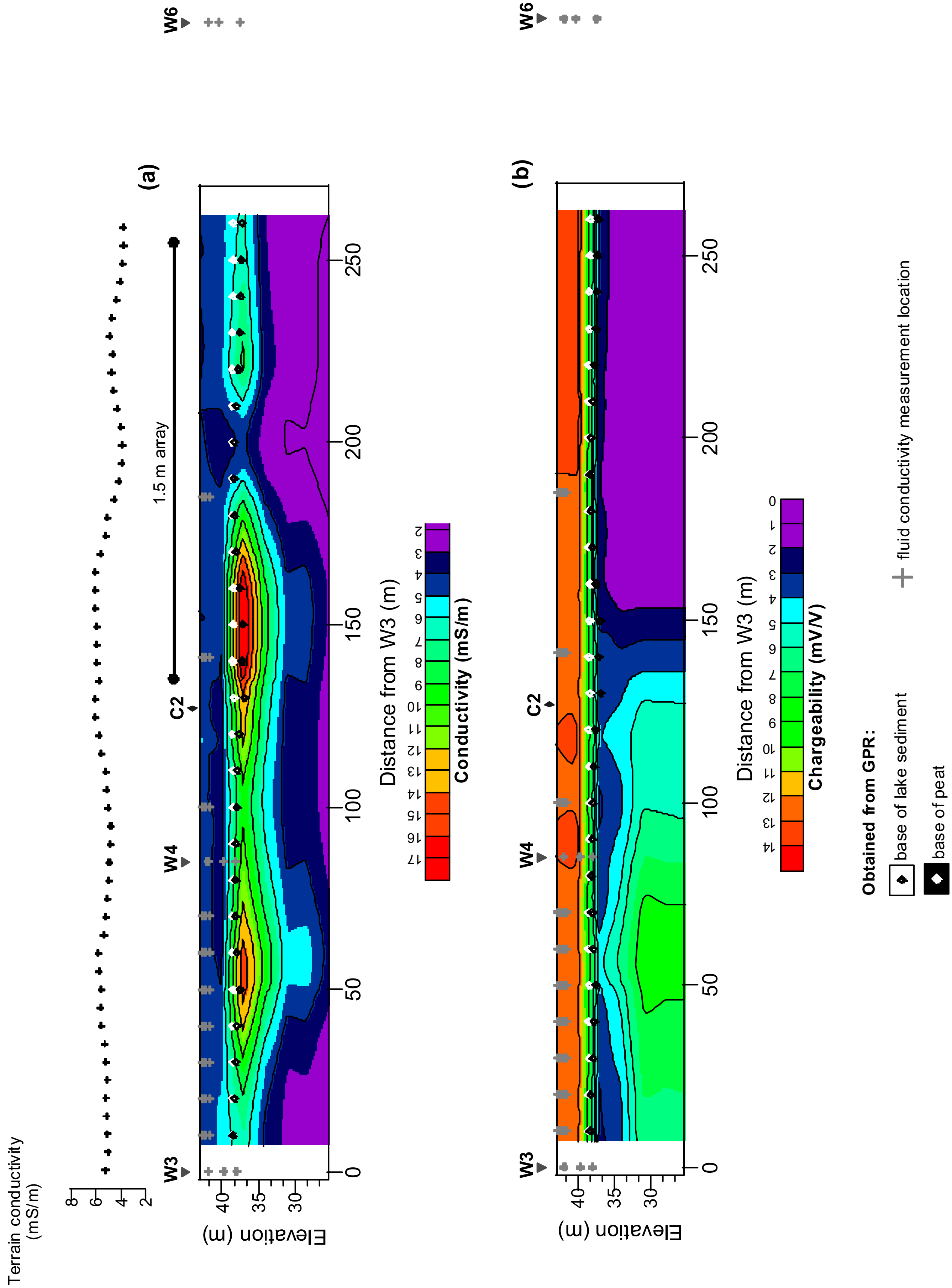

Figure 4. Electrical images along Line 0 compared with prominent reflectors observed with GPR. Electrode spacing = 5 m: (a) conductivity (b) chargeability. Terrain conductivity measurements are also shown. The high conductivity layer is interpreted as the glaciomarine silt-clay and lake sediment. Vertical scale exaggerated by factor of 2.

The IP models resolve the peat as chargeable, relative to the underlying lake sediment and glaciomarine sediment. Polarization of the peat presumably results from the high surface charge density on the organic material. The chargeability (*M*) appears to be an indicator of the peat thickness. The lake sediment appears electrically similar to the glaciomarine sediment, despite being physically different from the overlying peat. The continuous lower resistive layer observed in the conductivity models is not evident in the IP models. Chargeability beneath 35 m elevation is small, although it varies on both lines. Based on available regional geologic data, we suspect that a sand and gravel unit underlies the glaciomarine sediment. The variation in chargeability below 35 m elevation on both lines may reflect changes in the lithology (likely clay content or grain size distribution) of this lower layer.

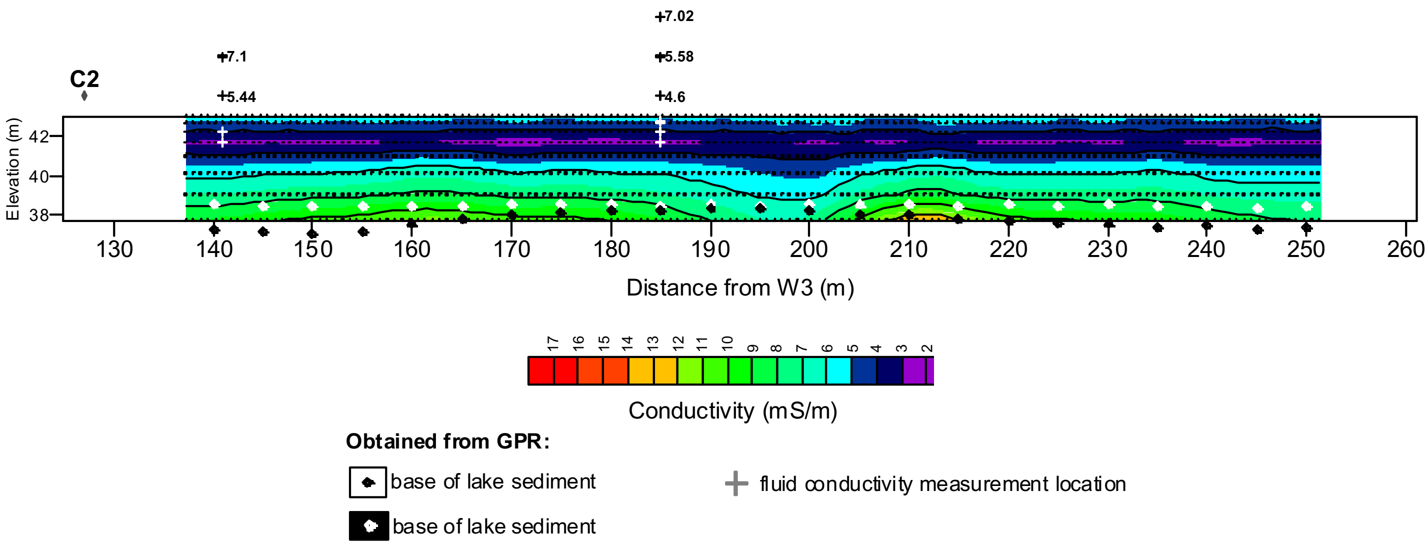

Figure 5. Conductivity image along Line 0 compared with prominent reflectors observed with GPR. Electrode spacing = 1.5 m. Vertical scale exaggerated by factor of 2.

EM31 measurements

EM31 measurements along Line 0 and W6 Traverse are plotted above the conductivity image in **Figure 4**. Terrain conductivity values are consistent with modeled conductivity of the peat from the inversion. The EM31 profiles correlate with the thickness of the second layer in the conductivity model: where layer thickness increases, terrain conductivity increases. As discussed above, the conductive unit in the imaging represents the glaciomarine sediment, the lake sediment and the bottom portion of the peat. The EM31 response is likely mainly a response to glaciomarine sediment thickness, although it may partly reflect lake sediment thickness also. Along Line 0 we consider the EM31 conductivity an indictor of glaciomarine sediment thickness. This premise holds if terrain conductivity responds to lake sediment thickness also, as GPR and electrical imaging show that lake sediment thickens where the glaciomarine sediment is thickest. This is expected, assuming this area was a topographic depression over the past 10,000 years, with the thickest deposits of glaciomarine and lacustrine sediment accumulating in the deepest parts of the basin. We made EM31 measurements on an irregular grid over approximately 18 km^2. A contour plot of the EM31 data is shown in **Figure 6**. We interpret high terrain conductivity as indicative of regions where lake sediment and glaciomarine sediment deposition within topographic depressions was greatest.

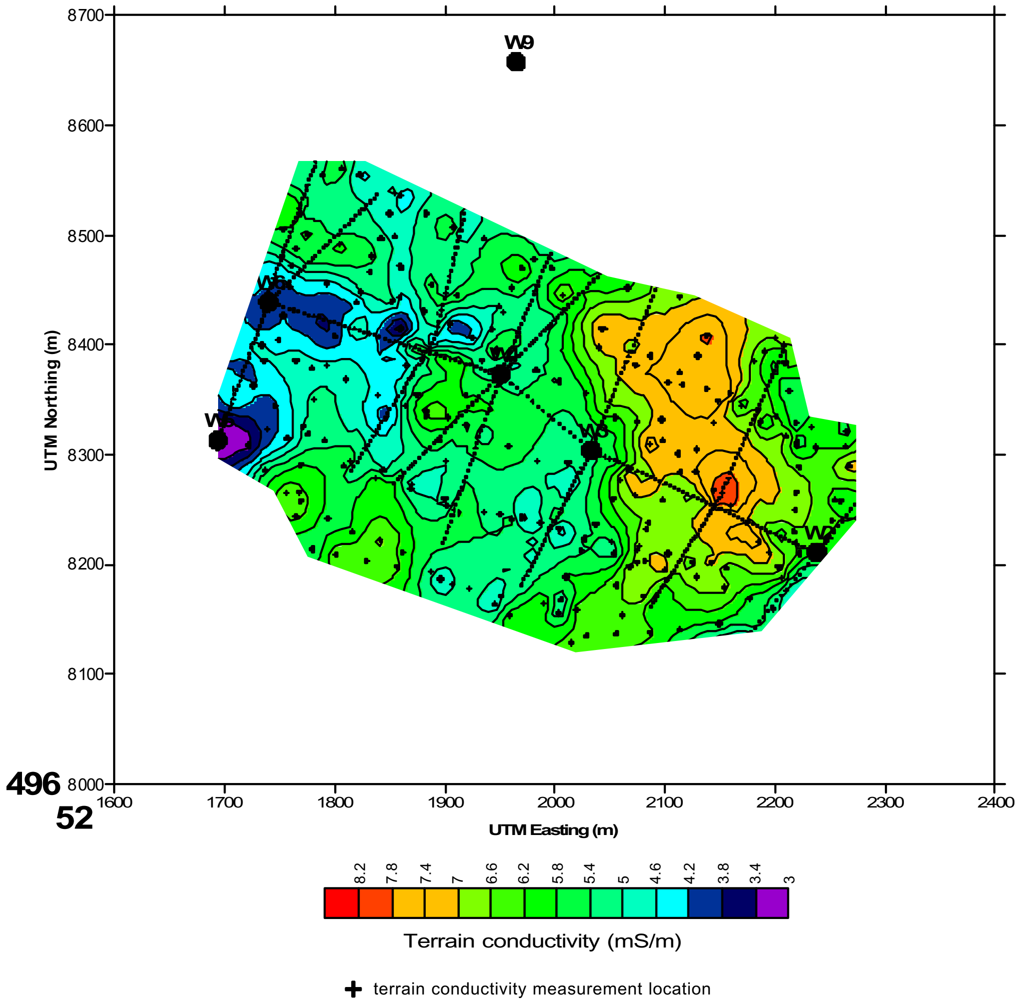

Figure 6: Interpolated terrain conductivity map for surveyed area of peat basin. Contours are generated from point measurements across grid and measurements made at 5m intervals along survey lines

Discussion

Integrated use of radar, resistivity, IP and terrain conductivity was an effective approach to investigating the stratigraphy and hydrogeologic framework of a large peatland. GPR resolved the mineral soil contact to a maximum depth of 8 m. The relatively high penetration depth resulted from the low conductivity of the peat soil. We also observe an important transition between peat and lake sediment. The GPR data reveal the sedimentary history of the basin, with deposition of lake sediment on an irregular glacial surface, followed by development of a thick peat sequence.

Electrical imaging is valuable for investigating basin stratigraphy, including beneath the mineral soil contact, beyond the range of GPR. In this study, the elevated conductivity of the confining clay, lake sediment and lowermost portion of the peat complicated interpretation of conductivity images. These are resolved as a single layer in the image. Consequently, conductivity is not a good indicator of the base of the peat, but is a good indicator of the combined thickness of lake and glaciomarine sediment.

In contrast to conductivity, chargeability is an excellent indicator of the thickness of the peat. Relative to the marine clay and lake sediment, the peat is chargeable. We associate this with the high surface charge and resulting high CEC of partially decomposed organic matter (Hobbs, 1986). Comparison with GPR data shows that the base of the upper chargeable layer is coincident with the base of the peat. High fluid conductivity within peat can limit the value of the GPR method for determining depth to mineral basement (Theimer et al., 1994). This is not a limitation of the IP method. Further IP measurements in peatlands will better resolve the value of the method.

Terrain conductivity mapping was effective for qualitatively defining variation in the thickness of the glaciomarine sediment across a large area of the peatland. An important factor in the correlation of terrain conductivity with glaciomarine sediment thickness is the uniformity in the electrical properties of the peat. Conductivity and IP models indicate a laterally uniform upper layer, although conductivity does increase with depth. Direct measurements of fluid conductivity show minimal variability laterally. Given the lateral uniformity of the peat, terrain conductivity appears primarily sensitive to the development of the glaciomarine sediment. In a peatland with greater lateral variability in fluid chemistry, terrain conductivity measurements will not be as sensitive mineral soil properties.

The geophysical interpretation may offer an explanation for the distribution of vegetation within the peatland. A distinct pattern of vegetation occurs within this peat basin, which is similar to that observed in other peatlands. We observed sphagnum and sedge dominated areas where the glaciomarine sediment, determined from electrical imaging, was thickest. In regions where the glaciomarine sediment thins, the vegetation abruptly changes to woody shrubs and stunted black spruce. Where the glaciomarine sediment thins, the ground was notably drier, suggesting increased drainage in these areas. Hydrogeologic measurements indicate that in the summer, the water table is highest and downward vertical hydraulic gradients are present near points W3 and W4, supporting our interpretation that the glaciomarine sediment is reducing drainage from the peat. We hypothesize that vertical flow, controlled by the thickness of the confining glaciomarine silt-clay layer, controls the nutrient availability by regulating solute transport and the position of the water table in the peat.

Conclusions

This integrated electrical study of a large peatland in Maine demonstrates the value of GPR, resistivity imaging, IP imaging and EM terrain conductivity mapping to the studies of peatlands. Consistent with previous work, we find that GPR is an excellent method for mapping peat stratigraphy above the mineral soil. The mineral soil contact was resolved at up to 8 m depth. An important boundary between peat and lake sediment was also mapped with GPR. No information was obtained beneath the mineral soil contact from GPR.

Conductivity and IP imaging are excellent methods for investigating electrical properties of the peat and the mineral soil. Imaging to a depth of 18 m identified the peat, confining clay unit and an unidentified resistive unit beneath the clay. The conductivity images resolved the variability in thickness of the confining glaciomarine sediment, a parameter that appears to control the hydrogeology of this peatland. IP was an excellent indicator of the thickness of peat. Peat is chargeable, due to enhanced polarization presumably caused by the high surface charge density on the organic matrix. Terrain conductivity measurements correlated with thickness of the confining glaciomarine sediment and were used to qualitatively map variations in glaciomarine sediment thickness over 17.6 km^2. This integrated geophysical approach may provide a valuable insight into important controls on peatland hydrology and its impact on the distribution of vegetation communities in a peatland.

Acknowledgments

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