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Geophysical and Hydrological Evaluation of Two Bog Complexes in a Northern Peatland: Implications for the Distribution of Biogenic Gases at the Basin Scale

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Geophysical and hydrological evaluation of two bog complexes in a northern peatland: Implications for the distribution of biogenic gases at the basin scale

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[1] Ground penetrating radar (GPR) was used to determine peat basin geometry and the spatial distribution of free-phase biogenic gasses in two separate units of a northern peatland (Central and Southern Unit of Caribou Bog, Maine). The Central Unit is characterized by a deep basin structure (15 m maximum depth) and a raised (eccentric) bog topographic profile (up to 2 m topographic variation). Here numerous regions of electromagnetic (EM) wave scattering are considered diagnostic of the presence of extensive free-phase biogenic gas. In contrast, the Southern Unit is shallower (8 m maximum depth) and has a slightly convex upwards bog profile (less than 1 m topographic variation), and areas of EM wave scattering are notably absent. The biogenic gas zones interpreted from GPR in the Central Unit are associated with: (1) wooded heath vegetation at the surface, (2) open pools at the surface, (3) high water table elevations near the center of the basin, and (4) a region of overpressure (at approximately 5 m depth) immediately below the zone of free-phase gas accumulation. The latter suggests (1) a transient pressure head associated with low hydraulic conductivity resulting from the biogenic gasses themselves or confining layers in the peat that restrict both gas release and groundwater flow and/or (2) overpressure in the peat column as a result of the gas buildup itself. In contrast, the Southern Unit, where zones of EM scattering are absent, is characterized by: (1) predominantly shrub vegetation, (2) a lack of open pools, (3) only minor variations (less than 1 m) in water table elevation throughout the entire unit; and (4) generally upward groundwater flow throughout the basin. The results illustrate the nonuniformity of free-phase biogenic gas distribution at the peat basin scale and provide insights into the processes and controls associated with CH_4 and CO_2 accumulation in peatlands.

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1. Introduction

[2] Northern peatlands emit significant amounts of methane (CH_4) and carbon dioxide (CO_2) to the atmosphere [*Cicerone and Oremland*, 1988], and play an important role in the global carbon (C) cycle. Northern peatlands account for approximately 7% of the global annual CH_4 emissions to the atmosphere [*Khalil*, 2000]. The effect of global warming on emissions remains a major uncertainty in climate modeling due to the high temporal and spatial variability in emission rates [*Moore et al.*, 1990]. Both laboratory studies showing the reduction in hydraulic conductivity due to formation of gas bubbles in peat soils [e.g., *Beckwith and Baird*, 2001], and field studies of ebullition fluxes of carbon gas from peatlands to the atmosphere [e.g., *Romanowicz et al.*, 1995; *Glaser et al.*, 2004], indicate the close connection between carbon cycling and hydrological processes. However, uncertainty exists regarding the volume and spatial distribution of biogenic gasses stored in peatlands; in particular the size and distribution of gas that is stored in the free-phase (as opposed to the dissolved phase) is the subject of uncertainty [e.g., *Kellner et al.*, 2004].

[3] CH_4 production in peatlands depends directly on anaerobic microbial activity within peat. Two critical factors indirectly controlling C-cycling and CH_4 production in peatlands are plant community structure, and position of redox

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boundaries associated with the water table [e.g., *Bubier et al.*, 1993; *Bubier*, 1995]. CO_2 production is the result of soil organic C mineralization and plant respiration. Carbon mineralization depends on oxygen availability, and is generally correlated positively with lower and/or fluctuating water tables and the abundance of vascular plants [*Blodau*, 2002]. Recent laboratory and field studies show that free-phase gas deposits represent a very significant contribution to the total ebullition flux of gasses from peatlands [e.g., *Beckwith and Baird*, 2001; *Glaser et al.*, 2004].

[4] The significance of vegetation on biogenic gas emissions has been addressed by *Bubier* [1995]. She concluded that plant communities may act as a conduit for CH_4 transport. *Yavitt et al.* [1997], in a study of multiple northern peatlands, observed higher CH_4 production in nonforested than in forested peatlands. Other studies show a correlation between vascular plants and CH_4 flux. *Waddington et al.* [1996] found a positive correlation between vascular plants and enhanced CH_4 emissions in peatlands under wet conditions (water table near the peat surface). They related this correlation to the interaction of the vascular plant roots with the saturated/anaerobic zone (or CH_4 production zone) during wet periods. In this situation, vascular plant roots are able to provide substrates for methanogenesis [*Whiting and Chanton*, 1992] more efficiently by directly reaching the anaerobic zone (higher during wet periods). Plant community structure also influences the degree of degradation of organic material as higher quality organic substrate induces higher methane production [*Granberg et al.*, 1997].

[5] The significance of water table elevation CH_4 and CO_2 emissions is well documented [e.g., *Roulet et al.*, 1993; *Hamilton et al.*, 1994]. Water table elevation influences the extent of the oxic/anoxic zone. The size of the oxic zone is the major factor determining the amount of methane produced in the anoxic zone that will oxidize before reaching the atmosphere [*Granberg et al.*, 1997]. In a review of the controls on C cycling in peatlands, *Blodau* [2002] concluded that CH_4 production and emission decrease exponentially with lower water tables. *Bubier et al.* [1993] measured higher CH_4 fluxes at open water ponds and adjacent areas (both associated with water tables close to the soil surface, or free-water surface above soil surface) from a total of 19 wetland sites in Canada. *Waddington and Roulet* [1996] observed flux variation as a result of topographic differences in a peatland in Sweden, with higher CH_4 emissions also correlated with pool areas, and stronger variations at the microtopographic scale, where water table elevation contrasts were maximal. *Roulet et al.* [1997] identified a beaver pond as a particularly large source of CO_2 and CH_4 emission to the atmosphere during the summer, relating the pond sediments (with high organic content) as the most probable source of carbon.

[6] The objective of this paper was to investigate the accumulations of biogenic gases at the basin scale in Caribou Bog (Maine) using the ground-penetrating radar (GPR) geophysical method. The paper also considers the implications of the findings with regard to the control of water table elevation and plant community structure on the accumulation of free-phase biogenic gasses.

2. Ground-Penetrating Radar

[7] Ground-penetrating radar (GPR) is a geophysical technique for subsurface exploration. A transmitting antenna generates a continuous high-frequency electromagnetic (EM) wave that penetrates the subsurface and is returned as a sequence of reflections from stratigraphic interfaces. The velocity of this EM wave is primarily controlled by the relative dielectric permittivity (ε_r), a geophysical property strongly dependent on water content. Moisture content changes at major sediment interfaces, owing to changes in porosity and organic matter content, cause strong GPR reflections [*Warner et al.*, 1990]. High fluid electrical conductivity in peat, or high percent of clay in the mineral soil, can excessively attenuate EM wave propagation, reducing the depth of penetration. This usually prevents the recording of reflections below the mineral soil interface often found underlying peat deposits [*Theimer et al.*, 1994; *Slater and Reeve*, 2002].

[8] Studies of hydrocarbon contaminated sites have shown that free-phase gas impacts GPR data in a similar manner to that described for seismic data collected over gas hydrates [e.g., *Judd and Hovland*, 1992; *Okyar et al.*, 1994]. Regions of faint or absent reflectors result from scattering of the acoustic energy by free-phase gas. *Daniels et al.* [1995] recorded regions of "EM blanking" (scattering of EM energy) in GPR data that they attributed to the displacement of water by hydrocarbon gas vapors. When using GPR to monitor hydrocarbon leakage, *Lopes de Castro and Branco* [2003] also identified regions of strongly attenuated reflections or shadow zones due to the build up of hydrocarbon vapors.

[9] In a recent study, *Comas et al.* [2005a] used surface and borehole ground penetrating radar (GPR), combined with moisture probe and direct gas sampling measurements, to investigate free-phase biogenic gasses in a small section (5 m long) of the Central Unit of Caribou Bog, Maine. The study site was situated next to an open pool. GPR profiles showed a contrast between areas with loss of reflections and a general chaotic trace signal, and the surrounding regions characterized by a continuous sequence of strong reflectors. These EM wave scattering regions were associated with biogenic gas accumulations and coincided with: (1) high CH_4 and CO_2 gas concentration, (2) high total free-phase gas concentration (maximum 10%) calculated from borehole GPR measurements using the complex refractive index (CRIM) model [e.g., *Huisman et al.*, 2003] and (3) relatively low moisture content determined from moisture probe profiles.

[10] In this paper, we expand upon *Comas et al.* [2005a] by utilizing surface GPR as a non-invasive technique to investigate the spatial variability of zones of high free-phase biogenic gas concentration at the basin-scale. Whereas *Comas et al.* [2005a] conducted a small-scale proof-of-concept GPR survey to detect biogenic gas accumulations within an approximate 40 m^2 area, in this paper the survey is upscaled to the basin

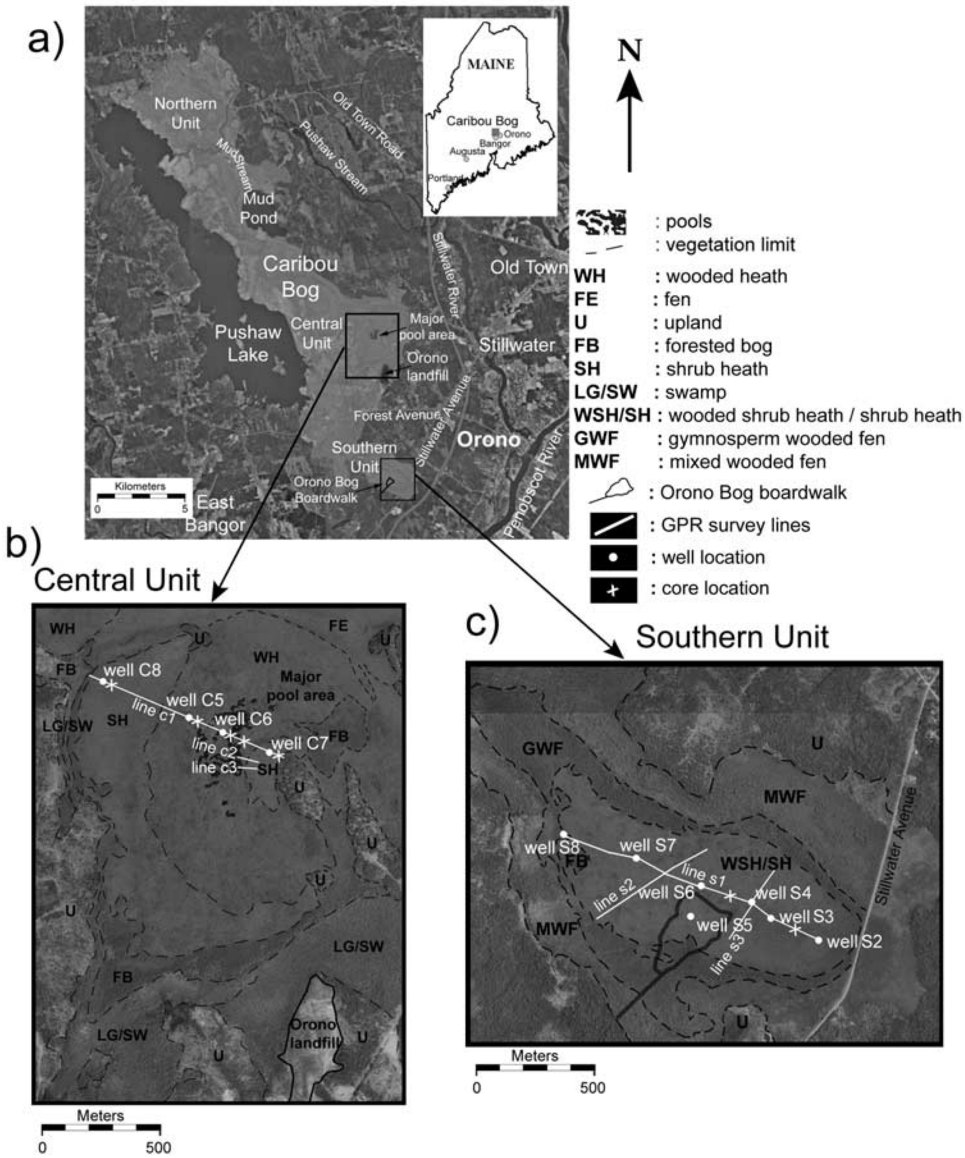

Figure 1. (a) Satellite image (USGS) showing the location of Caribou Bog and its three major units (Northern, Central, and Southern Units). The insert at top shows the location of Caribou Bog in Maine; (b) satellite image (USGS) showing the Central Unit of Caribou Bog, vegetation patterns (modified from *Davis and Anderson* [1999]), open pools, monitoring wells, geophysical survey lines, and core locations; (c) satellite image (USGS) showing the Southern Unit of Caribou Bog, vegetation patterns (modified from *Davis and Anderson* [1999]), monitoring wells, geophysical survey lines, and core locations.

level (up to 8000 m^2). On the basis of the clear results of *Comas et al.* [2005a], we assume that zones of EM scattering in surface GPR data observed in Caribou Bog result from accumulations of free-phase biogenic gasses. The geophysical measurements reported here are then considered to define the spatial extent of zones of EM wave attenuation that we attribute to regions of elevated free-phase gas concentration within the peat basin. Supporting hydrological and vegetation data yield valuable insights into the potential controls on the formation of these free-phase biogenic gases in peat basins and also display evidence for the regulation of peatland hydrological processes by biogenic gasses.

3. Field Site

[11] Caribou Bog, situated near Bangor, Maine (inset in Figure 1a), is a 2200-ha multiunit peatland composed of several raised bog complexes that sometimes coalesce with each other [*Davis and Anderson*, 1999]. Three units are distinguished in Caribou Bog and named based on geographic location as follows: Northern Unit, Central Unit and

Southern Unit (Figure 1a). The study area includes the Central Unit (Figure 1b), and the Southern Unit (Figure 1c) of Caribou Bog. Previous published work in Caribou Bog includes ecological characterization [e.g., *Davis and Anderson*, 2001], detailed vegetation surveys [*Davis and Anderson*, 1999], stratigraphic data [*Cameron et al.*, 1984], and paleoecological reconstructions [*Gajewski*, 1987; *Hu and Davis*, 1995]. The Southern Unit is probably the most extensively studied unit in Caribou Bog. Geophysical measurements (resistivity imaging, ground penetrating radar, terrain conductivity) were conducted in the Southern Unit to evaluate peatland stratigraphy [*Slater and Reeve*, 2002]. Geophysical and hydrological studies of the Central Unit of Caribou Bog were used to test the association of vegetation and pool patterning with peat basin stratigraphy [*Comas et al.*, 2004] and mineral soil composition [*Comas et al.*, 2005b].

[12] The Central and Southern Units of Caribou Bog exhibit distinct differences in size, vegetation patterning, groundwater hydrology, the presence/absence of pools at the surface, stratigraphy and topography [*Davis and Anderson*, 1999]. The Central Unit (covering approximately 3600 m^2) shows the topography and stratigraphy characteristic of an eccentric bog [*Davis and Anderson*, 2001], a domed bog where the highest point of the peat mound is displaced from the center of the basin area and water drains mainly in one direction. *Comas et al.* [2004] combined GPR data, electrical resistivity imaging and ground truth data, to detect peat thickness reaching 11 m in places, underlain by lake sediment (thicker than 5 m in the center of the basin), glacio-marine sediment and esker or till deposits. The Central Unit is characterized by sharp changes in vegetation patterns as depicted in Figure 1b. Two major plant communities are (1) bryophytes in *Sphagnum* lawn and low shrub (SH) dominated areas, and (2) vascular plants in wooded heath (WH) dominated areas. A large wooded heath area containing numerous pools (ranging from 10 m^2 to 600 m^2 in area) is surrounded by an elongated shrub region, and other smaller communities [*Davis and Anderson*, 1999]. The surveyed area of the Central Unit exhibits three major vegetation changes: from east to west, upland (U)-shrub (SH), shrub (SH)-wooded heath (WH), and wooded heath (WH)-shrub heath (SH) (Figure 1b). The Southern Unit (covering approximately 2000 m^2) has a flatter topography corresponding to a gently convex upwards bog (according to the classification by *Davis and Anderson* [2001]), with maximum elevations of the raised part above the surrounding fen typically less than 1 m. Previous geophysical data collected in the Southern Unit of Caribou Bog resolved the stratigraphy of this peat basin [*Slater and Reeve*, 2002]. Open pools are notably absent in the Southern Unit and the vegetation alternates between wooded shrub heath and shrub heath (WSH) [*Davis and Anderson*, 1999] (Figure 1c).

4. Methods

[13] A sequence of monitoring well clusters was installed in each unit during 2000 to permit monitoring of water levels within the peat and lake sediment deposits. Each cluster contained a minimum of three wells screened at multiple depths from the surface to the interface of the peat or lake sediment with the mineral soil. The depths of the screens varied between well clusters but were designed to measure the head in the shallow, intermediate and deep peat at each location. Wells were surveyed using a dual frequency global positioning system with a nominal accuracy of 1 cm and water levels within wells were measured using an electrical water level indicator during April 2000 at the Central Unit, and May 2000 at the Southern Unit.

[14] One main survey transect oriented SE–NW was established in the Central Unit (line c1 in Figure 1b) crossing a total of four well clusters (wells C5–C8 in Figure 1b). This longitudinal cross section of the bog basin crosses five major vegetation zones (from east to west: upland (U), shrub heath (SH), wooded heath (WH), shrub heath (SH), and forested bog (FB), Figure 1b), and an extensive area with open pools (between well C7 and well C5, within the WH). In the Southern Unit a total of six well clusters (wells S2–S8) follow a main transect (s1 in Figure 1c) also oriented SE–NW. This line represents a longitudinal cross section of the bog basin and is characterized by a single major vegetation type alternating between wooded shrub heath (WSH) and shrub heath (SH).

[15] GPR measurements were collected using a Mala-RAMAC system equipped with 100-MHz antennas that provide a good compromise between investigation depth and resolution in Caribou Bog [*Slater and Reeve*, 2002]. The spacing between traces was 0.1 m and sixteen stacks were used for each trace. The sampling time window was 680 ns, providing a maximum investigation depth of 12 m with approximate 25-cm resolution (based on one-quarter wavelength), assuming constant ε_r with depth and an average electromagnetic wave velocity (v) of 0.0355 m/ns in peat as determined from (1) the time move out of the reflection recorded from the peat-mineral soil contact observed in common-midpoint (CMP) surveys, and (2) measurement of the two-way travel time at invasive sampling locations where the peat-mineral soil contact was precisely measured. Processing steps were limited to (1) application of a time-varying gain (to distribute amplitudes equally in the time axis for each trace), (2) a "dewow" filter (to eliminate low frequencies by subtraction of a mean amplitude calculated for each trace over a 10 ns time window), (3) a band-pass filter (to eliminate high- and low-frequency noise), (4) a static correction to eliminate the time delay between trigger and recording, and (5) static correction to account for bog topography. Although peatland topography is generally irrelevant for short profiles, it was significant for these basin-scale surveys.

[16] In the Central Unit, areas with dense wooded heath vegetation and open pools across line c1 prevented GPR surveying in places, creating data gaps in this transect. Two smaller GPR transects (line c2 and line c3 in Figure 1b) crossing the major vegetation change from shrub heath (SH) to wooded heath (WH), and finishing in the region of open pools, were also established. In the Southern Unit a GPR survey was conducted along line s1 (Figure 1c), and two

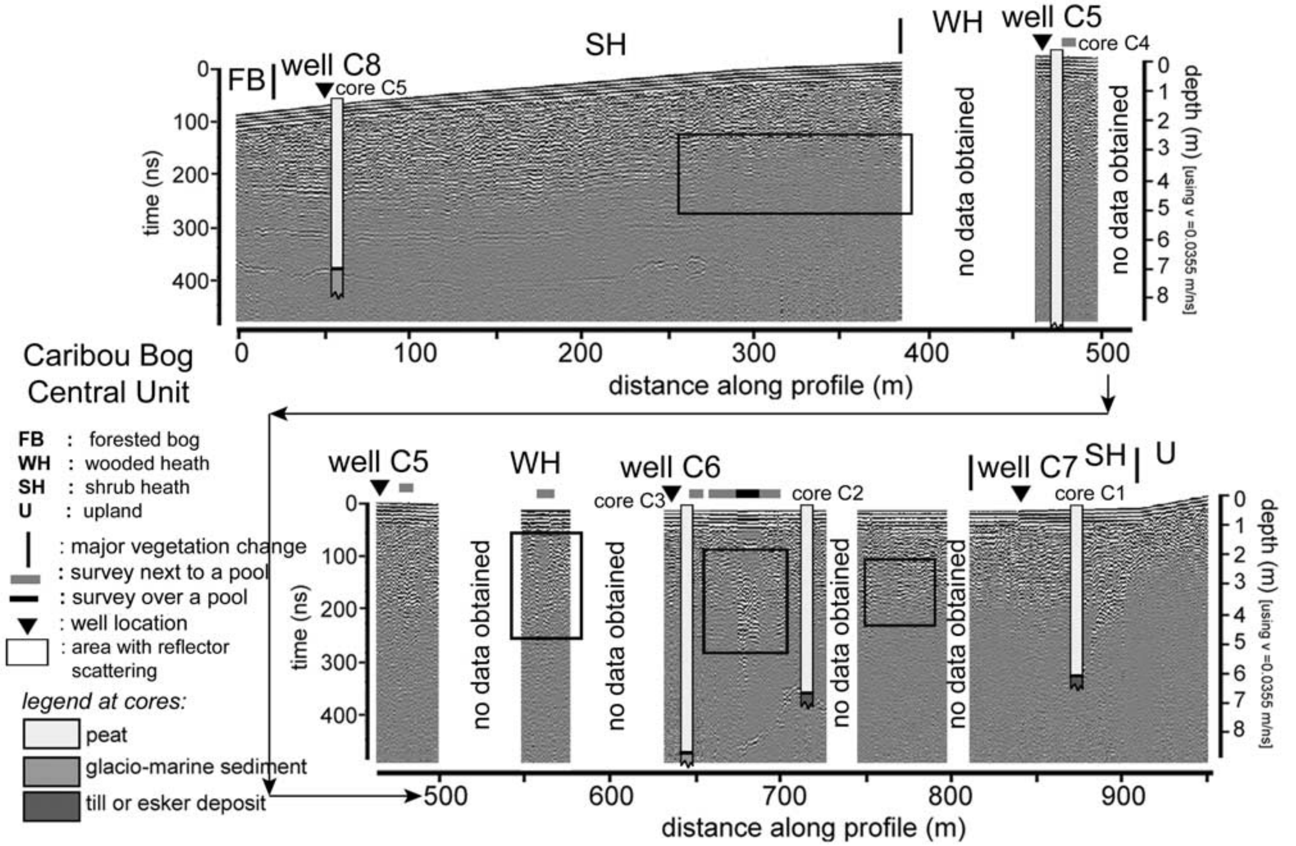

Figure 2. GPR profile results along line c1 (see Figure 1b for location) in the Central Unit of Caribou Bog. Vegetation at surface, open pools, well location, and coring results are also shown.

smaller GPR transects (line s2 and line s3 in Figure 1c) were used for comparison.

5. Geophysical Results

5.1. GPR Profiles in the Central Unit of Caribou Bog

[17] The GPR results for line c1 (see Figure 1b for location) of the Central Unit of Caribou Bog are displayed in Figure 2. The GPR profile, combined with coring at selected locations, depicts a thick peat deposit exceeding 9 m in places (e.g., in the center of the basin, around well C5, Figure 2). This GPR profile is characterized by the presence of areas of EM wave signal scattering (loss of coherent, laterally continuous reflectors) at shallow depths (approximately between 1 m to 5 m from the surface). As shown in Figure 2, several areas showing EM wave scattering contrast with the clear, continuous sequence of reflectors throughout most of the unit. The major areas of scattering and reflector loss are outlined with boxes in Figure 2: (1) between 275 and 375 m along the profile and at depths ranging between 2.5 to 4 m; (2) between 550 and 575 m along the profile and 1-4 m deep; (3) between 650 and 700 m along the profile and 1–5 m deep; (4) between 750 and 775 m along the profile and 2–4 m deep.

[18] To support the results of the main transect in the Central Unit, two shorter lines were run perpendicular to the SH/WH vegetation boundary and into the pool area (location on line c1 where EM wave scattering was observed). Figures 3a and 3b show lines c2 and c3, respectively, from the Central Unit. Both lines are characterized by strong and continuous reflector sequences, lack of EM scattering areas, and vegetation dominated by shrub from 0 m to approximately 50 m on the transect. EM wave scattering occurs on both lines (between 50 to 70 m along c2 as shown in Figure 3a; and although less pronounced still showing the characteristic chaotic reflectors between 55 to 70 m along c3 as shown in Figure 3b) and is associated with the transition to wooded heath vegetation and open pool areas at the surface. These results are consistent with the presence of EM scattering in areas dominated by wooded heath vegetation and open pools in line c1.

5.2. GPR Profiles in the Southern Unit of Caribou Bog

[19] GPR data fully characterizes the basin geometry of the Southern Unit owing to the relatively shallow depth (maximum 8 m) to the mineral soil (see Figure 4). GPR results are correlated with direct coring and indicate a layer of terrestrial peat, with an approximate thickness of 4–4.5 m, characterized by numerous strong GPR reflections resulting from moisture content changes within the peat. At about 4.5 m depth, a distinct reflector is detected and interpreted as the lake sediment boundary. The lake sediment is associated with a distinct change in physical properties being characterized by the absence of reflectors.

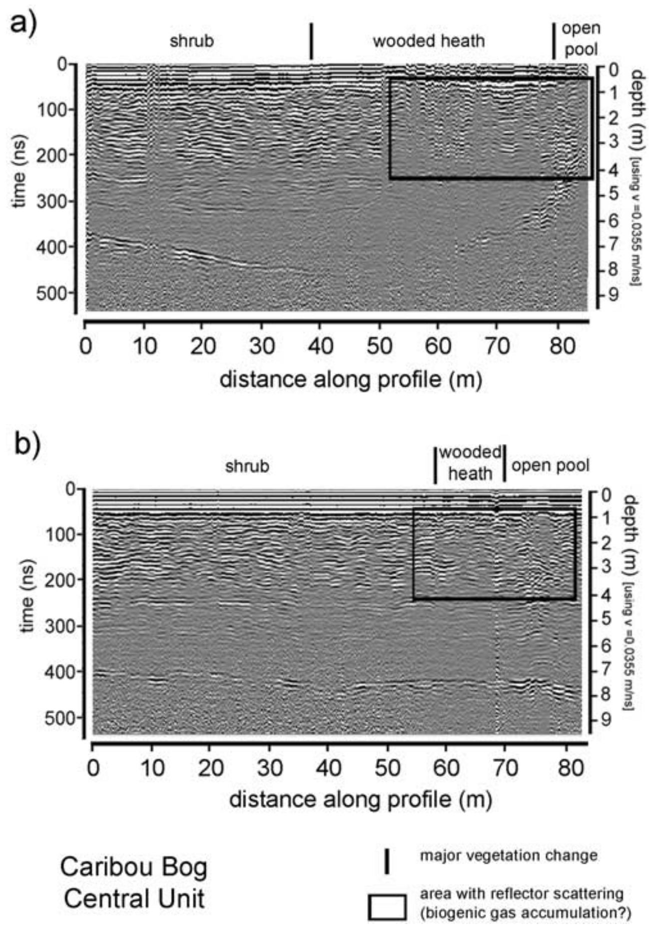

Figure 3. GPR profile results along (a) line c2 and (b) line c3 (see Figure 1b for location) in the Central Unit of Caribou Bog. Vegetation at surface, open pools, and well location are also shown. Squares outline areas showing GPR reflector scattering interpreted as free-phase biogenic gas accumulations.

Glacio-marine sediment underlies the lake sediment and is resolved as a single, flat reflector, with complete attenuation of the GPR signal in the clay-rich deposits below.

[20] The characteristic feature of the 1.1 km of GPR data (Figure 4) obtained in the Southern Unit is the presence of numerous and continuous reflections from the surface down to the peat-lake sediment interface. Areas of EM wave scattering (loss of coherent reflectors) are entirely absent. Results for lines s2 and s3 at the Southern Unit (Figure 5) are consistent with that described for line s1, most notably in that areas of EM scattering are again entirely absent. All GPR data obtained in the Southern Unit is characterized by (1) a continuous sequence of numerous GPR reflectors within the peat layer, and (2) an absence of zones of EM wave scattering. This result suggests that zones of high free-phase biogenic gas concentration are absent in the Southern Unit.

6. Hydrological Results

[21] Figure 6 shows the hydraulic head patterns as a function of depth for wells S2–S8 in the Southern Unit of Caribou Bog during May 2000. Groundwater within the peat generally flows slightly upwards to the northwest. Slight upward groundwater flow toward the southeast appears to occur between wells S3 and S2: well S3 most likely coincides with a drainage divide associated with the point of highest elevation on the slightly convex bog surface. There is some evidence for downward flow at depth (below 5 m) toward the west margin (from well S7 to well S8). The groundwater surface decreases toward the northwest (approximately 1 m difference from well S4 to well S8) and is associated with the topographic variation (less than 1 m).

[22] Figure 7 shows hydraulic head patterns for wells C8–C7 in the Central Unit of Caribou Bog during April 2000. Flow within the Central Unit under the peat dome is characterized by downward flow below 5 m but slight upward flow within the top 4 m. The groundwater surface shows greater variation than observed in the Southern Unit (almost 2 m difference between well C5 and well C8), probably being associated with the greater topographic range in the Central Unit. Higher water table values are associated with the wooded heath and pool area (at wells C5 and C6, as also shown by *Comas et al.* [2004]), while lower water table elevations are associated with shrub areas (at wells C8 and C7). A striking difference between the hydrological patterns of the two units is the presence of a region of a high hydraulic head (overpressure) in the Central Unit at depth (approximately 5 m) between 500 m and 700 m along the profile. This region is where the highest hydraulic head values for the Central Unit are recorded and occurs immediately below the region of EM wave scattering observed with GPR.

7. Discussion

[23] GPR surveys across the Central and Southern Unit of Caribou Bog (Figures 2 and 4) illustrate stratigraphic differences between the basins. However, the most striking observation from this study is the contrast in zones of EM wave scattering observed in the GPR profiles, coupled with the different groundwater flow patterns, obtained from the two units. We infer that the EM scattering observed in the GPR profiles results from the dispersion of EM energy as it travels through a zone of high free-phase gas concentration as proposed by others [e.g., *Daniels et al.*, 1995]. In the Central Unit extensive areas of EM wave scattering attributed to biogenic gas accumulations are observed (Figure 2) and the peatland hydrology is characterized by elevated hydraulic head at depth. In the Southern Unit (Figure 4), not a single area of such EM wave scattering was detected on more than 2 km of GPR data and upward groundwater flow generally occurs throughout the basin.

[24] Interpreted free-phase biogenic gas accumulations in the Central Unit coincide with wooded heath and open pool areas as shown in the results for line c1 (Figure 2). Data from two additional lines (c2 and c3) that bisect the major vegetation change from shrub to wooded heath, and traverse part of the open pool area (Figure 3), support this suggestion. Such zones are entirely absent in the profile across the Southern Unit, which is characterized by a simpler vegeta-

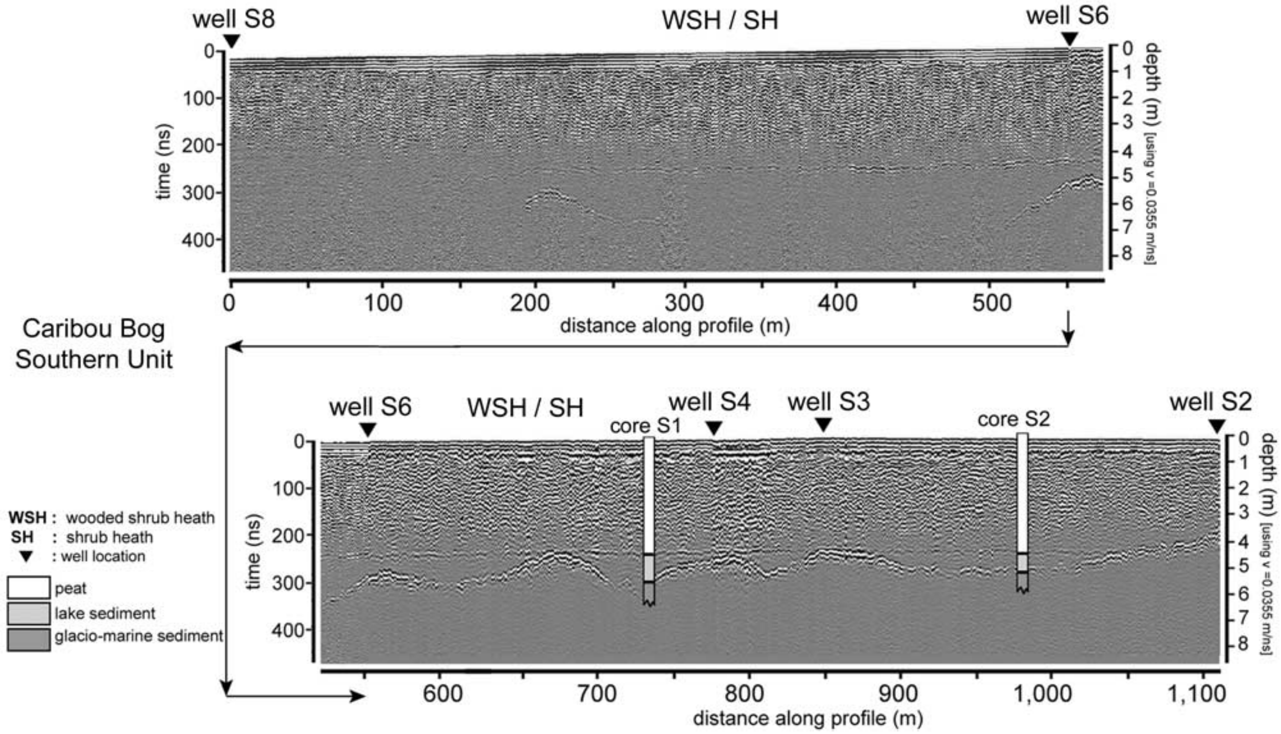

Figure 4. GPR profile results along line s1 (see Figure 1c for location) in the Southern Unit of Caribou Bog. Vegetation at surface, well location, and coring results are also shown.

tion structure comprised of mixed shrub interspersed with wooded heath.

[25] As previously postulated by others [e.g., *Romanowicz et al.*, 1995], the production of biogenic gas within the peat column may be a critical process influencing the groundwater flow patterns within peatland systems. High water table elevation and a downward groundwater flow below 4 m (Figure 7) coincide with the location of interpreted biogenic gas zones in the Central Unit. Most significantly, the region of high hydraulic head (elevated pressure) at about 5 m depth in the Central Unit (between 500 m and 700 m along the profile, as shown in Figure 7) is located immediately below the zones of high free-phase biogenic gas concentration inferred from the GPR data.

[26] Recent simulations of groundwater flow in a Minnesota peatland [*Reeve et al.*, 2005] suggested that high intermediate hydraulic heads may be partially due to increased storage of the peat induced by weather-driven temporal shifts in the water table position. However, accounting for the depth of the zone of high hydraulic conductivity recorded in this study (below 4 m), it seems reasonable to disregard climate forcing as a plausible hypothesis. We instead suggest that this region of overpressure reflects (1) the buildup of biogenic gasses themselves and resulting excess pore fluid pressure [e.g., *Beckwith and Baird*, 2001], and/or (2) a transient response associated with a zone of reduced hydraulic conductivity caused by confining layers in the peat that also trap biogenic gasses [e.g., *Romanowicz et al.*, 1995; *Glaser et al.*, 2004; *Comas et al.*, 2005a] or the biogenic gasses themselves [e.g., *Beckwith and Baird*, 2001]. Overpressures in peat columns due to the production of biogenic methane have previously been associated with the alteration of groundwater flow [e.g., *Romanowicz et al.*, 1993; *Glaser et al.*, 2004; *Kellner et al.*, 2004].

[27] Our results agree in a number of ways with previous studies. First they are consistent with previous investigations in other peatlands where accumulations of biogenic gas bubbles coincide with vascular plants (i.e., wooded heath) at the surface. Our findings in the Central Unit are also consistent with studies suggesting that major gas production in peatlands is associated with high hydraulic head (or elevated pressure) areas. Finally, the apparent correlation between the location of pools in the Central Unit and zones of EM scattering supports the correspondence between pools and methane emissions postulated by other authors [i.e., *Waddington and Roulet*, 1996].

[28] Previous studies suggest that carbon transport and sources of gas production in peatlands can be controlled by the groundwater flow regime [*Charman et al.*, 1994]. *Glaser et al.* [2004] in the study of biogenic gasses in a northern peatland, concluded that higher rates of methane production in deeper peat soils were stimulated by the downward transport of organic compounds previously released from plant roots. Although our hydrological results were not able to resolve groundwater flow patterns at the microscale, the presence of wooded heath vegetation roots may support this hypothesis by inducing downward transport of organic compounds and subsequent build up of biogenic gas accumulations in the Central Unit. Groundwater flow patterns in peat bogs have been shown to reverse seasonally [i.e., *Romanowicz et al.*, 1993] and it is possible

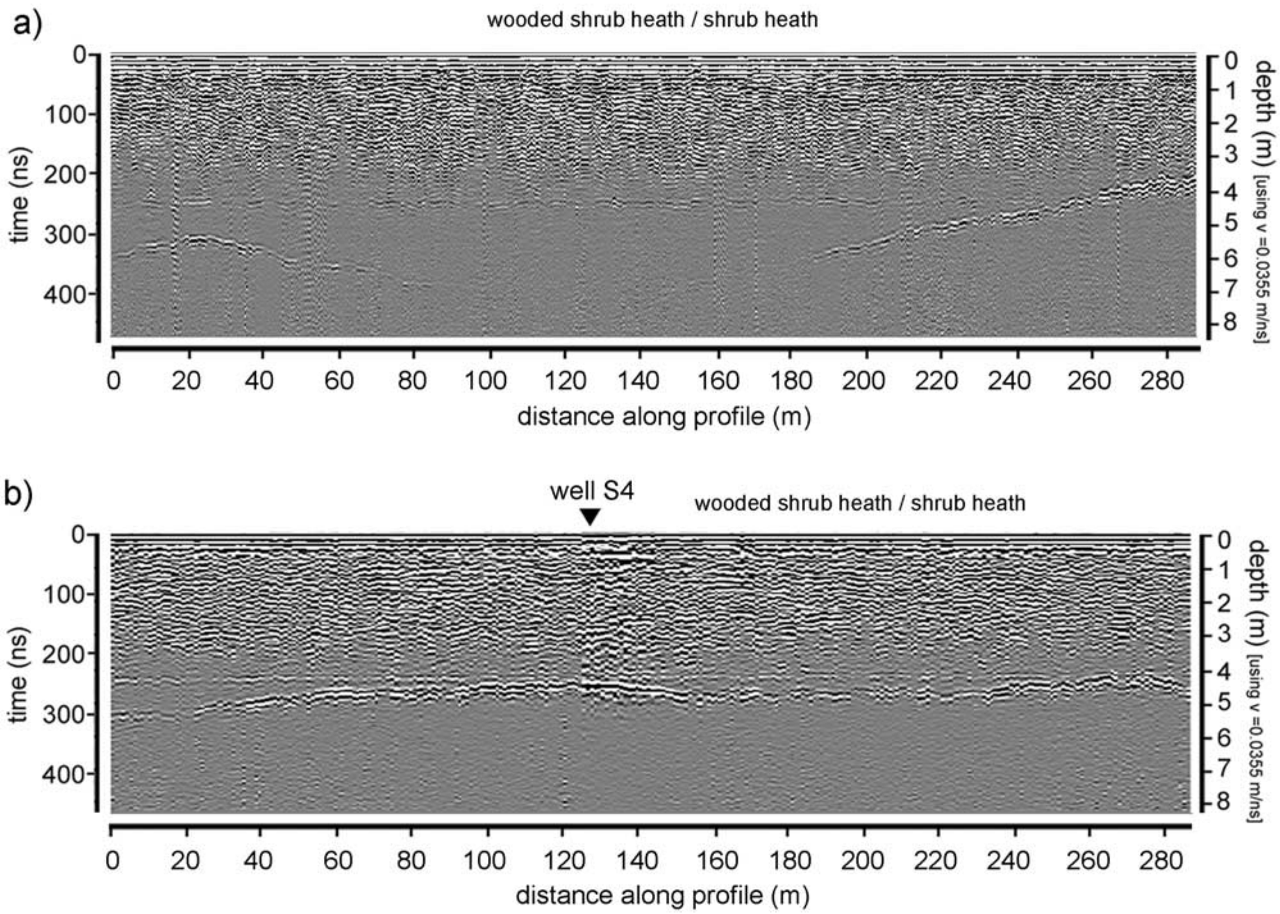

Figure 5. GPR profile results along (a) line s2 and (b) line s3 (see Figure 1c for location) in the Southern Unit of Caribou Bog. Vegetation at surface and well locations are also shown.

that such downward transport of organic compounds is more prevalent at other times of the year.

[29] We do not intend to imply that formation of CH_4 and CO_2 is exclusive to the Central Unit and does not occur at the Southern Unit, but to suggest a very different gas distribution between the two basins. Factors affecting this different distribution between the two units may include: different microbial activity, different rates of biogenic gas production, different form of accumulation, different emission rates to the atmosphere, or temporal variations in emission rates. Biogenic gasses may then exist in the Southern Unit as low concentration free-phase or high concentration dissolved phase; alternatively, accumulations are smaller (and pressurized zones in the peat

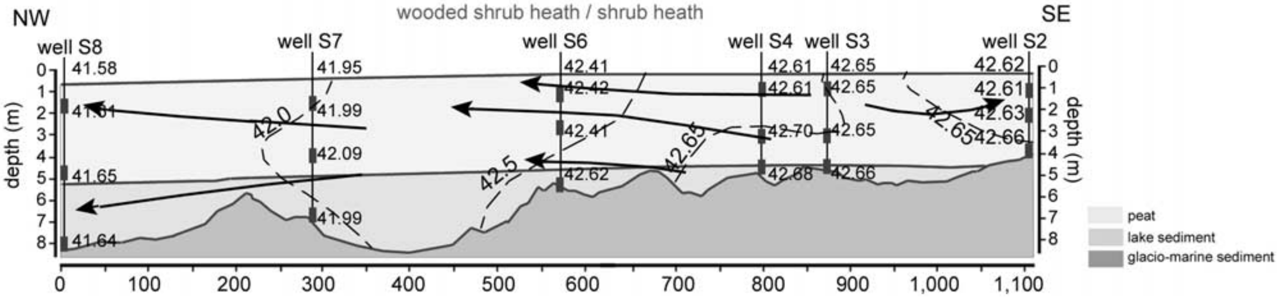

Figure 6. Interpreted cross section of the Southern Unit of Caribou Bog (line s1) showing the hydraulic head values as a function of depth, and the interpreted groundwater flow movement during May 2000. Major vegetation at surface is also shown. GPR data and core measurements are used to define the lake sediment-mineral soil interface.

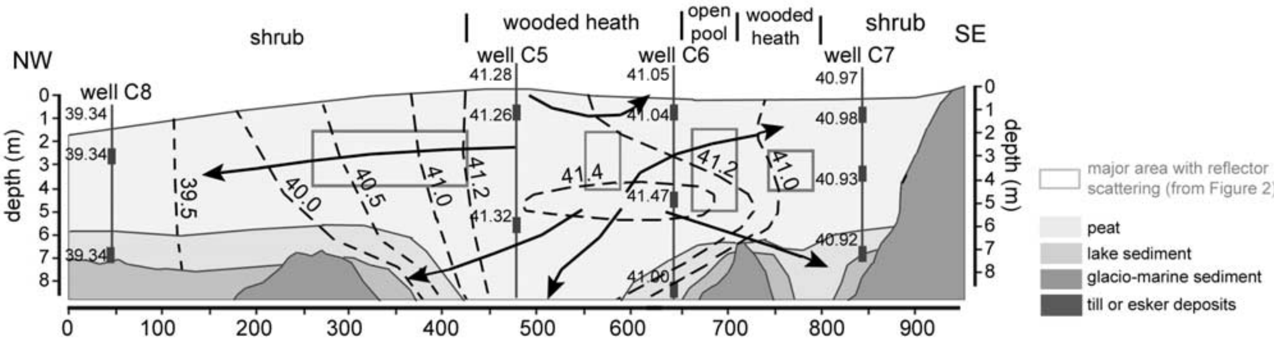

Figure 7. Interpreted cross section of the Central Unit of Caribou Bog (line c1) showing the hydraulic head values as a function of depth, and the interpreted groundwater flow directions during April 2000. Major vegetation patterns and the location of pools at the surface are also shown. GPR data and core measurements are used to define the lake sediment-mineral soil interface.

do not develop) owing to the absence of physical barriers thereby allowing a continuous gas release to the atmosphere. Previous studies [e.g., *Strack et al.*, 2005] have shown temporal patterns in free-phase methane accumulations with low bubble volumes in early summer and high volumes in mid to late summer. It is therefore possible that the biogenic gas distributions inferred from GPR will vary with season.

[30] Figure 8 shows a conceptual model depicting the development of free-phase biogenic gasses in the Central Unit of Caribou Bog. The accumulation of CH_4 and CO_2 gas detected with GPR (Figure 2) originates below wooded heath vegetation areas possibly associated with enhanced methanogenesis due to the downward transport of organic compounds from plant roots where water table elevations are high [*Glaser et al.*, 2004]. Development of free-phase biogenic gasses below open pool areas can be related to enhanced degradation of peat underlying the pools as described by others [e.g., *Foster et al.*, 1983; *Hamilton et al.*, 1994]. A zone of overpressure develops that is likely associated with a reduction of hydraulic conductivity due to the buildup of biogenic gasses themselves and/or the presence of confining layers in the peat.

8. Conclusions

[31] This study shows the potential of GPR as a noninvasive technique for investigating biogenic gasses in peatlands at the basin scale. The presence of areas of EM wave scattering detected with GPR and associated with high free-phase biogenic gas concentrations in the Central Unit of Caribou Bog contrast with the complete absence of such features in the Southern Unit; this suggests different processes or controls associated with CH_4 and CO_2 accumulation between the two units. The interpreted zones of high free-phase biogenic gas concentration are associated with: (1) wooded heath vegetation at the surface; (2) presence of open pools; (3) high water table elevations near the center of the basin; and (4) a region of high hydraulic head (elevated pressure) at depth (and below the zone of interpreted gas accumulation) that may be the result of: (1) a transient pressure head associated with a zone region of low hydrau-

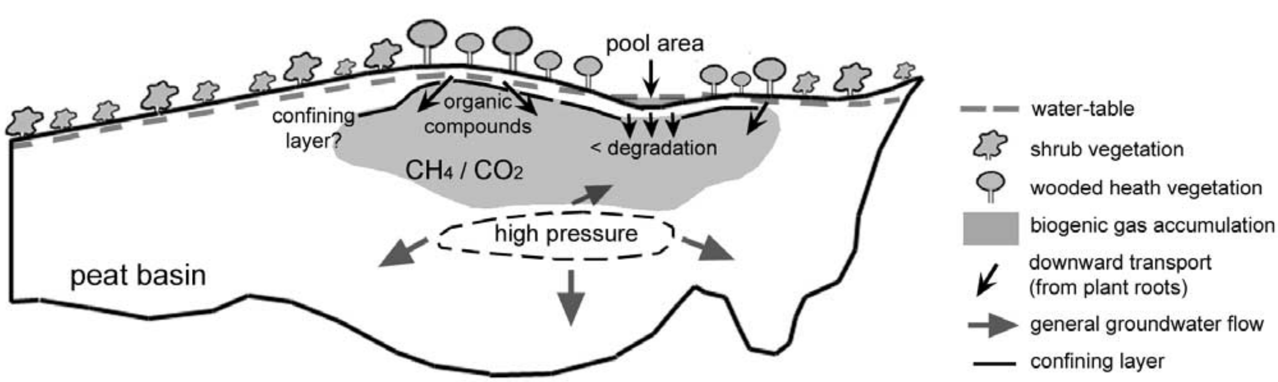

Figure 8. Interpreted model for biogenic gas accumulations in the Central Unit of Caribou Bog. CH_4 and CO_2 gas accumulation may be enhanced below wooded heath areas owing to the downward transport of organic compounds from plant roots, and owing to increased peat degradation underneath open pool areas. A region of overpressure may result below the zone of gas accumulation as a result of the a reduction of hydraulic conductivity due to the buildup of biogenic gasses themselves and/or the presence of confining layers in the peat.

lic conductivity resulting from the presence of confining layers in the peat that also impede biogenic gas release and/or the free-phase gasses themselves, or (2) an increase pore fluid pressure due to the production of bacterially induced methane itself as postulated by others. This geophysical method could conceivably be adapted to the temporal monitoring of free-phase biogenic gas in order to detect changes in gas concentration due to emission fluxes (i.e., ebullition), and to improve our understanding of carbon cycling in peatlands in general.

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