



# Thermokarst lake methanogenesis along a complete talik profile

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**Abstract.** Thermokarst (thaw) lakes emit methane (CH<sub>4</sub>) to the atmosphere formed from thawed permafrost organic matter (OM), but the relative magnitude of CH<sub>4</sub> production in surface lake sediments vs. deeper thawed permafrost horizons is not well understood. We assessed anaerobic CH<sub>4</sub> production potentials from various depths along a 590 cm long lake sediment core that captured the entire sediment package of the talik (thaw bulb) beneath the center of an interior Alaska thermokarst lake, Vault Lake, and the top 40 cm of thawing permafrost beneath the talik. We also studied the adjacent Vault Creek permafrost tunnel that extends through ice-rich yedoma permafrost soils surrounding the lake and into underlying gravel. Our results showed CH<sub>4</sub> production potentials were highest in the organic-rich surface lake sediments, which were 151 cm thick (mean ± SD: 5.95 ± 1.67 μg C–CH<sub>4</sub> g dw<sup>-1</sup> d<sup>-1</sup>; 125.9 ± 36.2 μg C–CH<sub>4</sub> g C<sub>org</sub><sup>-1</sup> d<sup>-1</sup>). High CH<sub>4</sub> production potentials were also observed in recently thawed permafrost (1.18 ± 0.61 μg C–CH<sub>4</sub> g dw<sup>-1</sup> d<sup>-1</sup>; 59.60 ± 51.5 μg C–CH<sub>4</sub> g C<sub>org</sub><sup>-1</sup> d<sup>-1</sup>) at the bottom of the talik, but the narrow thicknesses (43 cm) of this horizon limited its overall contribution to total sediment column CH<sub>4</sub> production in the core. Lower rates of CH<sub>4</sub> production were observed in sediment horizons representing permafrost that has been thawing in the talik for a longer period of time. No CH<sub>4</sub> production was observed in samples obtained from the permafrost tunnel, a non-lake environment. Our findings imply that CH<sub>4</sub> production is highly variable in thermokarst lake systems and that both modern OM supplied to surface sediments and ancient OM supplied to both surface and deep

lake sediments by in situ thaw and shore erosion of yedoma permafrost are important to lake CH<sub>4</sub> production.

## 1 Introduction

Permafrost contains an estimated 1140–1476 Pg of soil organic carbon (OC; Hugelius et al., 2014). It is considered to be a vulnerable carbon (C) pool in a warming climate (Schaefer et al., 2014; Schuur and Abbott, 2011), as both models and observations indicate that permafrost is warming and thawing in many regions (Romanovsky et al., 2010). Large uncertainties remain about the magnitude, timing, and form of C loss to the atmosphere from thawing permafrost; however, some studies suggest thawing permafrost will release 19–208 Pg C by 2050 (Schuur et al., 2013; Harden et al., 2012). A substantial portion (~450 Pg) of the deep permafrost C pool is stored in permafrost soils of the yedoma region, both in undisturbed yedoma and in the organic-rich sediments of thermokarst lake basins in the yedoma region (Walter Anthony et al., 2014). Yedoma refers to the icy late-Pleistocene loess-dominated permafrost soil type that occurs predominantly in previously unglaciated lowland regions of Beringia (NE Siberia, Alaska, and NW Canada; Grosse et al., 2013b; Zimov et al., 2006). Typical yedoma deposits in Alaska are 10–30 m thick, but can reach local thicknesses greater than 60 m (Pewe, 1975). Late Pleistocene yedoma ice wedges range from 2 to 6 m in width and can extend tens of meters below the ground surface (Kanevskiy et al., 2011). In addition to being ice-rich, the OC content of yedoma is

high (2–5 %) for mineral soils (Walter Anthony et al., 2014; Strauss et al., 2013; Schirrmeister et al., 2011; Kholodov et al., 2003), and yedoma soils typically contain OC contents 10–30 times higher than that of similar loess-dominated non-permafrost soils (Zimov et al., 2006).

In a warming climate, or when subjected to ground-surface disturbance, ice-rich yedoma is prone to thermokarst lake formation, a process by which the melting of massive ground ice forms depressions that fill with water (Soloviev, 1973). In yedoma-dominated regions, up to 90 % of all lakes are thermokarst lakes (Pienitz et al., 2008). Thermokarst lakes strongly alter the local thermal balance of the land surface and transfer heat from the water body into the underlying ground more effectively than other land cover types (Grosse et al., 2013a; Burn, 2005), especially when the depth of a lake exceeds the thickness of the winter lake ice. The enhanced heat flux triggers rapid permafrost thaw and talik (thaw bulb) formation underneath the lake (Plug and West, 2009), which can lead to the mobilization of freshly thawed OC from yedoma (Kessler et al., 2012).

As permafrost thaws, it releases previously frozen OC, which can subsequently be processed by microorganisms that produce methane (CH<sub>4</sub>) and carbon dioxide (CO<sub>2</sub>). It is estimated that arctic systems annually emit 15–50 Tg of CH<sub>4</sub> (McGuire et al., 2009), a potent greenhouse gas which has 34 times more global warming potential than CO<sub>2</sub> over a 100-year time period (Myhre et al., 2013). Many lakes formed in permafrost-dominated landscapes, particularly yedomatype thermokarst lakes, have high rates of CH<sub>4</sub> emission (Sepulveda-Jauregui et al., 2015; Walter et al., 2007). The CH<sub>4</sub> emitted from arctic lakes largely originates in terrestrial sources such as the Holocene soils of the lakes' watersheds (Kling and Kipphut, 1991), the thaw of Holocene- and Pleistocene-aged permafrost soil beneath and surrounding the lakes (Walter Anthony and Anthony, 2013; Brosius et al., 2012; Walter et al., 2008; Zimov et al., 1997), and decomposition of contemporary organic matter (OM) in the lakes (Walter Anthony et al., 2014).

The location of CH<sub>4</sub> production in thermokarst lake systems is not well understood. Using radiocarbon dating, stable isotopes, and spatial mapping of CH<sub>4</sub> emissions within lakes, Walter et al. (2006) concluded that the highest rates of CH<sub>4</sub> emission occur along thermokarst margins, originating from actively expanding taliks. Numerical modeling of CH<sub>4</sub> production in thermokarst lakes confirmed field-based observations that CH<sub>4</sub> production is concentrated along permafrost thaw margins of lakes (Kessler et al., 2012). Surface lake sediments contain contemporary OM as well as re-deposited, thawed permafrost OM. Both sources may fuel CH<sub>4</sub> production. At greater sediment depths, permafrost thaw in taliks under thermokarst lakes also supplies substrate for methanogenesis. However, the labile fraction of thawed permafrost OM is in limited supply so, given enough time, CH<sub>4</sub> production in thawed permafrost sediments can diminish (Walter Anthony et al., 2014; Kessler et al., 2012).

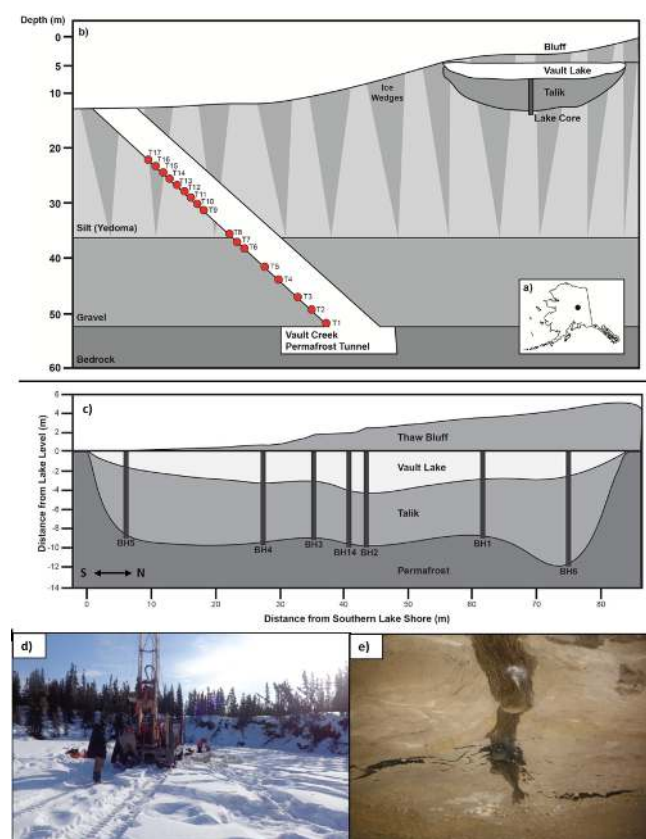
The objective of this study was to constrain the location and magnitude of CH<sub>4</sub> production in a thermokarst lake environment. We conducted long-term anaerobic incubations using sediment samples collected from a deep thermokarst lake core in the center of the lake that extended from the sediment surface, through the talik, and into the yedoma permafrost underlying the talik. We compared CH<sub>4</sub> production rates from the lake core to those of samples collected from an adjacent permafrost tunnel, which extended through yedoma deposits into the underlying gravel. We also measured the thickness of the talik at various locations in the lake to help constrain the spatial variability of CH<sub>4</sub> production in the lake.

## 2 Methods

### 2.1 Study site

The Vault Creek permafrost tunnel and Vault Lake (informal name; 65.0293° N, 147.6987° W) are located approximately 40 km north of Fairbanks, Alaska, USA, in a region characterized by discontinuous permafrost (Fig. 1). The region experiences a continental climate with a mean annual air temperature of −2.39 °C and 274.6 mm mean annual precipitation (Fairbanks International Airport 1981–2010, National Climate Data Center). The 220 m long Vault Creek permafrost tunnel, previously described by Meyer et al. (2008), extends through a 25 m thick yedoma sequence and a 15 m thick gravel horizon down to bedrock. The tunnel entrance is secured by a steel tube, making the top 8 m of the profile inaccessible to sampling. Vault Lake (3200 m<sup>2</sup>, 4.6 m maximum depth, 3.7 m average depth; Walter Anthony, unpublished data), located within 60 m of the subsurface tunnel, is a first-generation thermokarst lake formed by the melting of permafrost ground ice, including massive ice wedges. Steep, eroding bluffs, tilted spruce trees along the margins, and numerous CH<sub>4</sub> bubbling seeps across the lake surface indicate that the lake is still actively deepening and laterally expanding.

We measured lake and talik depth in March 2013 by drilling boreholes through thawed sediments to the permafrost table at six points along a transect spanning the long axis of the lake and at eight additional points distributed across the lake. Lake area and thermokarst bank height were measured by differential GPS (Leica Viva GS15, Leica Geosystems, Norcross, Georgia, USA) in November 2013. Talik temperatures were measured in galvanized steel tubes placed in two boreholes, one near the center of the lake (borehole (BH) 13) and the other 6.1 m from an actively expanding thermokarst margin (BH10). We installed temperature sensors (Onset TMCx-HD, accuracy ±0.21 °C, Onset Corporation, Bourne, Massachusetts, USA) at four depths below the sediment–water interface within the talik (BH10: 0.5, 1.0, 6.2, and 8.85 m; BH13: 0.5, 1.0, 5.7, and 6.2 m). With the ex-



**Figure 1.** Location map (a), study site overview (b), and Vault Lake morphology shown in cross section along the long axis of the lake (c) for Vault Lake and Vault Creek permafrost tunnel, Alaska, USA (65.0293° N, 147.6987° W). Height of the thaw bluffs was measured using differential GPS (DGPS). Depth of the Vault Lake talik was measured using the delineated borehole transect (c). Thaw bluff heights, lake depth, talik depths, and distance between boreholes (b, c) are shown to scale. Vault Lake is a 3230 m<sup>2</sup>, 3.7 m deep thermokarst lake with thermokarst bluffs (d) ranging from 0.2 to 4.5 m in height and a 5.9 m deep talik underneath. The Vault Lake core was collected from the center of the lake (BH14). The Vault Creek permafrost tunnel extends 220 to 40 m depth below the ground surface. Ice wedges (e) are present to 23 m depth. Tunnel sampling sites are marked as red dots; numbers adjacent to the dots represent incubation sample IDs. Photographs by K. M. Walter Anthony (d) and J. K. Heslop (e).

ception of a missing-data period between 25 July 2014 and 11 November 2014, temperatures were recorded hourly from May 2013 through December 2014.

## 2.2 Sediment sample collection, preparation, and characterization

During March 2013, a 590 cm long sediment core was collected from the center of Vault Lake (BH14, 4.0 m water depth). Using a Boart Longyear diamond core drilling system, continuous sediment cores were retrieved by percussion

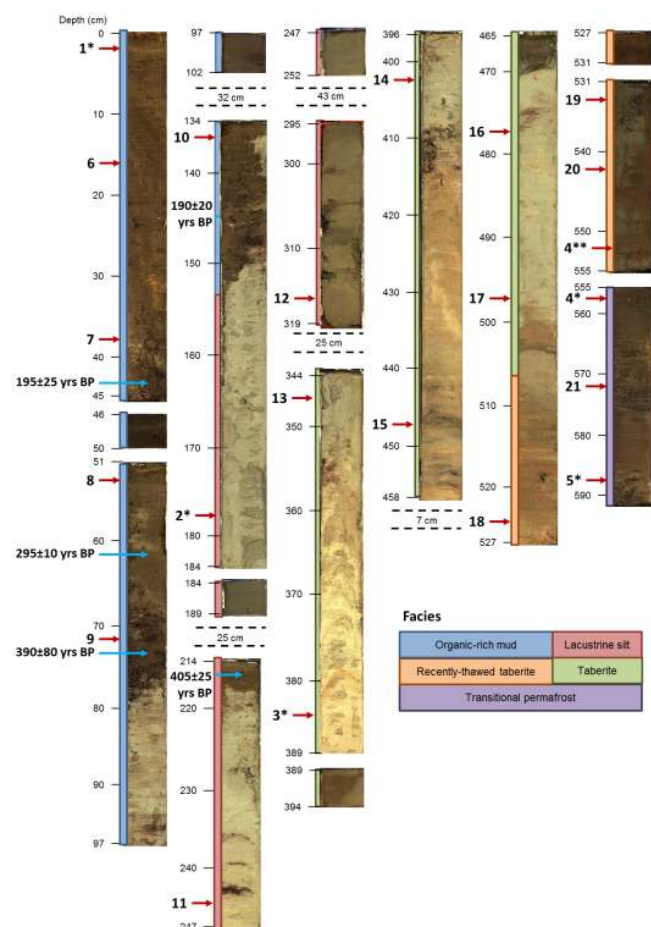
coring with a split spoon sampler. Sediment core sections were retrieved in 6 cm diameter clear plastic liners inside of core barrels in approximately 60 cm intervals from the same hole. Casing inside the hole ensured that adjacent sediments did not slough. The sediment core captured nearly the entire sequence of thawed lake sediments in the talik (550 cm) and the top 40 cm of permafrost beneath the talik, though several short sections of core were lost from tubes during retrieval (Fig. 2). Thawed core sections were sealed and stored in the laboratory at 3 °C. The permafrost section was sealed and stored in the laboratory at −10 °C.

We measured magnetic susceptibility on the intact Vault Lake core using a loop sensor on an automated core logger (Geotek MSCL-X, Geotek Limited, Daventry, Northamptonshire, United Kingdom) at the Limnological Research Center Core (LacCore) Facility in the University of Minnesota, Minneapolis, Minnesota, USA. Then we split the core lengthwise and immediately sealed and archived one half of the core at 3 °C for later use in anaerobic incubations. This first half of the core was sealed with four layers of oxygen- (O<sub>2</sub>) and moisture-barrier film (Krehalon PC101, Filcon, Clare, Michigan, USA).

On the second half of the core, we conducted initial core descriptions and made the following measurements at LacCore. We imaged the core using a line scan camera (Geotek Geoscan-III, Geotek Limited, Daventry, Northamptonshire, United Kingdom). High-resolution magnetic susceptibility was measured in 0.5 cm intervals using a point sensor on an automated core logger (Geotek MSCL-XYZ, Geotek Limited, Daventry, Northamptonshire, United Kingdom). We sampled sediments in 10 cm intervals along the core at a known volume (3 cm<sup>3</sup>). We weighed samples at field moisture, then dried them at 105 °C for 48 h and reweighed them to determine the weight loss compared to the total weight of the wet sample (gravimetric water content) and dry sediment weight per unit volume (dry bulk density). Smear slides were created from samples taken every 10 cm along the core and analyzed under a microscope to quantify the relative abundance of organic and mineral matter, sponge spicules, and diatoms.

We quantified plant macrofossils in a subset of lake sediment core samples (Table S1 in the Supplement). Macrofossil samples were sieved using a 250 µm sieve, and the remaining plant material was examined in a petri dish in a slurry with deionized water using a binocular microscope. Relative percentages of each macrofossil type were calculated for each sample. Any macrofossils worth noting (seeds, leaves, needles, etc.) that did not comprise a large enough fraction of the sample were counted separately and simply noted as present.

In addition to the lake sediment core, triplicate samples of permafrost soils exposed in the Vault Creek tunnel adjacent to the lake were collected using a 75 cm<sup>3</sup> hole saw mounted on a hand-held hammer drill from 16 distributed depths along the tunnel walls. The sediment samples repre-



**Figure 2.** The Vault Lake core with the five facies (Organic-rich mud, Lacustrine silt, Taberite, Recently thawed taberite, and Transitional permafrost) delineated. Core depth values are indicated; core subsampling locations for incubations are marked using red arrows with bold numbers indicating incubation sample IDs; locations of picked and  $^{14}\text{C}$  dated macrofossil are shown by blue arrows and calibrated  $^{14}\text{C}$  ages (calendar years BP). Labeled breaks represent gaps in the sediment core.

sented the accessible profile from 9 to 40 m vertical depth beneath the ground surface. Permafrost samples were collected from both the yedoma horizon and the silty matrix of the underlying gravel horizon. Permafrost samples were stored in the laboratory at  $-10^\circ\text{C}$  until further analyses.

### 2.3 Sediment facies classification

Using the imagery, smear slides, macrofossil data, and our knowledge of thermokarst lake sediment facies classification based on Murton (1996), Walter Anthony et al. (2014), and Farquharson et al. (2015), we classified the Vault Lake core into five facies for subsampling: Organic-rich mud, Lacustrine silt, Taberite, Recently thawed taberite, and Transitional permafrost (Fig. 2).

Organic-rich mud consisted of the top 152 cm thick section of the lake core containing alternating layers of dark, organic-rich sediments, some peaty layers with variable sized plant debris, and lighter, mineral silt dominated layers. Smear slides and macrofossil analyses revealed relatively higher abundances of aquatic and terrestrial macrofossils indicative of the thermokarst-affected late-Holocene black spruce ecosystem with peaty, organic rich soil that is still observed around the lake today. Aquatic indicators included spicules, diatoms, *Daphnia ephippia*, and benthic mosses. Terrestrial macrofossils included mosses (*Aulacomnium palustre*, *Sphagnum* spp., *Tomenthypnum nitens*, *Polytrichum* spp.), and roots and leaves of ericaceous shrubs, and spruce (*Picea* spp.) needles (Table S1).

The Lacustrine silt facies, 178 cm thick (153–330 cm) and underlying the Organic-rich mud, consisted of massive mineral sediment with occasional peat balls, representing material that sloughed off exposed thermokarst margins of the lake. Since sediments of Lacustrine silt were exposed to the lake water column during erosion and re-deposition, they contained some, albeit fewer, aquatic indicators (spicules, diatoms, and *Daphnia ephippia*). Few other macrofossils were found in the silt-dominated matrix. These were primarily undifferentiated organic detritus with a few fragments of terrestrial mosses, bark, and ericaceous rootlets.

Taberite sediments (331–550 cm), representing yedoma sediment which thawed in situ and remained underneath the lake (Walter Anthony et al., 2014; Schirrmeister et al., 2011), were identified as massive, mostly mineral (silt)-dominated sediments. We did not find diatoms or any other aquatic indicators in this facies. The little OM that was present was dominated by fine, indistinguishable detritus. The bottom 43 cm of the taberite (508–550 cm), representing the most recently thawed sediments, was designated as Recently thawed taberite.

Beneath the thawed portion of the lake core, we sampled 40 cm of transitional permafrost (551–590 cm), which is close to the thaw transition with a large amount of unfrozen water in the inter-pore space but with numerous small lenses of bulk ice still present (Williams and Smith, 1989). The Transitional permafrost section of our core was ice-bearing, silt-dominated soil with few organic remains, identified as graminoid detritus indicative of the cold, dry Pleistocene steppe ecosystem.

### 2.4 Lake age

We estimated the age of Vault Lake by obtaining accelerator mass spectrometry (AMS) radiocarbon dates on terrestrial plant macrofossils picked from the lake center sediment core. Samples were analyzed at the National Ocean Sciences AMS (NOSAMS) facility (Table 1). All radiocarbon ages were calibrated to calendar  $2\sigma$  years before present (BP) using Calib 7.0 (Reimer et al., 2013).

**Table 1.** Radiocarbon ages of macrofossils picked from the Vault Lake sediment core, calibrated to calendar  $2\sigma$  years before present (BP) using Calib 7.0 (Reimer et al., 2013).

Depth in core (cm)	Lab ID	NOSAMS ID	$^{14}\text{C}$ age (yr BP)	Calibrated age (cal yr BP)	Average age (cal yr BP)	Material dated
45	VAULT13-14A-1G-1-W 48–50 cm	122576	$150 \pm 25$	172–223	195	Bryophyte ( <i>Aulacomnium palustre</i> )
62	VAULT13-14A-3N-1-W 10.5–12.5 cm	122577	$240 \pm 20$	285–303	295	Bryophyte ( <i>Aulacomnium palustre</i> ), leaf fragments from ericaceous shrubs or <i>Betula nana</i> , <i>Picea</i> needles
72	VAULT13-14A-3N-1-W 20.5–22.5 cm	122578	$320 \pm 30$	356–432	394	Bryophyte ( <i>Aulacomnium palustre</i> )
144	VAULT13-14A-4N-1-W 8–19 cm	122579	$170 \pm 20$	170–214	190	Bryophyte ( <i>Aulacomnium palustre</i> ), leaf fragments from ericaceous shrubs or <i>Betula nana</i> , <i>Picea</i> needles
214	VAULT13-6N-1-W 1–3 cm	122580	$315 \pm 20$	375–429	405	Leaf fragments from ericaceous shrubs or <i>Betula nana</i>

## 2.5 Geochemical analyses

Sediment samples ( $3\text{ cm}^3$ ) from both the core and tunnel were oven-dried ( $105^\circ\text{C}$  for 48 h), homogenized using a mortar and pestle, and analyzed for total C ( $C_{\text{tot}}$ ) and nitrogen ( $N_{\text{tot}}$ ),  $C_{\text{tot}}:N_{\text{tot}}$  ratios, and isotope ratios  $\delta^{15}\text{N}_{\text{tot}}$  using an elemental analyzer (Finnigan DeltaPlus XP, Thermo Scientific) coupled to a Costech ECS4010 Elemental Analyzer (Costech Scientific, Valencia, California, USA) at the University of Alaska Stable Isotope Facility, Fairbanks, Alaska, USA. A subsample of the homogenized oven-dried sediments was acidified using muriatic acid (31.45 % HCl), rinsed five times with deionized (DI) water, and used to measure total organic carbon ( $C_{\text{org}}$ ) and  $\delta^{13}\text{C}_{\text{org}}$  on the same elemental analyzer. Measurement of an internal laboratory standard (peptone,  $n = 7$ ) indicated measurement precision of  $\leq 0.4\%$  for both sets of C and N isotopes. Sediment  $C_{\text{tot}}$ ,  $C_{\text{org}}$ , and  $N_{\text{tot}}$  contents are reported in weight percentage (wt %).  $\delta^{13}\text{C}_{\text{org}}$  and  $\delta^{15}\text{N}_{\text{tot}}$  contents are reported in parts per mil (‰). All  $\delta^{13}\text{C}_{\text{org}}$  and  $\delta^{15}\text{N}_{\text{tot}}$  values are expressed relative to Vienna Pe Dee Belemnite (VPDB) and ambient air, respectively. We report all results in mean  $\pm$  standard deviation (SD).

## 2.6 Anaerobic laboratory incubations

Sediment slurries were prepared and incubated in triplicate for 21 depths along the Vault Lake core and 16 depths along the Vault Creek permafrost tunnel (Figs. 1 and 2; Table 2). We homogenized sediment samples under anaerobic conditions with  $\text{O}_2$ -free, sterilized DI water while flushing the slurry with ultra-high-purity (UHP)  $\text{N}_2$  gas (Air Liquide,

Houston, Texas, USA) in a solution container. Subsamples of slurry were oven-dried ( $105^\circ\text{C}$  for 48 h) and analyzed for dry sediment  $C_{\text{tot}}$ ,  $C_{\text{org}}$ ,  $N_{\text{tot}}$ ,  $\delta^{13}\text{C}_{\text{org}}$ , and  $\delta^{15}\text{N}_{\text{tot}}$  contents using the methods outlined above. Fifty milliliters of the anaerobic slurry was transferred to 100 mL glass serum bottles (Wheaton, Millville, New Jersey, USA) using a pipette. Serum bottles were degassed using a constant stream of UHP  $\text{N}_2$  gas and sealed with butyl rubber stoppers (Bellco Glass, Vineland, New Jersey, USA). The slurry in each incubation bottle was reduced by injecting L-cysteine (Sigma-Aldrich, St. Louis, Missouri, USA) to a concentration of 0.025 % ( $wt/v$ ; Gorini, 1961). Anaerobic conditions in the bottles were subsequently verified by measuring  $\text{O}_2$  concentrations in the headspace using gas chromatography (Shimadzu GC-2014, Shimadzu, Kyoto, Japan). We incubated the bottles at  $3^\circ\text{C}$  until linear  $\text{CH}_4$  production rates were achieved in all Vault Lake sediment core incubation bottles. The bottles remained sealed to maintain anaerobic conditions throughout the incubation period, which was 175 days for lake sediments and 220 days for permafrost tunnel samples.

We measured headspace  $\text{CH}_4$  concentrations in each incubation bottle every 30 days using gas chromatography (Shimadzu GC-2014, Shimadzu, Kyoto, Japan).  $\text{CH}_4$  production potential rates were calculated by the slope of the  $\text{CH}_4$  concentration in headspace over time. We normalized  $\text{CH}_4$  production rates across incubation bottles in two ways: dividing the  $\text{CH}_4$  production rates by the mass of dry sediment and the mass of  $C_{\text{org}}$  in each bottle.  $\text{CH}_4$  production rates are reported in units of  $\mu\text{g C-CH}_4 \text{ g dw}^{-1} \text{ d}^{-1}$  and  $\mu\text{g C-CH}_4 \text{ g C}_{\text{org}}^{-1} \text{ d}^{-1}$ . We calculated whole sediment-column  $\text{CH}_4$  production ( $\mu\text{g C-CH}_4 \text{ cm}^{-2} \text{ d}^{-1}$ ) for the cen-

**Table 2.** Vault Lake core and Vault Creek permafrost tunnel facies, their depths and thicknesses, and the representative number of samples used in anaerobic laboratory incubations.

Profile	Facies	Depth (cm)	Thickness (cm)	Incubation samples ( <i>n</i> )
Vault L. core	Organic-rich mud	0–152	152	6
	Lacustrine silt	153–330	178	3
	Taberite	331–507	177	6
	Recently thawed taberite	508–550	43	4
	Transitional permafrost	551–590	40	3
Vault Cr. tunnel	Permafrost (silt)	0–2400	2400	7
	Permafrost	2400–4000	1600	9
	(Silty matrix of gravel)			

ter lake core as the sum of facies' products of mean CH<sub>4</sub> production ( $\mu\text{g C-CH}_4 \text{ g dw}^{-1} \text{ d}^{-1}$ ), dry bulk density ( $\text{g cm}^{-3}$ ), and facies thickness (cm). Using a conversion factor of 0.01, we report whole sediment-column CH<sub>4</sub> production in units of  $\text{g C-CH}_4 \text{ m}^{-2} \text{ d}^{-1}$ .

## 2.7 Statistics

Sediment characteristics (dry bulk density, gravimetric water content,  $C_{\text{tot}}$ ,  $C_{\text{org}}$ ,  $N_{\text{tot}}$ ,  $C_{\text{tot}} : N_{\text{tot}}$ ,  $\delta^{13}\text{C}_{\text{org}}$ , and  $\delta^{15}\text{N}_{\text{tot}}$ ) and CH<sub>4</sub> production rates ( $\mu\text{g C-CH}_4 \text{ g dw}^{-1} \text{ d}^{-1}$ ,  $\mu\text{g C-CH}_4 \text{ g C}_{\text{org}}^{-1} \text{ d}^{-1}$ ) were tested for normal distribution using the Jarque–Bera test (MATLAB R2013a Student Version, MathWorks, Natick, Massachusetts, USA). All parameters except CH<sub>4</sub> production rate expressed as  $\mu\text{g C-CH}_4 \text{ g C}_{\text{org}}^{-1} \text{ d}^{-1}$  were non-normally distributed ( $\alpha = 0.05$ ); therefore, differences among facies were tested for statistical significance using Wilcoxon rank sum tests (MATLAB R2013a Student Version). Differences were considered statistically significant when  $p \leq 0.05$ . Spearman's rank correlation coefficients (MATLAB R2013a Student Version) were used to determine correlations between explanatory variables ( $C_{\text{tot}}$ ,  $C_{\text{org}}$ ,  $N_{\text{tot}}$ , and  $C_{\text{tot}} : N_{\text{tot}}$  ratios) and anaerobic CH<sub>4</sub> production ( $\mu\text{g C-CH}_4 \text{ g dw}^{-1} \text{ d}^{-1}$ ) in our incubations.

## 3 Results

### 3.1 Lake age, morphology, and talik temperatures

Calibrated ages of macrofossils picked from the Organic-rich mud facies of the Vault Lake core ranged from  $190 \pm 20$  to  $405 \pm 25$  calendar years BP (Fig. 2; Table 1).

Lake water depths determined at the borehole locations ranged from 0.7 to 4.6 m (mean  $\pm$  SD  $2.9 \pm 1.1$  m,  $n = 14$  boreholes). Talik depths below the sediment–water interface ranged from 0 to 8.8 m (mean  $\pm$  SD  $5.9 \pm 2.1$  m,  $n = 14$  boreholes). Figure 1c shows borehole data for the long axis of the lake, including the lake center borehole (BH 14) from which our sediment core was taken. The talik was  $\sim 50\%$  thicker

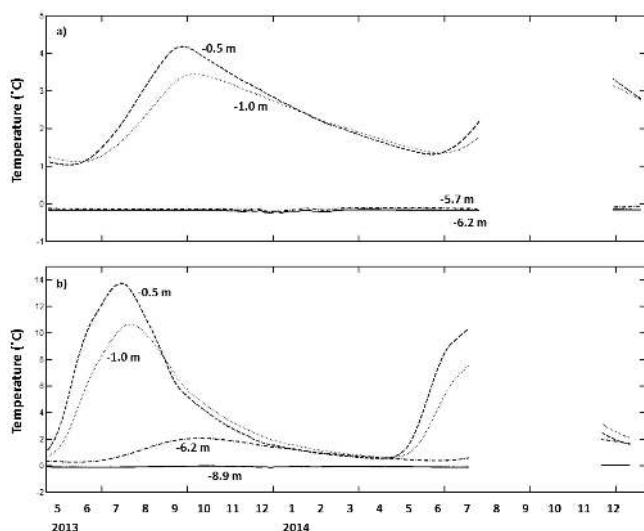
adjacent to the southern thermokarst margin than it was in the lake center.

Vertical profile temperatures measured along the borehole in the center of Vault Lake, where water depth was 4.0 m and talik thickness was 5.7 m, ranged from  $-0.40$  to  $4.22^\circ\text{C}$  (Fig. 3a). In the borehole adjacent to the southwest thermokarst margin (6.1 m offshore), talik thickness was greater (8.6 m), lake water shallower (1.4 m), and sediment temperatures were warmer than in the lake center ( $-0.40$  to  $14.00^\circ\text{C}$ ; Fig. 3b). In both profiles, temperatures in the shallower sediment depths ( $-0.5$  to  $-1.0$  m (0 m = sediment/water interface), temperature range  $0.14$  to  $14.00^\circ\text{C}$ , mean annual temperature  $3.57^\circ\text{C}$ ) were warmer and showed clear seasonal variations (Fig. 3a and b). Temperatures along the thaw boundary ( $-5.70$  to  $-8.85$  m, temperature range  $-0.40$  to  $2.07^\circ\text{C}$ , mean annual temperature  $0.13^\circ\text{C}$ ) were colder and relatively more consistent throughout the year.

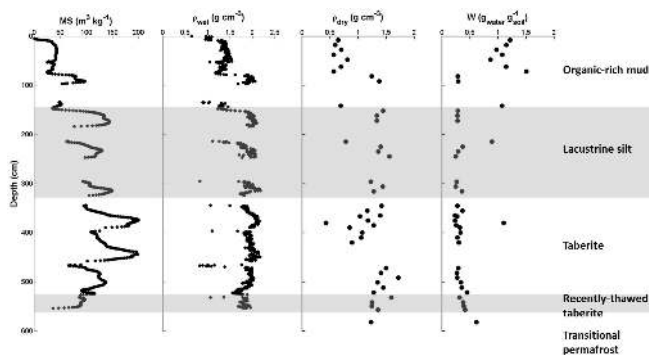
The temperature data also indicated a strong thermal lag and lateral offset in the propagation of summer heat into deeper sediments and the lake center. The maximum temperature in the near-shore surface sediments ( $14.00^\circ\text{C}$  at  $-0.5$  m) occurred on 10 August 2013, while maximum temperature at  $-6.2$  m ( $2.07^\circ\text{C}$ ) and  $-8.9$  m ( $-0.03^\circ\text{C}$ ) depths in the same vertical profile occurred on 22 October 2013. In the lake center, where water depth was deeper, the maximum temperature of  $4.22^\circ\text{C}$  occurred on 24 September 2013 at  $-0.5$  m sediment depth, and also showed a thermal lag of heat propagation to greater depths in the same profile.

### 3.2 Sediment attributes

Sediment properties in the Vault Lake core and Vault Creek permafrost tunnel varied by facies and are summarized in Table 3. Magnetic susceptibility (MS) results indicate two points with low MS values at approximately 100 and 400 cm depth in the lake core (Fig. 4). These points are associated with diamagnetic materials in the core, potentially indicative of tephra. Tephra layers were observed in the Vault Creek permafrost tunnel, albeit at greater depths below the surface



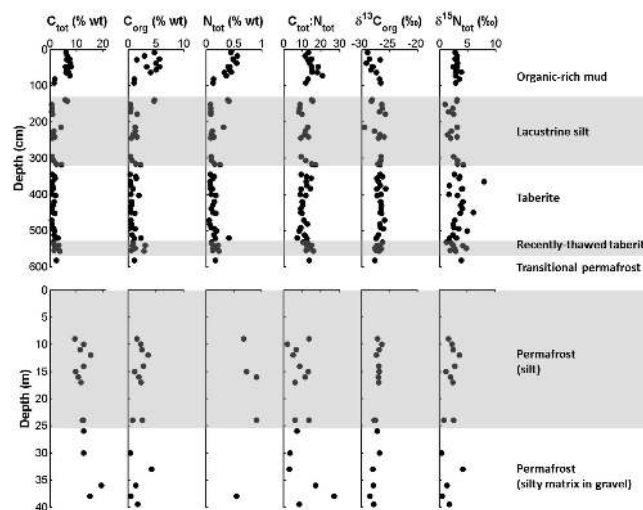
**Figure 3.** Vertical profile temperatures measured in the lake center (< 1 m from BH14; **a**) and 6.1 m offshore of the southwestern thermokarst margin (**b**). Negative depth values indicate depth from the sediment–water interface (0 m) at each of the examined boreholes. Loggers did not record temperature between 25 July and 11 November 2014.



**Figure 4.** Depth profiles for magnetic susceptibility (MS), wet bulk density ( $\rho_{\text{wet}}$ ), dry bulk density ( $\rho_{\text{dry}}$ ), and gravimetric water content ( $W$ ) in the Vault Lake sediment core. Two MS values at 95.4 and 405.4 cm were  $-493.1$  and  $-488.0 \text{ m}^3 \text{ kg}^{-1}$ , respectively (not shown).

(Meyer et al., 2008). The Organic-rich mud facies had the lowest bulk density values in the lake core (Table 3). Differences in dry bulk density values between the remaining facies and between the silt and silty matrix of the gravel horizons of the permafrost tunnel were not statistically significant. Organic-rich mud had higher gravimetric water content values and Taberite had lower values than the remainder of the core (Table 3). High dry bulk density values had a strong linear correlation with low gravimetric water contents in samples ( $R^2 = 0.74$ ).

Sediment geochemical parameters varied among the lake core and permafrost tunnel facies (Fig. 5) and are sum-



**Figure 5.** Depth profiles for sediment geochemical characteristics: total carbon ( $C_{\text{tot}}$ ), organic carbon ( $C_{\text{org}}$ ), total N ( $N_{\text{tot}}$ ),  $C_{\text{tot}} : N_{\text{tot}}$  ratios,  $\delta^{13}\text{C}_{\text{org}}$ , and  $\delta^{15}\text{N}_{\text{tot}}$ . Values for the Vault Lake core are in the top panel; values for the Vault Creek permafrost tunnel are in the bottom panel.

marized in Table 4. The Organic-rich mud facies had the highest soil C concentrations (mean  $\pm$  SD  $C_{\text{tot}}$   $6.01 \pm 1.90$ ;  $C_{\text{org}}$   $3.83 \pm 1.66$ ) in the core (Table 4), while the Taberite facies had the lowest C concentrations (mean  $\pm$  SD  $C_{\text{tot}}$   $1.21 \pm 0.44$ ;  $C_{\text{org}}$   $0.84 \pm 0.45$ ). The remaining lake core facies grouped together had lower C concentrations ( $C_{\text{tot}}$   $1.24$ – $2.52$  %;  $C_{\text{org}}$   $0.84$ – $1.52$  %). Table 4 shows the C concentrations for individual facies, but C concentrations among the Lacustrine silt, Recently thawed taberite, and Transitional permafrost were not significantly different from each other.

High levels of  $C_{\text{tot}}$  were observed in the permafrost tunnel (Table 4), and differences between relatively high levels of  $C_{\text{tot}}$  (mean  $\pm$  SD  $86.5 \pm 8.4$  % of total C) and lower levels of  $C_{\text{org}}$  (mean  $\pm$  SD  $1.9$  % wt) indicate significant inorganic C content in the permafrost tunnel soils (mean  $\pm$  SD  $33.4 \pm 17.8$  % of total C) in the lake sediment core samples.

Among the lake core facies, the highest  $N_{\text{tot}}$  concentrations occurred in the Organic-rich mud ( $0.40 \pm 0.13$  % wt). The permafrost tunnel horizons also had high  $N_{\text{tot}}$  concentrations ( $2.39 \pm 2.37$  % wt). The Taberite facies had the lowest  $C_{\text{tot}} : N_{\text{tot}}$  ratios among all facies and the Organic-rich mud had the highest  $C_{\text{tot}} : N_{\text{tot}}$  ratios, but there were no statistically significant differences among the other core facies. The Taberite facies had higher  $\delta^{13}\text{C}_{\text{org}}$  values ( $-26.58 \pm 0.44$ ) than the remaining lake sediment core facies (Table 4).

### 3.3 $\text{CH}_4$ production potentials and depth-integrated $\text{CH}_4$ production

Mean  $\text{CH}_4$  production potentials varied across the lake core facies (Table 5) and no  $\text{CH}_4$  production was observed in

**Table 3.** Summary of dry bulk density ( $\rho$ ) and gravimetric water content ( $W$ ) data from the Vault Lake core and the Vault Creek permafrost tunnel. Data are presented as mean  $\pm$  SD.

Profile	Sample Facies	Sediment properties	
		$\rho$ ( $\text{g cm}^{-3}$ )	$W$ ( $\text{g}_{\text{water}} \text{g}_{\text{sediment}}^{-1}$ )
Vault L. core	Organic-rich mud	$0.79 \pm 0.29^{\text{a}}$	$0.96 \pm 0.39^{\text{a}}$
	Lacustrine silt	$1.32 \pm 0.21$	$0.35 \pm 0.19$
	Taberite	$1.22 \pm 0.33$	$0.29 \pm 0.04^{\text{b}}$
	Recently thawed taberite	$1.36 \pm 0.15$	$0.38 \pm 0.05$
	Transitional permafrost	$1.29 \pm 0.06$	$0.52 \pm 0.10$
Vault Cr. tunnel	Permafrost (silt)	$0.89 \pm 0.28$	$0.91 \pm 0.40$
	Permafrost (Silty matrix of gravel)	$1.28 \pm 0.21$	$0.44 \pm 0.20$

<sup>a, b</sup> Different letters indicate significant differences from other facies in the same profile at the  $\alpha = 0.05$  level. Vault L. core and Vault Cr. tunnel profiles were analyzed separately.

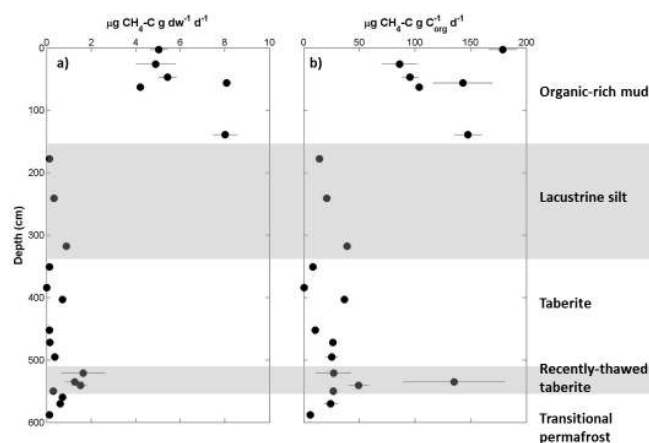
**Table 4.** Summary of geochemical properties and stable isotopes measured on sediment samples from the Vault Lake core and Vault Creek permafrost tunnel. Data are presented as mean  $\pm$  SD.

Profile	Sample Facies	Geochemistry					
		$C_{\text{tot}}$ (% wt)	$C_{\text{org}}$ (% wt)	$N_{\text{tot}}$ (% wt)	$C_{\text{tot}} : N_{\text{tot}}$	$\delta^{13}\text{C}_{\text{org}}$ (‰)	$\delta^{15}\text{N}_{\text{tot}}$ (‰)
Vault L. core	Organic-rich mud	$6.01 \pm 1.90^{\text{a}}$	$3.83 \pm 1.66^{\text{a}}$	$0.40 \pm 0.13^{\text{a}}$	$15.0 \pm 2.5^{\text{a}}$	$-28.11 \pm 1.12$	$3.05 \pm 0.34^{\text{a}}$
	Lacustrine silt	$1.60 \pm 1.24$	$1.04 \pm 0.58$	$0.13 \pm 0.07$	$11.3 \pm 2.7$	$-26.85 \pm 0.92$	$2.49 \pm 0.90$
	Taberite	$1.24 \pm 0.44^{\text{b}}$	$0.84 \pm 0.45^{\text{b}}$	$0.12 \pm 0.04^{\text{b}}$	$10.8 \pm 1.9^{\text{b}}$	$-26.58 \pm 0.44^{\text{a}}$	$3.70 \pm 1.46^{\text{a}}$
	Recently thawed taberite	$2.04 \pm 0.79$	$1.36 \pm 0.80$	$0.18 \pm 0.10$	$12.2 \pm 2.4$	$-26.94 \pm 0.51$	$2.72 \pm 1.13$
	Transitional permafrost	$2.52 \pm 1.10$	$1.52 \pm 1.18$	$0.18 \pm 0.05$	$14.0 \pm 1.9$	$-27.28 \pm 0.39$	$2.88 \pm 0.98$
Vault Cr. tunnel	Permafrost (silt)	$11.88 \pm 1.75^{\text{b}}$	$2.21 \pm 0.80^{\text{a}}$	$1.91 \pm 1.60$	$8.8 \pm 4.1$	$-27.02 \pm 0.40$	$2.21 \pm 0.80^{\text{a}}$
	Permafrost (Silty matrix of gravel)	$18.77 \pm 6.80^{\text{a}}$	$1.31 \pm 1.66^{\text{b}}$	$3.19 \pm 3.32$	$11.2 \pm 9.4$	$-27.63 \pm 0.60$	$1.40 \pm 1.55^{\text{b}}$

<sup>a, b</sup> Different letters indicate significant differences from other facies in the same profile at the  $\alpha = 0.05$  level. Vault L. core and Vault Cr. tunnel profiles were analyzed separately.

the thawed permafrost tunnel samples.  $\text{CH}_4$  production potentials in the lake core over the 175-day incubation period ranged from 0.002 to  $8.08 \mu\text{g C}-\text{CH}_4 \text{ g dw}^{-1} \text{ d}^{-1}$  and 0.51 to  $178.9 \mu\text{g C}-\text{CH}_4 \text{ g C}_{\text{org}}^{-1} \text{ d}^{-1}$  (Fig. 6). The highest production potentials were observed in the Organic-rich mud and the lowest rates occurred in Taberites and Transitional permafrost (Table 5). We found that  $C_{\text{tot}}$  ( $r = 0.47$ ,  $p = 0.043$ ) and  $C_{\text{org}}$  ( $r = 0.47$ ,  $p = 0.043$ ) were positively correlated with  $\text{C}-\text{CH}_4$  production. Total N and  $C_{\text{tot}} : N_{\text{tot}}$  ratios were unrelated to  $\text{CH}_4$  production potentials in our incubations.

The ratios ( $R$ ) of facies'  $\text{CH}_4$  production potentials to their thickness in the lake center sediment column revealed the highest  $\text{CH}_4$  production per unit of sediment were in the Organic-rich mud ( $R = 2.6$ ) and Recently thawed taberite ( $R = 1.2$ ) facies, while  $R$  of the remaining facies was lower ( $R = 0.2$  to  $0.5$ ; Table 5). Specifically, the Organic-rich mud facies, which represented 26 % of the sediment column thickness, dominated (67 %) whole-column  $\text{CH}_4$  production in the lake center sediment core ( $5.2 \text{ g C}-\text{CH}_4 \text{ m}^{-2} \text{ d}^{-1}$ ; Table 5). The Lacustrine silt facies, which represented 30 % of the sediment column thickness, had the second largest contribution (14 %;  $1.1 \text{ g C}-\text{CH}_4 \text{ m}^{-2} \text{ d}^{-1}$ ) to whole-column  $\text{CH}_4$  production. Results for other facies are shown in Table 5.

**Figure 6.** Depth profile for  $\text{CH}_4$  production potentials in the Vault Lake core. Samples were anaerobically incubated at  $3^\circ\text{C}$ . Methane production potentials are represented as mean value  $\pm$  SD among replicates and normalized per gram dry weight sediment (a) and per gram organic carbon ( $C_{\text{org}}$ ; b).



**Table 5.** Summary of facies' CH<sub>4</sub> production potentials and depth-integrated CH<sub>4</sub> production for the total sediment column. Data are presented as mean ± SD. It should be noted that, based on optical properties (Fig. 2), dry bulk density (mean ± SD, 1.31 ± 0.07 g cm<sup>-3</sup>), gravimetric moisture content (29 ± 0.00 %), and C<sub>org</sub> (1.64 %) values measured on two samples in the depth interval 77–97 cm of the core, which were similar to those of Lacustrine Silt and very different from the remainder of the Organic-rich mud facies segments, we applied CH<sub>4</sub> production rates measured on Lacustrine silt samples to this 21 cm interval of the Organic-rich mud section. This was done because no samples from this 21 cm thick, mineral-dominated segment of organic-rich mud were represented in the incubation.

Sample		CH <sub>4</sub> production potentials (μg C–CH <sub>4</sub> d <sup>-1</sup> )		Sediment column CH <sub>4</sub> production			
Profile	Facies	g dw <sup>-1</sup>	g C <sub>org</sub> <sup>-1</sup>	g C–CH <sub>4</sub> m <sup>-2</sup> d <sup>-1</sup>	% Total C–CH <sub>4</sub> production	% Total column thickness	R (% production/ % thickness)
Vault L. core	Organic-rich mud	5.95 ± 1.67 <sup>a</sup>	125.9 ± 36.2 <sup>a</sup>	5.2	67	26	2.6
	Lacustrine silt	0.45 ± 0.39	24.6 ± 12.8	1.1	14	30	0.5
	Taberite	0.25 ± 0.26 <sup>b</sup>	17.9 ± 13.6	0.5	7	30	0.2
	Recently thawed taberite	1.18 ± 0.61	59.6 ± 51.5	0.7	9	7	1.2
	Transitional permafrost	0.48 ± 0.31	15.3 ± 9.1 <sup>b</sup>	0.2	3	7	0.5

<sup>a, b</sup> Different letters indicate significant differences from other facies in the same profile at the  $\alpha = 0.05$  level.

## 4 Discussion

### 4.1 CH<sub>4</sub> production potentials

Our study indicates that, in the center of the lake, the Organic-rich mud facies contributed the most (67 %) to whole-column CH<sub>4</sub> production despite occupying a lesser fraction (26 %) of sediment column thickness. This is consistent with findings from a study examining an 8 m deep Holocene permafrost core from the Lena Delta, in which the top (125 cm) section of permafrost sediments were also found to have the highest observed CH<sub>4</sub> production in the sediment column (Wagner et al., 2007).

A main reason for the Organic-rich mud facies in our study having high CH<sub>4</sub> production potentials is its relatively high OM content. Past studies have suggested that CH<sub>4</sub> production rates in natural ecosystems are controlled by environmental conditions, including substrate availability (Tranvik et al., 2009; Wallmann et al., 2006; Bergman et al., 1999; Valentine et al., 1994; Westermann, 1993). Correlation analyses showed that CH<sub>4</sub> production in our study was positively correlated to sediment C<sub>tot</sub> and C<sub>org</sub> contents ( $p = 0.043$  for both). This indicates that facies with higher C contents, such as the Organic-rich mud, would have higher CH<sub>4</sub> production potentials compared to other facies.

Following the Organic-rich mud facies, relatively high CH<sub>4</sub> production potentials were also observed in the Recently thawed taberite facies. However, the narrowness of the Recently thawed taberite in the center of the lake limited its overall contribution to total sediment column CH<sub>4</sub> production potentials. The thickest sequence, which consisted of combined Lacustrine silt and Taberite facies (60 % of total core thickness), had low CH<sub>4</sub> production potentials, contributing only 21 % of whole sediment column CH<sub>4</sub> produc-

tion potential. Our results of higher CH<sub>4</sub> production in the Recently thawed taberite facies compared to the Lacustrine silt and Taberite facies are consistent with model simulations of CH<sub>4</sub> production in a thermokarst lake that showed CH<sub>4</sub> production among the thawed yedoma horizons to be highest along the talik's downward progressing thaw boundary (Kessler et al., 2012). Assuming homogenous C contents along the full yedoma profile in numerical modeling, the higher CH<sub>4</sub> production at the thaw boundary was explained by fresh OM made available to microbial decomposition by permafrost thaw. Conversely, lower CH<sub>4</sub> production in the overlying mineral-dominated sediments, which represent permafrost that thawed earlier, is explained by earlier microbial decomposition that previously exhausted a large fraction of the labile C pool of permafrost sediment OM.

Total soil OC consists of various OC pools with turnover times ranging from less than a year to up to thousands of years (Schädel et al., 2014). OC pool sizes and turnover times significantly impact how OC behaves in the global C cycle and remain a significant uncertainty in estimating how permafrost OC will be processed as it thaws (Schädel et al., 2014; Strauss et al., 2013). In our study, CH<sub>4</sub> production potential rates in the Recently thawed taberite facies, which we estimate thawed during approximately the previous decade based on downward talik growth rates determined through numerical modeling of a similar yedoma thermokarst lake system (Kessler et al., 2012), were approximately 4.7 times higher than those in the overlying taberite, which we estimate thawed over longer periods of time (up to 400 years). This suggests that, upon thaw, labile fractions of OC in the talik are depleted over decadal to century timescales and the remaining OC pool is less susceptible to processing upon thaw. Prior studies of Siberian yedoma suggest that approximately 30 % of the yedoma C pool is bioavailable upon thaw under

anaerobic conditions in yedoma-lake taliks (Walter Anthony et al., 2014). Under aerobic conditions, 5–30 % of the total C pool in both organic and mineral circumpolar permafrost samples are estimated to have a rapid turnover time (mean  $0.35 \pm 0.6$  years) upon thaw (Schädel et al., 2014; Shaver et al., 2006). Remaining permafrost C contains 10–90 % “slow” C (mean turnover time  $7.21 \pm 4.32$  years) and 5–85 % “passive” C (mean turnover time  $> 2500$  years; Schädel et al., 2014) under aerobic decomposition regimes. However, further research is necessary to determine the relative sizes of permafrost C pools and better assess what proportion of permafrost OC can be processed into CH<sub>4</sub> upon thaw in an anaerobic thermokarst lake environment.

Within the Organic-rich mud facies, we observed higher CH<sub>4</sub> production potentials ( $\text{g C}_{\text{org}}^{-1}$ ) near the surface of the Vault Lake core and slightly decreasing CH<sub>4</sub> production potentials with depth through the facies. Surface lake sediments originate from both allochthonous (terrestrial soils and vegetation) and autochthonous (i.e., lake biota) sources (Tranvik et al., 2009; Cole et al., 2007; Wetzel, 2001). Surface sediments typically contain the most recently deposited materials while deeper sediments represent older deposited materials (Smol, 2008; Cohen, 2003). The higher CH<sub>4</sub> production near the surface of the Organic-rich mud facies may be explained by these more recently deposited surface sediments containing fresher, more labile substrates than the older, underlying sediments. Another possibility is that autochthonous organic matter in the surface sediments provides a labile C substrate that may prime decomposition of more recalcitrant allochthonous C in the sediments, leading to higher total CH<sub>4</sub> production than in underlying sediments that do not receive the autochthonous C.

#### 4.2 CH<sub>4</sub> production potentials versus observed emissions

Laboratory incubations measure maximum CH<sub>4</sub> production potentials, while CH<sub>4</sub> emissions observed in the field represent in situ production minus CH<sub>4</sub> consumption, dissolved CH<sub>4</sub>, and trapped CH<sub>4</sub> accumulating in the system (Blazewicz et al., 2012; Wright et al., 2011; Westermann, 1993). Because of this, the CH<sub>4</sub> production potentials measured in our study may be higher than in situ CH<sub>4</sub> production in the Vault thermokarst lake system, possibly explaining the discrepancies among potential CH<sub>4</sub> production rates for the total lake center sediment core in our study ( $2819 \text{ g CH}_4 \text{ m}^{-2} \text{ yr}^{-1}$ ) and observed, lower CH<sub>4</sub> emission rates from across Vault Lake ( $41 \text{ g CH}_4 \text{ m}^{-2} \text{ yr}^{-1}$ ; Sepulveda-Jauregui et al., 2015) and observations in the literature for northern ( $> 54^\circ \text{ N}$ ) lakes ( $\sim 7 \text{ g CH}_4 \text{ m}^{-2} \text{ yr}^{-1}$ ; Bastviken et al., 2011). It is possible that CH<sub>4</sub> emissions at Vault Lake are underestimated due to lake sediments storing large quantities of CH<sub>4</sub> which are released during rare extreme-low pressure events and are unlikely to be captured by the ebullition ice-bubble surveys combined with bubble trap measurements

utilized by Sepulveda-Jauregui et al. (2015). Other possible explanations for higher potential CH<sub>4</sub> production rates observed by laboratory incubations in this study compared to emissions observed through field measurements are poor representation of spatial heterogeneity in the lake by a single lake center core and CH<sub>4</sub> oxidation. Aerobic and anaerobic oxidation in sediments and the water column consumes a significant fraction of CH<sub>4</sub> produced in lakes (Lofton et al., 2014; Borrel et al., 2011; Deutzmann and Schink, 2011; Bastviken et al., 2008; Kankaala et al., 2006). A simulated CH<sub>4</sub> production study found CH<sub>4</sub> production in a modeled thermokarst lake talik was up to 10 times higher than observed emissions in the field (Kessler et al., 2012). Produced CH<sub>4</sub> may also be oxidized in anaerobic environments (Gupta et al., 2013; Smemo and Yavitt, 2007; Valentine, 2002), but the magnitude of anaerobic CH<sub>4</sub> oxidation in lake environments is not well understood. The combined effects of aerobic and anaerobic CH<sub>4</sub> oxidation may also account for, in part, the higher talik CH<sub>4</sub> production potentials compared to lake emissions observed by Kessler et al. (2012).

Differences between our incubation temperature ( $3^\circ \text{ C}$ ) and actual temperatures in the talik environment may also lead to some differences between the CH<sub>4</sub> production potentials observed in our incubations and in situ CH<sub>4</sub> production at Vault Lake. Observed annual temperatures under Vault Lake ranged from  $-0.4$  to  $14.0^\circ \text{ C}$  (mean  $\pm$  SD  $1.61 \pm 2.80^\circ \text{ C}$ ). Microorganisms show increased methanogenesis with temperature increases (Yvon-Durocher et al., 2014; Yavitt et al., 2005; Schulz et al., 1997). Therefore, depending on the actual temperatures throughout the talik profile, CH<sub>4</sub> production rates at a given time at Vault Lake may be higher or lower than those measured at our reference incubation temperature of  $3^\circ \text{ C}$ .

#### 4.3 Spatial patterns of CH<sub>4</sub> production and emission within lakes

Previous field and modeling studies found CH<sub>4</sub> emissions to be up to an order of magnitude higher along thermokarst margins of yedoma lakes than in lake centers (Kessler et al., 2012; Walter et al., 2006). While our sediment incubation study was limited to a single lake center core, other physical data measured along the thermokarst margin at Vault Lake lend support to the findings of previous studies. The talik was 50 % deeper along the expanding thermokarst lake margin (measured 6.1 m offshore; Sect. 3.1) compared to the lake center core site. This suggests that the Recently thawed taberite facies would be substantially thicker along the lake margin than in the lake center, though individual facies thicknesses were not measured. This would also be consistent with field measurements of <sup>14</sup>C–CH<sub>4</sub> ages being older (35 000 to 43 000 years old) along yedoma thermokarst lake margins compared to lake centers (Brosius et al., 2012; Kessler et al., 2012; Walter et al., 2006). Based on field observations of cross-basin sediment stratigraphy in other yedoma lakes

(Walter Anthony et al., 2014; Farquharson et al., 2015), it is possible that the overlying lake sediment (Organic-rich mud facies) is thinner along the lake margin than in our lake center core; however, Walter Anthony et al. (2014) observed > 2 m thick lake sediments within 15 m of the shore in much larger Siberian yedoma thermokarst lakes. Regardless of relative facies thicknesses, the thermokarst margin zone of the lake was more recently converted from permafrost-dominated terrestrial landscape into an open-water lake environment compared to the lake center core location. This suggests that sediments along the margin have had less time to decompose and, therefore, should have an overall higher fraction of labile OM remaining, consistent with higher total-column CH<sub>4</sub> production rates described in the literature.

#### 4.4 CH<sub>4</sub> production in thermokarst, permafrost, and non-permafrost systems

Among long-term anaerobic incubations (> 115 days), observed CH<sub>4</sub> production rates in the Vault Lake sediment core incubations at 3 °C were comparable to rates observed in incubations of shallow (< 1 m) permafrost from non-lake environments in Alaska (0.01 to 1.14 μg C–CH<sub>4</sub> g dw<sup>-1</sup> d<sup>-1</sup>; Lee et al., 2012). However, these soil samples were incubated at a significantly higher temperature (15 °C), which would yield higher CH<sub>4</sub> production rates than incubations performed at 3 °C. Terrestrial soils from other shallow (< 1 m) permafrost and active layer sites in Alaska incubated at 5 °C (Waldrop et al., 2010) produced CH<sub>4</sub> at rates approximately an order of magnitude lower than the Vault Lake sediments in our study. Some of the sampling locations of Lee et al. (2012) and Waldrop et al. (2010) are underlain by yedoma-type permafrost; however, samples collected from shallow surface depths (≤ 1 m) were likely disturbed and thawed at some point during the Holocene, as indicated by the depth of Pleistocene ice-wedge surfaces (Jorgenson et al., 2013; Kanevskiy et al., 2011; Meyer et al., 2008). Deeper Pleistocene-aged yedoma soils (up to 5 m depth) from the Lena Delta region of Siberia incubated at 4 °C had similar CH<sub>4</sub> production rates (approximately 0.1 to 1.3 μg C–CH<sub>4</sub> g dw<sup>-1</sup> d<sup>-1</sup>; Knoblauch et al., 2013) to the lake sediment facies dominated by thawed yedoma in our study; however, these high rates in the non-lake yedoma sediments in Siberia were only observed after a significant lag time (average 963 days). Comparisons across these studies suggest that undisturbed Pleistocene-aged yedoma permafrost may have more biolabile OM than younger or previously thawed yedoma permafrost soils. This conclusion is consistent with findings of Lee et al. (2012), in which yedoma samples had the highest anaerobic C release per gram soil C among a variety of mineral soil samples.

CH<sub>4</sub> production rates in high latitude, non-permafrost lake sediments (eight lakes in central Sweden) incubated at 4 °C were generally much lower (0.002 to 0.06 μg C–CH<sub>4</sub> g dw<sup>-1</sup> d<sup>-1</sup>; Duc et al., 2010) than the rates we observed in the Organic-rich mud facies of the Vault Lake sediment core.

These differences could be due to a combination of Vault Lake's yedoma environment containing more biolabile OM derived from yedoma permafrost thawing along lake margins as well as potentially higher rates of Holocene-aged organic matter loading to Vault Lake resulting from thermokarst expansion and high primary production in and around the lake enhanced by nutrients released from thawing yedoma (Walter Anthony et al., 2014).

It is interesting to note that studies of deep permafrost (non-lake) sediments found that (a) no CH<sub>4</sub> was produced (Wagner et al., 2007; this study), (b) CH<sub>4</sub> production rates were an order of magnitude lower (Lee et al., 2012), or (c) CH<sub>4</sub> production was only observed after a significant lag time (Knoblauch et al., 2013). In contrast, in studies of shallow-permafrost sediments, CH<sub>4</sub> production potentials were observed in anaerobic incubations (Knoblauch et al., 2013; Lee et al., 2012; Waldrop et al., 2010; Wagner et al., 2007). We suggest a potential explanation for these observations in the following section.

#### 4.5 Role of modern methanogens in CH<sub>4</sub> production from old C

The quantity of methanogens preexisting in soil samples can influence the rate of methanogenesis in laboratory experiments (Gutknecht et al., 2006; Yavitt et al., 2000). In our study, all samples collected from the Vault Lake core produced CH<sub>4</sub> within 60 days of incubation, including the Transitional permafrost samples at the bottom of the lake core. In contrast, no samples collected from the Vault Creek permafrost tunnel had detectable CH<sub>4</sub> production during the observed 220 days of incubation. A possible explanation for the lack of detectable CH<sub>4</sub> production in the permafrost tunnel could be a paucity of viable methanogens naturally present in deep permafrost soils (Wagner et al., 2007; Steven et al., 2006; Gilichinsky et al., 2003; Rivkina et al., 1998). In previous anaerobic incubations of deep permafrost, little or no CH<sub>4</sub> production has been observed and there was either no observed CH<sub>4</sub> production (non-yedoma permafrost; Wagner et al., 2007), a significant delay before detectable CH<sub>4</sub> production occurred (yedoma permafrost; Knoblauch et al., 2013), or no CH<sub>4</sub> production until samples were inoculated with modern lake sediments (yedoma permafrost; Walter et al., 2007; S. Zimov, personal communication, 2002). Since we observed CH<sub>4</sub> production in the Transitional permafrost (thawing yedoma) beneath Vault Lake but no CH<sub>4</sub> production in the permafrost tunnel samples (yedoma and underlying gravel horizons) it is possible that, in thermokarst lake environments, CH<sub>4</sub> produced from yedoma OM requires the reproduction of modern and/or ancient microbes along a thermally expanding substrate source as permafrost thaws radially beneath lakes.

## 5 Conclusions

Our study suggests that in the center of a first-generation thermokarst lake, whole-column CH<sub>4</sub> production is dominated by methanogenesis in the Organic-rich mud facies; however, it is likely that other facies contribute significantly more to CH<sub>4</sub> production along laterally expanding thermokarst lake margins. Variability in permafrost C source, quality, and biodegradability remain significant uncertainties in estimating how thawing permafrost OC will be processed. Labile fractions of OC seem to be more absent in near-surface portions of the taberite, reducing CH<sub>4</sub> production rates compared to the underlying Recently thawed taberite along the permafrost thaw boundary. The rapid depletion of the most labile OC pools suggests OC quality may be a limiting factor in determining how thawing permafrost C is processed in a thermokarst lake environment. The knowledge as to where CH<sub>4</sub> originates and what proportion of produced CH<sub>4</sub> is emitted will aid in estimations of how C release and processing in a thermokarst lake environment differs from other thawing permafrost and non-permafrost environments.

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