

Cryostratigraphy and Permafrost Evolution in the Lacustrine Lowlands of West-Central Alaska

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ABSTRACT

The influence of permafrost growth and thaw on the evolution of ice-rich lowland terrain in the Koyukuk-Innoko region of interior Alaska is fundamental but poorly understood. To elucidate this influence, the cryostratigraphy and properties of perennially frozen sediments from three areas in this region are described and interpreted in terms of permafrost history. The upper part of the late Quaternary sediments at the Koyukuk and Innoko Flats comprise frozen organic soils up to 4.5 m thick underlain by ice-rich silt characterised by layered and reticulate cryostructures. The volume of visible segregated ice in silt locally reaches 50 per cent, with ice lenses up to 10 cm thick.

A conceptual model of terrain evolution from the Late Pleistocene to the present day identifies four stages of yedoma degradation and five stages of subsequent permafrost aggradation-degradation: (1) partial thawing of the upper ice wedges and the formation of small shallow ponds in the troughs above the wedges; (2) formation of shallow thermokarst lakes above the polygons; (3) deepening of thermokarst lakes and yedoma degradation beneath the lakes; (4) complete thawing of yedoma beneath the lakes; (5) lake drainage; (6) peat accumulation; (7) permafrost aggradation in drained lake basins; (8) formation of permafrost plateaus; and (9) formation and expansion of a new generation of thermokarst features. These stages can occur in differing places and times, creating a highly complex mosaic of terrain conditions, complicating predictions of landscape response to future climatic changes or human impact. Copyright © 2014 John Wiley & Sons, Ltd.

KEY WORDS: permafrost; ground ice; thermokarst; Alaska; cryostratigraphy; Quaternary sediments

INTRODUCTION

Understanding permafrost history during the Late Pleistocene and Holocene is essential in assessing the future of permafrost and ecosystems under a changing climate. The patterns of permafrost transformation are highly variable across the diverse terrain of central Alaska (Jorgenson *et al.*, 2013). Of particular interest are plains and lowlands, where fine-grained aeolian, alluvial and lacustrine deposits comprise a significant part of the upper permafrost. Although fairly uniform in soil composition, these materials vary from ice-poor to extremely ice-rich, depending on climate, topography, ecosystems and the history of permafrost development.

Studies of ice-rich permafrost are especially important because the transformation of such deposits due to climate changes or human activities has significant consequences (e.g. terrain collapse due to thermokarst or thermal erosion and the release of large amounts of organic carbon). The most prominent example of ice-rich deposits in Alaska is yedoma – extremely ice-rich syngenetically frozen silt with huge ice wedges up to 10 m wide and 50 m tall. Sections of yedoma have been observed in many areas of Siberia and North America that were unglaciated during the Late Pleistocene (Kanevskiy *et al.*, 2011; Grosse *et al.*, 2013; Schirrmeister *et al.*, 2013, and citations therein). Numerous studies on permafrost degradation and the evolution of thermokarst lakes have been performed in Siberia (Soloviev, 1962; Czudek and Demek, 1973; Shur, 1977, 1988a, 1988b; Romanovskii, 1993) and North America (Wallace, 1948; Burn and Smith, 1990; Osterkamp *et al.*,

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2000; Jorgenson *et al.*, 2008, 2012, 2013; Shur *et al.*, 2012; Kokelj and Jorgenson, 2013).

Data on ground ice and permafrost dynamics in the Koyukuk-Innoko region of interior Alaska are very limited, and the evolution of this permafrost-dominated landscape lacks a satisfactory explanation. The goal of this paper is to assess the origin of these interior plains in relation to permafrost evolution from the Late Pleistocene to the present, based on the results of our field research performed at three study areas during 2006–09 in the Koyukuk and Innoko Flats (Figure 1). The specific objectives are to: (1) delineate the extent of the lacustrine lowlands in the Koyukuk-Innoko region in relation to other lowland landscapes; (2) describe the cryostratigraphy of perennially frozen sediments; (3) quantify ground ice contents using different methods; and (4) develop a conceptual model of the history of aggradation and degradation of permafrost and terrain development of the lacustrine plains. This study was part of an integrative effort to assess the effects of permafrost aggradation and degradation on the water and carbon balance of boreal ecosystems (Jorgenson *et al.*, 2010, 2013), soil carbon decomposition in previously frozen organic materials and the accumulation of new organic material (O'Donnell *et al.*, 2012; Harden *et al.*, 2012), and the release of trace gases associated with thermokarst features (Johnston *et al.*, 2012).

STUDY AREA

The three study areas (Figure 1) are located in the Koyukuk and Innoko National Wildlife Refuges within the Yukon River basin. We conducted field sampling at Finger Lake on the Koyukuk Flats (65°15'20"N, 157°2'10"W) in 2006, at Two Lakes on the Koyukuk Flats (65°11'50"N, 157°38'20"W) in 2008 and at Horseshoe Lake on the Innoko Flats (63°34'30"N, 157°43'30"W) in 2009.

Elevations of the Koyukuk and Innoko Flats usually do not exceed 100 m asl. The climate of the Koyukuk-Innoko region is continental, with a mean annual air temperature of -4°C and mean annual precipitation of about 330 mm (according to the nearest meteorological station at Galena, unpublished data, Alaska Climate Research Center).

Quaternary deposits of the study area comprise Holocene floodplain deposits and undivided Holocene and Pleistocene deposits, including alluvial, colluvial, glacial and aeolian deposits (Patton *et al.*, 2009). Within the Yukon-Koyukuk lowland, Weber and Péwé (1970) distinguished floodplain alluvium, younger (low) and older (high) terrace deposits, aeolian sand dunes and loess deposits in the foothills. Much of the area experienced aeolian silt deposition during the Late Pleistocene (Muhs *et al.*, 2003; Muhs and Budahn, 2006).

Permafrost in the study area is discontinuous and its thickness usually varies from 10 m to 130 m (Jorgenson

et al., 2008). Permafrost occurs mainly within uplifted peat plateaus, interspersed with unfrozen bogs and fens (Jorgenson *et al.*, 2012; O'Donnell *et al.*, 2012). Mean annual soil temperature at the base of the active layer within permafrost plateaus at the Koyukuk Flats study area is close to 0°C ; vegetation on peat plateaus is typified by black spruce and *Sphagnum* spp. moss (O'Donnell *et al.*, 2012). Weber and Péwé (1961, 1970) reported the presence of large vertically and horizontally oriented ground ice masses in the Yukon-Koyukuk lowland and widespread polygonal ground with ice wedges up to 1 m wide and 4.5 m tall, but information on ground ice is limited. In our study areas, no evidence for ice-wedge polygons within peat plateaus has been observed (O'Donnell *et al.*, 2012).

METHODS

Landscape Mapping

We classified and mapped lowland landscapes of the Koyukuk and Innoko regions to better quantify the extent of lacustrine-affected terrain relative to other geomorphic units in these central Alaska lowlands. We used an ecological mapping approach that differentiates ecosystems at various levels of organisation (US Forest Service, 1993) and differentiates landscapes at the subsection level of mapping (Jorgenson and Grunblatt, 2012). The landscapes (i.e. repeating associations of geomorphic units, soils and vegetation) were differentiated by their physiography and dominant geomorphic units. Mapping was carried out by interpreting Landsat imagery using ARCmap software (ESRI, Inc., 380 New York Street Redlands, CA 92373-8100) at 1:250 000 scale. Existing geologic maps and pertinent literature of the region (Fernald, 1960; Weber and Péwé, 1970; Koster *et al.*, 1984; Patton *et al.*, 2009) helped to differentiate surficial deposits.

Cryostratigraphy

The cryostratigraphy of frozen soils was described in each of the three study areas. Along transects 300 m to 700 m long, three to five plots were established for coring or sampling of exposures of collapsing banks. Ground surface elevations were surveyed by levelling along transects and at the plots. A permafrost probe was used to measure the active layer thicknesses and depths of closed taliks. Frozen cores were obtained with a SIPRE corer (Jon's Machine Shop, Fairbanks, AK. <http://www.jonsmachine.com/> (7.5-cm inner diameter)). Exposures and cores were documented by hundreds of photographs and numerous sketches. Cryostratigraphy methods and cryofacies analysis (Katasonov, 1978; French and Shur, 2010) were used to differentiate patterns of syngenetic and epigenetic permafrost formation. Cryostructures were described using a classification system modified from several Russian and

North American classification systems (Zhestkova, 1982; Murton and French, 1994; Shur and Jorgenson, 1998; Melnikov and Spesivtsev, 2000; French and Shur, 2010; Kanevskiy *et al.*, 2013a) (Figure 2).

Ground Ice Content

The gravimetric and volumetric moisture contents of frozen soils were determined in 160 samples by oven-drying

(90°C, 72 h). The small size of the samples (typically 250–500 ml) makes it problematic to estimate the moisture content of mineral soils in the study area due to the irregular distribution of ice lenses and inclusions. To check the accuracy of laboratory analyses, we compared gravimetric and volumetric moisture contents to those calculated from the volume of visible ice. To estimate the total volumetric moisture content W_{tv} through the volume of visible ice, we used the equation (Kanevskiy

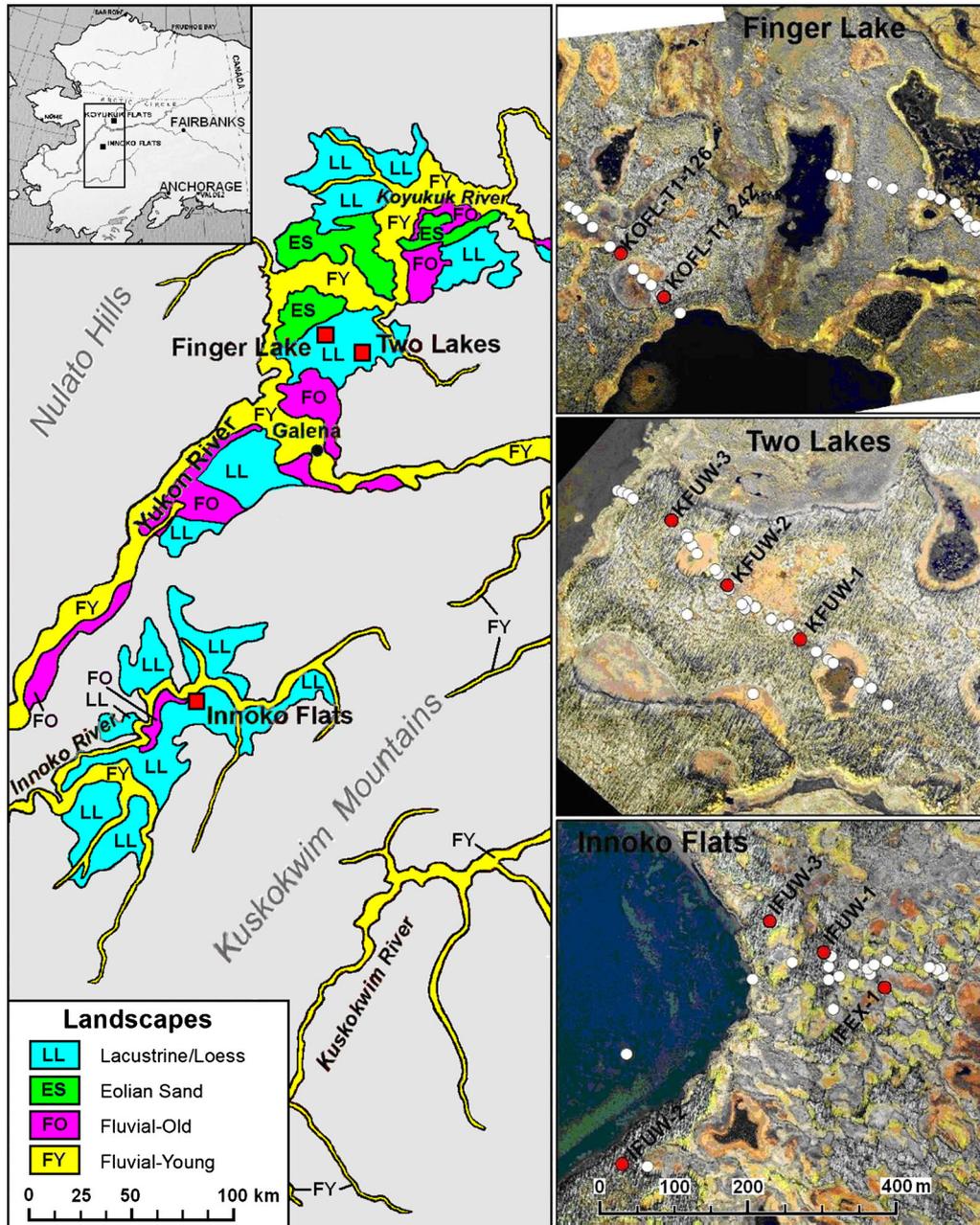


Figure 1 Location of the three study areas within the Yukon River lowlands in relation to the dominant lowland landscapes (left). Locations of boreholes and exposure in permafrost plateaus (red dots) and sampling points at unfrozen bogs and fens (white dots) are shown in high-resolution aerial photographs of the three sites (right). This figure is available in colour online at wileyonlinelibrary.com/journal/ppp

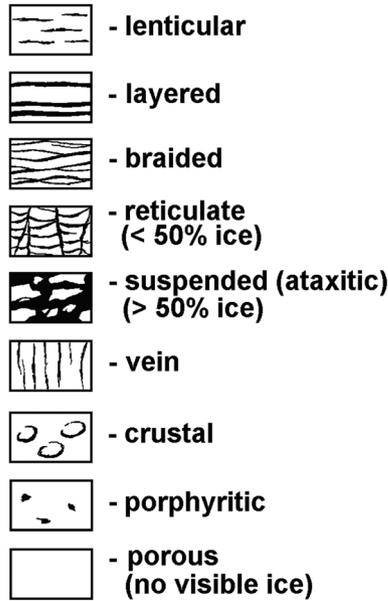


Figure 2 Main types of cryostructures in mineral soils used in permafrost descriptions (ice is black). Modified from several Russian and North American classifications (Zhestkova, 1982; Murton and French, 1994; Shur and Jorgenson, 1998; Melnikov and Spesivtsev, 2000; French and Shur, 2010) (based on Kanevskiy *et al.*, 2013a).

et al., 2013b):

$$W_{iv} = \frac{G_s W_s + V_i}{1 + G_s W_s} = \frac{2.7 W_s + V_i}{1 + 2.7 W_s} \quad (1)$$

where V_i is the visible ice content, unit fraction; $G_s = 2.7$ is the specific gravity of solids; and W_s is the gravimetric moisture content due to pore ice, unit fraction. V_i was estimated with ImageJ (Ferreira and Rasband, 2012), by processing binary (black for ice and white for sediments) images based on photographs of the cores or the natural exposures. W_s was estimated from the processing of samples of frozen silt without visible ice.

To estimate the total gravimetric moisture content W_t through the volume of visible ice, we used the equation (Kanevskiy *et al.*, 2013b):

$$W_t = \frac{\frac{\gamma_i}{\gamma_w G_s} V_i + \frac{\gamma_i}{\gamma_w} V_i W_s + W_s - V_i W_s}{1 - V_i} \quad (2)$$

$$= \frac{0.33 V_i + W_s - 0.1 V_i W_s}{1 - V_i}$$

where $\gamma_i = 0.9$ is the unit weight of ice and $\gamma_w = 1.0$ is the unit weight of water; and $G_s = 2.7$.

Radiocarbon Dating

Radiocarbon dating was performed on 30 samples of organic material from depths of up to 405 cm below the ground

surface. Samples from the Two Lakes site (Koyukuk Flats) were processed by the W. M. Keck C Cycle Accelerator Mass Spectrometry (AMS) Laboratory at the University of California, Irvine. Samples from the Finger Lake site (Koyukuk Flats) were processed by the National Ocean Sciences AMS Facility at the Woods Hole Oceanographic Institution (Woods Hole, MA). Samples from Innoko Flats were sent to the United States Geological Survey (USGS) Radiocarbon Laboratory, Reston, Virginia for graphite preparation and then to the Center for AMS, Lawrence Livermore National Laboratory (Livermore, CA) for AMS measurement. Ages are reported as uncalibrated radiocarbon dates.

RESULTS

Landscape Characterisation

We differentiated four main lowland landscapes within the Koyukuk-Innoko region that have different depositional histories and permafrost characteristics: fluvial-young, fluvial-old, aeolian sand and lacustrine-loess (Figure 1).

The *fluvial-young* landscape comprises floodplains with elevations ranging from 10 m to 50 m asl. Permafrost typically is absent in early successional vegetation stages and sporadic in spruce forest (Jorgenson *et al.*, 2008). The areal extent of this landscape was not quantified because the floodplains extend beyond the study region (Figure 1).

The *fluvial-old* landscape consists of abandoned floodplains and the terrace above the present floodplain. Elevations range from 20 m asl to 60 m asl. Oxbow lakes and meandering abandoned channels are abundant. Occasional round thermokarst lakes indicate moderately ice-rich permafrost. This landscape covers 2922 km², or 20.5 per cent of the total area of the lowlands, which includes fluvial-old, aeolian sand and lacustrine-loess landscapes.

The *aeolian sand* landscape comprises active and inactive sand dunes and sand sheets, and is limited to the Koyukuk Flats region. Elevations range from 60 m asl to 220 m asl. The active Nogahabara sand dunes are the best studied portion of this landscape (Koster *et al.*, 1984). Permafrost existence is unknown. This landscape covers 1888 km² (13.3% of the lowlands).

The *lacustrine-loess* landscape consists of forested permafrost plateaus underlain by frozen peat and silt, rare gentle hills (presumably yedoma remnants), and thermokarst bogs and fens with thick organic deposits, mostly unfrozen. Elevations range mostly from 25 m asl to 40 m asl but in the areas adjacent to the uplands can reach 200 m asl. Thermokarst lakes are abundant. This landscape covers 9422 km² (66.2% of the lowlands). It was mapped as undivided Quaternary deposits by Patton *et al.* (2009).

Upland loess surrounds most of the lowland landscapes, but was not mapped and its extent is poorly known. There is often a broad transition zone between upland loess and lacustrine-loess landscapes. The upland loess occurs as low rounded hills and on the lower slopes of large hills. The loess

is probably widespread in areas with elevations from 100 m asl to 300 m asl, because most loess is deposited at elevations below 300 m asl (Péwé, 1975). Based on the occurrence of deep thermokarst lakes within this landscape, some surrounded by tall conical thermokarst mounds (baydzherakhs), we presume that most of the upland loess is yedoma.

Permafrost Stratigraphy of the Lacustrine Loess Landscape

Koyukuk Flats, Two Lakes Area.

The terrain at the Two Lakes study area consists of perennially frozen forested peat plateaus and unfrozen thermokarst bogs and fens, with water at the surface in the low-lying bogs and fens. Permafrost plateaus rise up to 4 m above the surface of bogs and fens (Figure 3A) and have active layer thicknesses ranging from 0.3 m to 0.7 m.

Three boreholes 4.3 m to 4.8 m deep were drilled at Two Lakes (Figures 1 and 4). In these sections, we distinguished three soil units: (1) surface terrestrial and semi-terrestrial peat; (2) lacustrine organic silt with peat inclusions; and (3) silt with peat inclusions underlain by organic-poor silt with rare small inclusions of organic material. Both organic and mineral soils contain excess ice (Figure 4; Table 1). The accumulation of terrestrial peat started in the early Holocene (Figure 4; Table 2).

The active layer comprised moss and woody sphagnum peat. The moisture content of unfrozen peat from the active layer was measured in 40 samples obtained from the three permafrost boreholes (sample location is not shown in Figure 4). The mean volumetric moisture content was 33 per cent and the mean gravimetric moisture content was 795 per cent for all boreholes. In borehole KFUW-2, with a thaw depth of 45 cm, unfrozen peat was also observed at depths from 63 cm to 79 cm, beneath the 18-cm thick frozen layer (Figure 4). The occurrence of this unfrozen layer

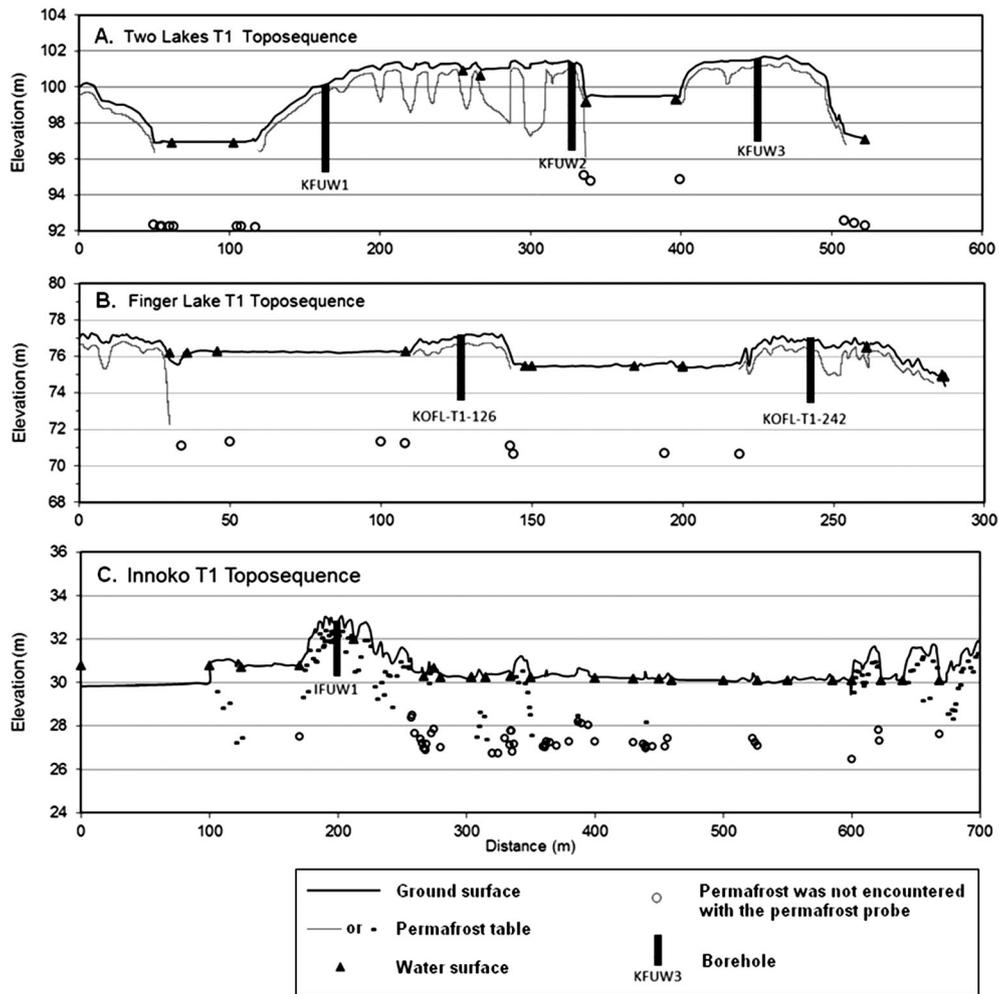


Figure 3 (A)–(C): Topographic profiles of the three study areas showing surface elevation, the permafrost table, the maximum observed unfrozen depth, water surface elevation and borehole locations.

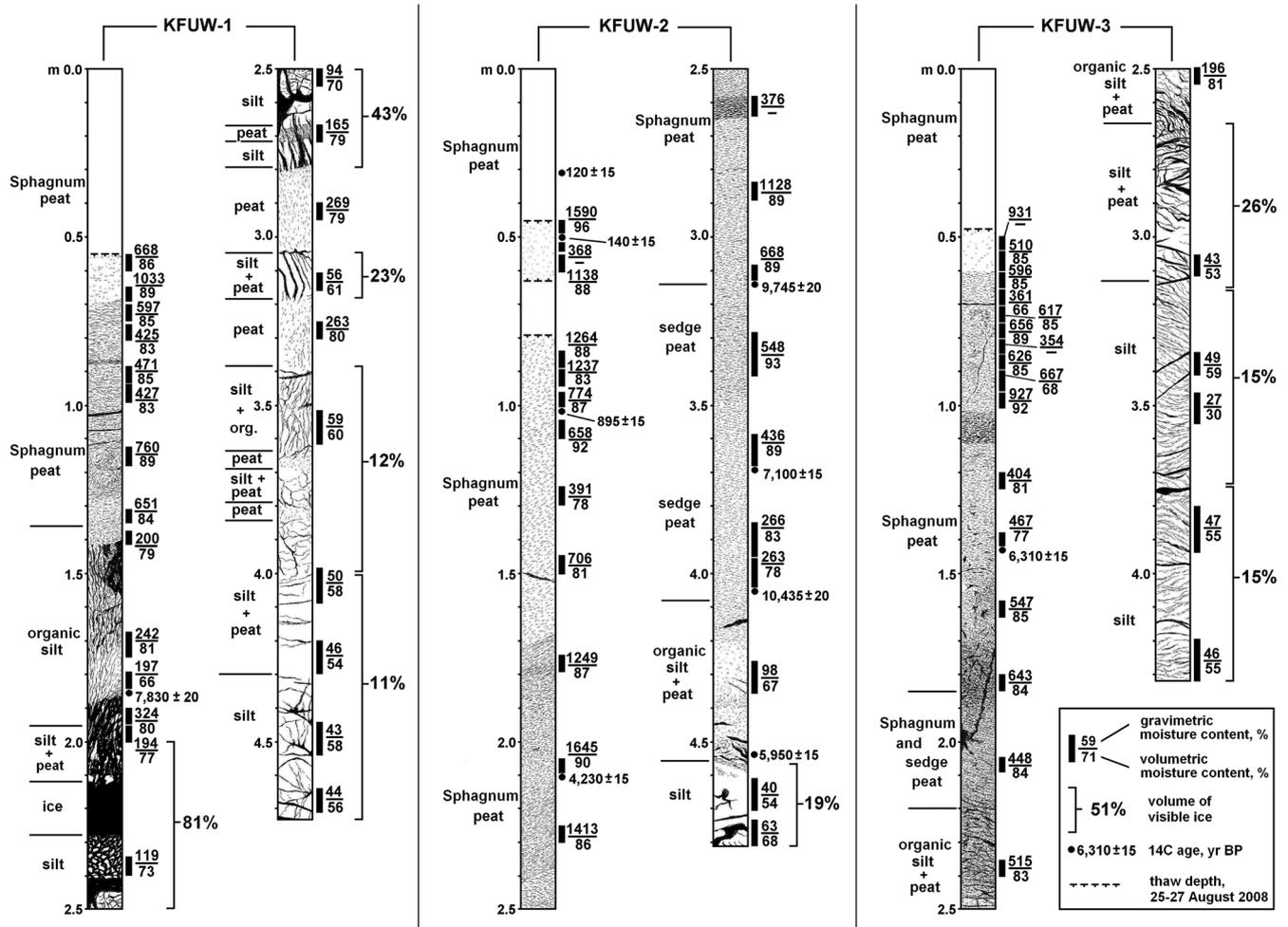


Figure 4 Cryostratigraphy (ice is black) and moisture content of frozen soils from boreholes KFUW-1, KFUW-2 and KFUW-3 at Two Lakes, Koyukuk Flats (location shown in Figure 1).

indicates that the permafrost is thermally unstable, which is supported by values of mean annual soil temperature close to 0°C recorded at the study area (O'Donnell *et al.*, 2012). During a cold winter with thin snow cover, this 16-cm thick residual thaw layer can return to a perennially frozen state.

The terrestrial peat comprised horizontally laminated reddish-brown, mostly sphagnum peat with occasional woody stems and distinct lenses of char near the surface, indicative of forest soils. In boreholes KFUW-2 and KFUW-3, sphagnum peat was underlain by sedge, or sphagnum and sedge peat, indicative of wet organic soils of sedge fens. A thick layer of sedge peat was distinguished in borehole KFUW-2 at depths from 3.13 m to 4.08 m. The frozen terrestrial peat is characterised by a combination of organic-matrix porphyritic cryostructure and micro-braided or micro-lenticular cryostructures, typical of syngenetic permafrost (Kanevskiy *et al.*, 2011) (Figures 4 and 5A; Table 1). The occurrence of distinct ice layers, or 'ice belts' (see KFUW-1 in Figure 4), which formed at the base of the active layer during peat accumulation, also suggests the syngenetic nature of the terrestrial

peat. Despite relatively small amounts of visible ice, the ice content of the peat was extremely high (e.g. in borehole KFUW-2, the gravimetric moisture content of many samples exceeded 1000%) (Figure 4).

The surface layer of terrestrial peat was underlain by a layer of olive-brown silty amorphous organic material formed by algae, indicating a lacustrine origin for this layer. This organic-mineral material locally contains inclusions of clean (organic-poor) silt and terrestrial peat associated with collapsing banks of the lake. The cryostratigraphy of the lacustrine organic silt was similar to that of forest peat, but the ice content was slightly lower.

The layer of lacustrine organic silt was underlain by grey organic-poor silt with some clay, which contained in places layers and inclusions of terrestrial peat or dark bands of detrital organic fragments. We presume that this organic material was retransported from collapsing banks of the lake. In borehole KFUW-1, the layers of grey silt were interbedded with layers of dark-brown peat and ice layers up to 20 cm thick (Figure 4). The ice was transparent, slightly yellowish, with rare irregular air bubbles less than 1.5 mm across.

Table 1 Cryostructures and moisture content of frozen soils of permafrost plateaus, Koyukuk and Innoko Flats.

Soil unit	Thickness, m	Thaw depth, cm	Number of samples	Moisture content of frozen soils		Cryostructures
				Gravimetric, % (mean ± SD values)	Volumetric, % (mean ± SD values)	
Koyukuk Flats, Two Lakes (KFUW-1, KFUW-2, KFUW3)						
Terrestrial peat	1.4–4.1	45–55	37	742 ± 363	85 ± 6	Organic-matrix porphyritic combined with micro-braided and micro-lenticular; with occasional ice 'belts'
Organic silt	0.5–0.6	—	9	268 ± 135	78 ± 7	Organic-matrix porphyritic combined with micro-braided and micro-lenticular
Silt	> 1.6	—	15	55 ± 23 45 ± 8*	58 ± 10 57 ± 4*	Layered, reticulate; visible ice content 23% average
Koyukuk Flats, Finger Lake (KOFL-T1-126, KOFL-T1-242)						
Terrestrial peat	1.1–2.0	45–80	10	1061 ± 594	90 ± 3	Organic-matrix porphyritic combined with micro-braided and micro-lenticular
Organic silt	0.2–0.9	—	5	215 ± 82	79 ± 3	Micro-braided and micro-lenticular (KOFL-T1-242); organic-matrix porphyritic combined with layered and braided (KOFL-T1-126)
Silt	> 1.5	—	8	92 ± 26	68 ± 6	Micro-braided and micro-lenticular (KOFL-T1-242); reticulate (KOFL-T1-126)
Innoko Flats (IFUW-1, IFUW-2, IFUW-3, IFEX-2)						
Terrestrial peat	0.7–1.1	55–65	4	470 ± 221	86 ± 5	Organic-matrix porphyritic combined with micro-braided and micro-lenticular
Organic silt	0.7–1.0	—	12	200 ± 71	77 ± 5	Micro-braided and micro-lenticular with occasional ice 'belts' and veins
Silt	> 3.4	—	28	98 ± 65 82 ± 19*	69 ± 11 71 ± 4*	Layered, reticulate and ataxitic; visible ice content 48% average

Note: Moisture content values represent mean ± standard deviation (SD).

*Calculated by Equations 1 and 2.

In borehole KFUW-3, peat inclusions were observed only in the upper part of this layer (2.66–3.12 m), and below it silt was massive, uniform and contained only small occasional inclusions of organic detritus. The total thickness of this layer was not determined. The maximum thickness (1.6 m) of this unit was obtained in borehole KFUW-3, in which layered and reticulate cryostructures predominated. Most of the ice lenses were inclined, and their thickness generally varied from 0.2 cm to 1 cm and occasionally reached 3 cm. Such cryostructures are typical of epigenetic permafrost formed from downward freezing of saturated soil. The mean visible ice content in silt was 23 per cent, and the mean volumetric and gravimetric moisture contents calculated by Equations 1 and 2 were 57 per cent and 45 per cent, respectively (Table 1).

Koyukuk Flats, Finger Lake Area.

The structure of the upper permafrost at Finger Lake was similar to that observed at Two Lakes. Permafrost plateaus rise up to 1.5 m above the surface of thermokarst bogs and fens (Figure 3B). Additionally, rare remnants of higher surfaces are represented by gentle hills up to 10 m higher than the surface of peat plateaus. The hills are composed

of frozen silt locally overlain by peat. On the top of one hill, we observed thermokarst mounds up to 2 m high and 15–30 m across forming a polygonal pattern. The mounds comprised mostly frozen silt and indicate degradation of relict ice wedges that presumably developed in the yedoma deposits during the Late Pleistocene. The hill also had several small, deep thermokarst lakes indicative of extremely high ice contents.

Similar to Two Lakes, three soil units were distinguished in two boreholes (KOFL-T1-126 and KOFL-T1-242) drilled in peat plateaus (Figures 1 and 3): (1) surface terrestrial and semi-terrestrial peat (sphagnum peat underlain by sedge peat); (2) lacustrine organic silt and peat; and (3) organic-poor silt with some peat inclusions on top (Figure 6; Tables 1 and 2).

In borehole KOFL-T-126, micro-cryostructures typical of syngenetic permafrost were observed only in terrestrial peat, while cryostructures of the lacustrine organic soils and underlying silt were typical of epigenetic permafrost. In borehole KOFL-T1-242, micro-cryostructures dominated all soil units, including terrestrial peat, lacustrine organic soils and silt (Figure 6; Table 1).

The drilling on top of the low hill located at the southern bank of Finger Lake (off the upper aerial photograph in

Table 2 AMS radiocarbon dating of organic material, Koyukuk and Innoko Flats.

Borehole/ exposure ID	Depth, cm	Lab ID	Radiocarbon age, yr BP	$\delta^{13}\text{C}$, ‰	Fraction modern	Soil unit	Dated material
Koyukuk Flats, Two Lakes (KFUW-1, KFUW-2, KFUW3)							
KFUW-1	185	UCIT21038	7830 ± 20	-26.1	0.3773	Organic silt	Detrital plant fragments
KFUW-2	31	UCIT21018	120 ± 15	-25.7	0.9849	Peat	<i>Sphagnum</i> leaves and stems
KFUW-2	50	UCIT21019	140 ± 15	-27.8	0.9828	Peat	<i>Chamaedaphne calyculata</i> leaves, few <i>Sphagnum</i>
KFUW-2	101	UCIT21020	895 ± 15	-26.1	0.8945	Peat	<i>Sphagnum</i> leaves and stems
KFUW-2	210	UCIT21021	4230 ± 15	-26.9	0.5906	Peat	<i>Sphagnum</i> leaves and stems
KFUW-2	313	UCIT21022	9745 ± 20	-27.5	0.2972	Peat	Sedge roots, <i>Calliergon</i> spp., moss
KFUW-2	369	UCIT21023	7100 ± 15	-27.2	0.4132	Peat	Detrital peat fragments
KFUW-2	405	UCIT21024	10435 ± 20	-28.4	0.2728	Peat	Fen peat, sedge leaves, <i>Scorpidum scorpioides</i> leaves and stems
KFUW-2	454	UCIT21025	5950 ± 15	—	0.4767	Organic silt	Detrital plant fragments
KFUW-3	143	UCIT21039	6310 ± 15	-23.8	0.4559	Organic silt	Detrital plant fragments with coarse sedge leaves (<i>Carex rostrata</i> ?)
Koyukuk Flats, Finger Lake (KOFL-T1-126, KOFL-T1-242)							
KOFL-T1-126	29	OS-67140	1240 ± 30	-24.1	0.8571	Peat	Moat peat, fine sedge
KOFL-T1-126	203	OS-67298	3270 ± 35	-26.8	0.6659	Organic silt	Sedge peat with willow stems
KOFL-T1-126	288	OS-67260	3580 ± 30	-25.0	0.6399	Organic silt	<i>Calliergon</i> , <i>Equisetum fluviatile</i>
KOFL-T1-242	21	OS-67142	85 ± 25	-25.1	0.9893	Peat	<i>Sphagnum fuscum</i>
KOFL-T1-242	65	OS-67264	590 ± 30	-24.7	0.9291	Peat	<i>Sphagnum</i> peat
KOFL-T1-242	115	OS-67263	4720 ± 40	-26.9	0.5558	Organic silt	Undifferentiated lacustrine peat
KOFL-T1-242	167	OS-67262	9470 ± 45	-27.1	0.3075	Silt	Undifferentiated terrestrial peat
Innoko Flats (IFUW-1, IFUW-2, IFUW-3, IFEX-2)							
IFUW-1	36	WW7898	1120 ± 20	-25.4	0.8698	Peat	<i>Sphagnum</i> sp. and forest peat (<i>Picea mariana</i>)
IFUW-2	60	WW7899	600 ± 30	-25.3	0.9281	Peat	Spruce wood
IFUW-2	90	WW7978	1935 ± 30	-26.2	0.7858	Peat	<i>Sphagnum</i> peat
IFUW-2	119	WW7979	3740 ± 25	-26.3	0.6278	Organic silt	Undifferentiated lacustrine peat
IFUW-2	146	WW7980	4935 ± 30	-27.1	0.5409	Organic silt	Undifferentiated lacustrine peat
IFUW-2	171	WW7900	4405 ± 30	-25.0	0.5780	Organic silt	Wood
IFUW-2	171	WW7982	5460 ± 40	-27.5	0.5068	Organic silt	Undifferentiated lacustrine peat
IFUW-2	198	WW7981	5860 ± 25	-27.5	0.4821	Organic silt	Undifferentiated lacustrine peat
IFUW-2	200	WW7901	4395 ± 25	-25.1	0.5787	Organic silt	Wood
IFUW-2	252	WW7902	4335 ± 25	-25.1	0.5830	Organic silt	<i>Sphagnum</i> sp.
IFUW-2	264	WW7903	4770 ± 30	-24.1	0.5523	Organic silt	Wood
IFUW-3	66	WW7904	125 ± 25	-26.1	0.9848	Peat	Woody peat
IFEX-2	175	WW7905	4455 ± 30	-28.4	0.5744	Organic silt	Wood

Figure 1) revealed a thick layer of sphagnum peat on the surface. Peat thickness in borehole KOFL-S2 (Figure 7) exceeded 2.5 m and the boundary with mineral soil was not reached. The ice content of the peat increased below 2.08 m, and we consider this lower part of the peat section to have been syngenetically frozen, as indicated by the presence of micro-cryostructures. The upper part lacked distinct cryostructures, suggesting that it had thawed and refrozen.

Borehole KOFL-S1 (Figure 7) was drilled through frozen silt at the bottom of a pit excavated in a collapsing bank (3 m below the top of the hill and ~100 m from borehole KOFL-S2). Ice-poor silt in this section was generally uniform, but contained peat layers and inclusions, and

was oxidised along thin irregularly oriented ice veins and lenses (Figures 5B and 7). Peat layers were usually deformed or displaced along the cracks and lacked visible ice. These features are typical of thawed and refrozen sediments. Gravimetric moisture contents were 26–41 per cent for clean silt and 53–74 per cent for silt with peat layers and inclusions (Figure 7). Ice-poor silt with similar features was also observed in the pit excavated below borehole KOFL-S1, 7.5 m below the top of the hill and 3.5 m above the lake.

Innoko Flats.

The terrain at the Innoko Flats is similar to that of the other two study areas. The permafrost plateaus rise 2–3 m above the surface of the thermokarst bogs and fens

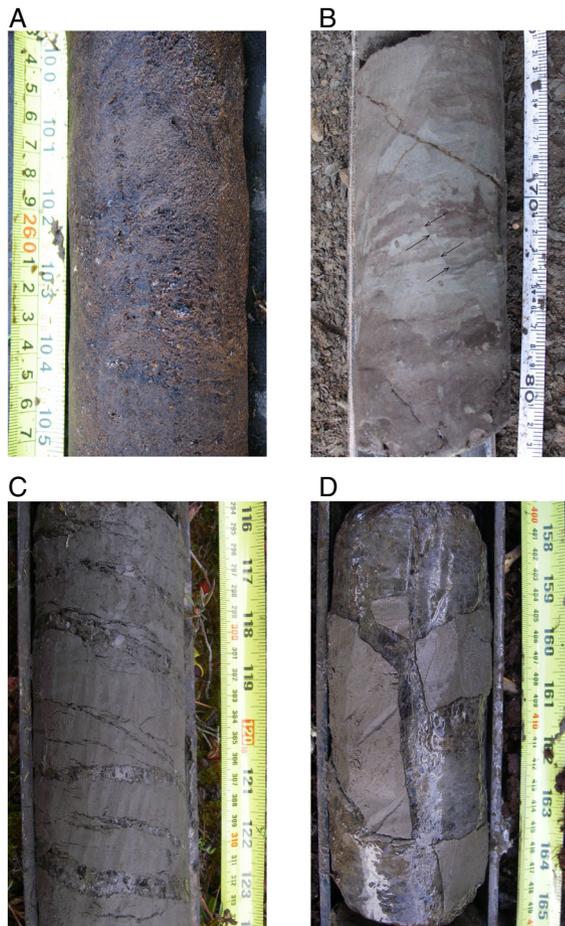


Figure 5 Permafrost cores with typical cryostructures of frozen soils. (A) Micro-braided cryostructure of syngenetically frozen peat (Koyukuk Flats, Two Lakes area, borehole KFUV-2). (B) Ice-poor epigenetically frozen silt (Koyukuk Flats, Finger Lake area, borehole KOFL-S1, depth 4.60 m to 4.83 m). Note the distorted peat layers and oxidation along the ice lenses (marked with arrows). (C) Layered cryostructure of epigenetically frozen silt (Innoko Flats, borehole IFUW-1). (D) Ataxitic (suspended) cryostructure of epigenetically frozen silt (Innoko Flats, borehole at the base of exposure IFEX-2). This figure is available in colour online at wileyonlinelibrary.com/journal/ppp

(Figure 3C), and have an active layer thickness of typically 0.5–0.8 m. Numerous newly developing thermokarst pits 2–5 m across have thaw depths of 1.1 m to 2.1 m (Figure 3). The bogs surrounding the plateaus were unfrozen to depths 3 m. Standing dead trees in the ‘moat’ along the margin of peat plateaus indicate active lateral permafrost degradation. Thaw probing along the margins revealed that a thaw bulb had developed underneath the edge of the permafrost plateaus, indicating some subsurface thawing similar to that described by Wallace (1948).

Similar to the study areas on the Koyukuk Flats, three soil units were distinguished on permafrost plateaus in three boreholes (IFUW-1, IFUW-2, IFUW-3) and one exposure (IFEX-2) (Figures 1 and 3): (1) surface terrestrial peat (mostly sphagnum); (2) lacustrine organic silt and peat; and (3) silt with peat inclusions underlain by organic-poor silt (Figures 8 and 9; Tables 1 and 2).

The active layer was formed entirely of forest peat. The mean volumetric moisture content of the active layer was 24 per cent and mean gravimetric moisture content was 62 per cent ($n=36$). Increased depth of seasonal thaw (1.3 m) on top of the exposure IFEX-2 (Figure 9) was related to a deeper seasonal thawing within the exposed bluff and did not represent the normal thickness of the active layer in this area (Table 1). In this exposure, the frozen terrestrial peat comprised dark- to light-brown, poorly decomposed sphagnum peat grading to moderately decomposed peat with some buried wood, roots and char, with several silt lenses at 1.3–1.6 m (Figure 9). A layer of lacustrine organic soils comprised brown silty peat and organic silt with numerous wood inclusions and irregular layers of reworked, slightly decomposed detrital organic matter. A layer of grey clean silt with rare inclusions of organic matter formed the lowest unit (total thickness unknown).

In boreholes IFUW-1 and IFUW-2 and exposure IFEX-2, the soil in the upper 20–40 cm of this unit was brown-grey silt with numerous inclusions of organic matter (transitional zone between lacustrine organic silt and clean silt). A combination of layered, reticulate and ataxitic cryostructures with relatively thick ice lenses divided by dense ice-poor soil aggregates (Figures 5C, D, 8 and 9) indicates epigenetic freezing of the silt. The thickness of ice lenses generally varied from 1 cm to 5 cm and occasionally reached 10 cm. The ice was clear, colourless and contained air bubbles that were round (diameter < 2 mm) or vertically elongate.

DISCUSSION

Cryostratigraphic Units and Age of the Sediments

The frozen sediments within elevated peat plateaus at the three study areas had similar cryostratigraphic patterns, indicating a similar landscape evolution. We distinguish three main cryostratigraphic units:

1. Surface terrestrial and semi-terrestrial peat (STSP). This unit consists of three sub-units: (1a) forest peat (woody sphagnum peat with roots and char) (upper sub-unit); (1b) bog (sphagnum); and/or (1c) fen (sedge and sphagnum-sedge) peat (lower sub-units). The peat was frozen syngenetically and/or quasi-syngenetically (Shur, 1988a; Kanevskiy, 2003), as indicated by the prevalence of micro-cryostructures and the occurrence of ice belts. In some sections, however, peat was frozen epigenetically as a result of thawing and refreezing of permafrost plateaus.
2. Lacustrine deposit (LD). This unit has an upper sub-unit (2a) of organic silt and sedimentary algal peat, and a lower sub-unit (2b) of organic silt with inclusions of silt and terrestrial peat that likely originated from the collapse of lake banks. Despite widespread micro-cryostructures typical of syngenetic permafrost, syngenetic freezing under shallow water in the area of warm discontinuous permafrost is highly unlikely. Instead, these sediments probably froze

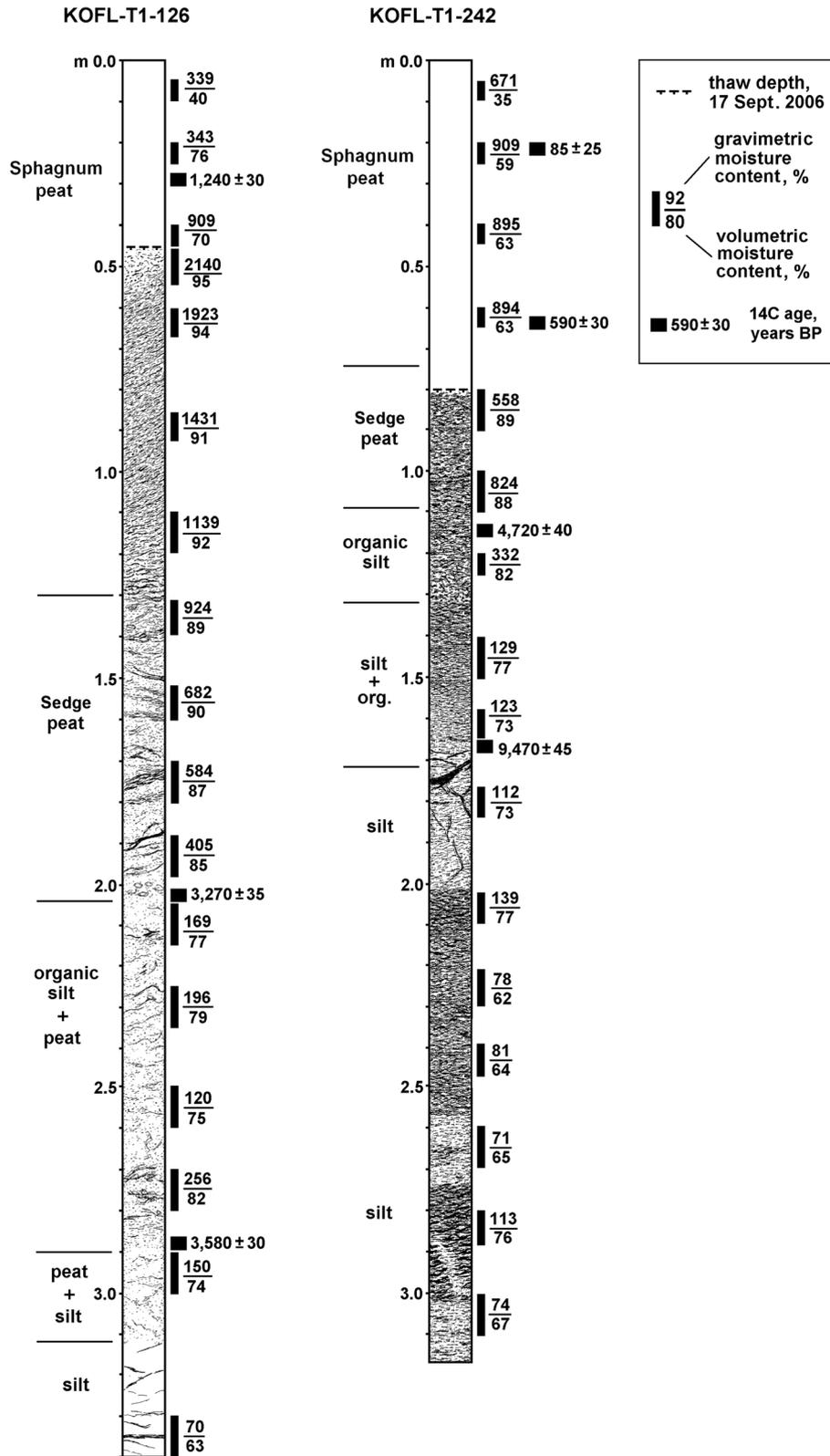


Figure 6 Cryostratigraphy (ice is black) and moisture content of frozen soils from boreholes KOFL-T1-126 and KOFL-T1-242 at Finger Lake, Koyukuk Flats (modified from Jorgenson *et al.*, 2012).

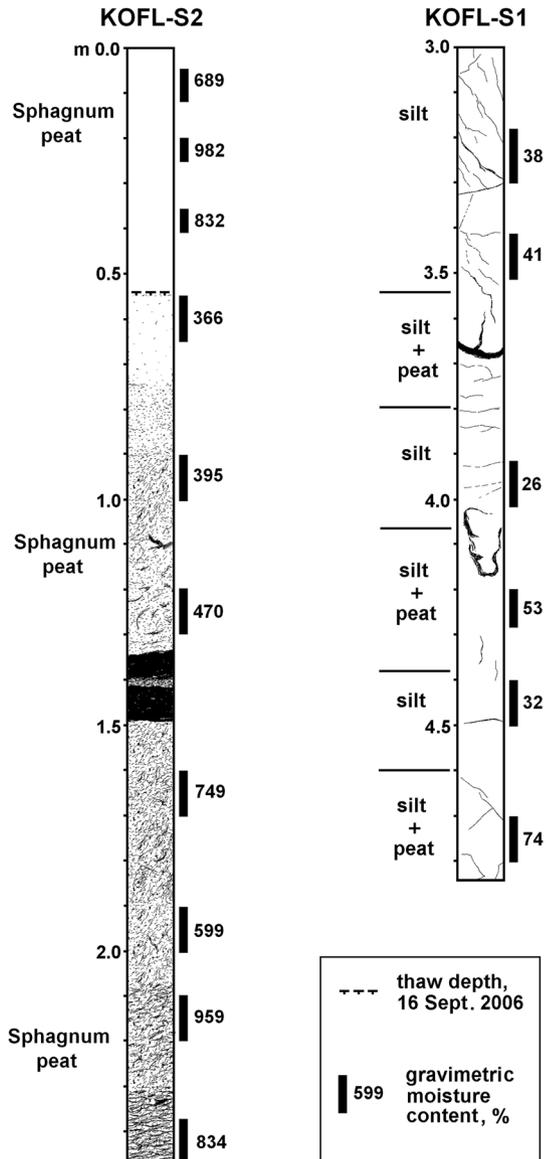


Figure 7 Cryostratigraphy (ice is black) and gravimetric water content of frozen soils from boreholes KOFL-S1 and KOFL-S2 at Finger Lake, Koyukuk Flats.

quasi-syngenetically during the accumulation and subsequent syngenetic freezing of the terrestrial peat, and occasionally epigenetically (KOFL-T1-126).

3. Reworked yedoma (RY). This unit has an upper sub-unit (3a) of silt with inclusions of surface terrestrial peat and organic material previously incorporated in yedoma, which originated from the collapse of lake banks, and a lower sub-unit (3b) of silt with rare small organic inclusions and slightly disturbed organic-rich layers. The upper sub-unit probably formed by reworking of yedoma soils within the lake, and the lower sub-unit by *in-situ* thawing of yedoma soils beneath the lake. The boundary

between the sub-units was not clearly detected in the studied sections, although the organic content of the silt decreased with depth. The lower sub-unit (thawed and refrozen yedoma) froze epigenetically, and the upper sub-unit (yedoma reworked by the lake) froze epigenetically and occasionally quasi-syngenetically (KOFL-T1-242).

Radiocarbon ages of organic material in the cores (Table 2; Figures 4, 6, 8 and 9) reveal a complex pattern of ages of the stratigraphic units across the three sites. The syngenetically frozen peat near the surface had ages mostly between 85 ¹⁴C yr BP and 1935 ¹⁴C yr BP, but at Two Lakes, three samples from the basal peat above the lacustrine organic silt had ages of between 7100 ¹⁴C yr BP and 10 435 ¹⁴C yr BP (Figure 4). At Innoko Flats, the age of peat sampled near its base was less than 2000 ¹⁴C yr BP (Figure 8). Lacustrine organic silt (15 samples) had ages between 7830 ¹⁴C yr BP and 3270 ¹⁴C yr BP. The ages of lacustrine organic silt at Two Lakes were older (7830 ¹⁴C yr BP to 5950 ¹⁴C yr BP) than those at Finger Lake (4720 ¹⁴C yr BP to 327 ¹⁴C yr BP) and Innoko Flats (5860 ¹⁴C yr BP to 3740 ¹⁴C yr BP) (Table 2).

The differences in radiocarbon dates and thicknesses of lacustrine and forest peat among sites indicate a long-term history of lake development and drainage occurring at different times over the landscape. At IFUW-2, eight ages within lacustrine organic silt showed inconsistent age-depth trends, which we attribute to mixing of aquatic and eroded materials during lake development. At KFUW-2, the inconsistent age of three samples near the base of the surface peat may be due to roots or other biotic mixing, cryoturbation, or other causes, but such reversals have been noted in permafrost sections elsewhere (Hamilton *et al.*, 1988; Kanevskiy *et al.*, 2011; O'Donnell *et al.*, 2011).

Ice Content

The ice content of sediments differed substantially among the three cryostratigraphic units (STSP, LD and RY) (Table 1). The highest mean volumetric and gravimetric ice contents characterised syngenetically frozen terrestrial and semi-terrestrial peat (STSP), particularly the gravimetric ice content due to the low dry density of the peat. Ice contents of the quasi-syngenetically frozen lacustrine organic silt (LD) were intermediate, but still very high. The mean ice contents of forest woody peat and lacustrine organic silt were higher at Koyukuk Flats (both study areas) than at Innoko Flats. When comparing gravimetric and volumetric moisture contents of silts (RY) obtained for Two Lakes and Innoko Flats by the 'traditional' method of sample processing (first method) with values calculated by Equations 1 and 2 from the volumes of visible ice (second method), we found that the two methods gave similar results (Table 1). The mean ice content of frozen silts was much higher at Innoko Flats and Finger Lake than at Two Lakes. Despite similar ice

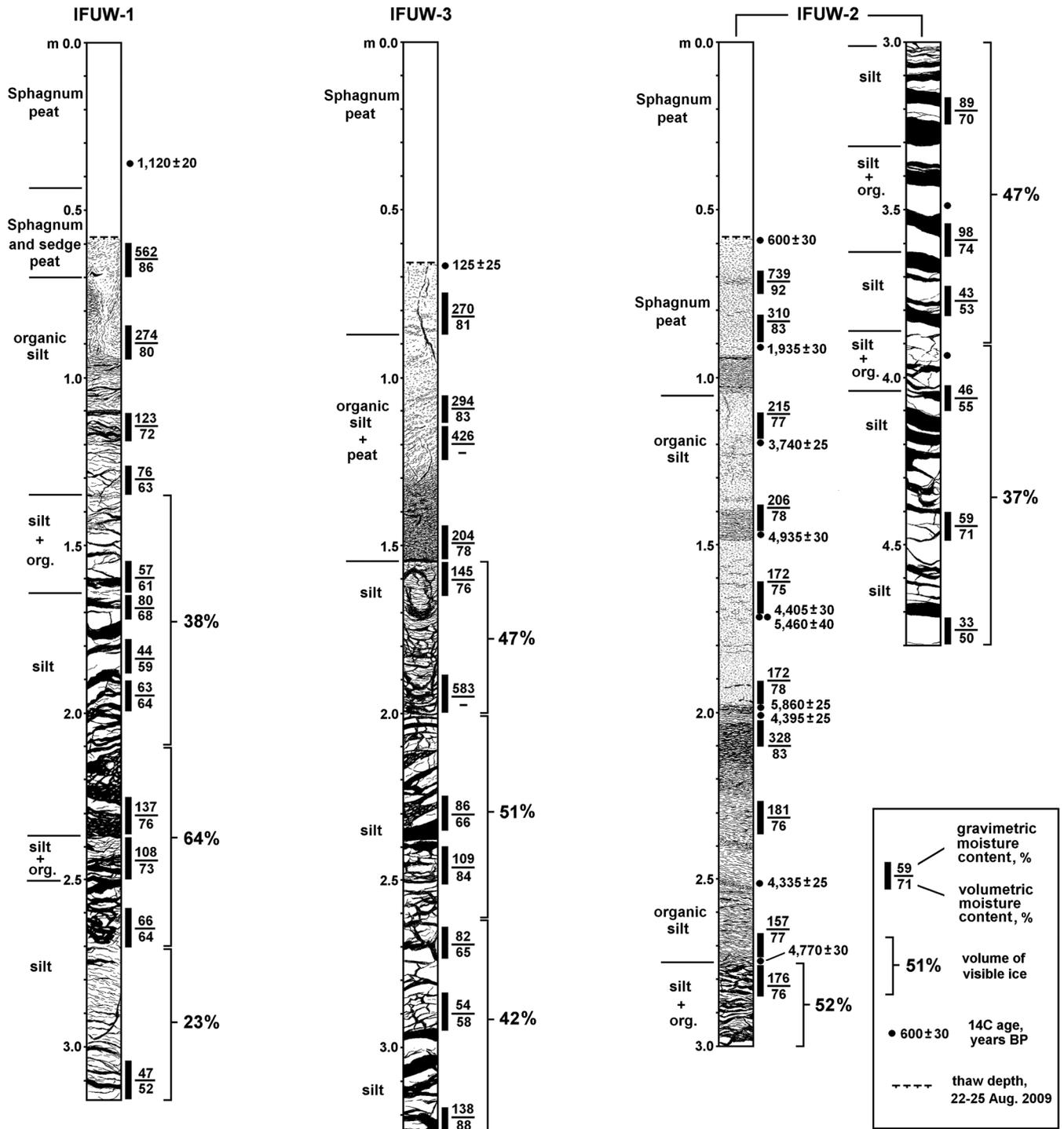


Figure 8 Cryostratigraphy (ice is black) and ice content of frozen soils from boreholes IFUW-1, IFUW-2 and IFUW-3, Innoko Flats.

contents at Innoko Flats and Finger Lake (Table 1), the cryostructures of silts at these two sites were different because the silts were mostly quasi-syngenetically frozen at Finger Lake (Figure 6, borehole KOFL-T1-242) and epigenetically frozen at Innoko Flats (Figures 8 and 9).

The high content of visible ice in silt, especially at Innoko Flats (48%), indicates a high potential thaw settlement of permafrost plateaus. Such a high visible ice content was not unusual for frozen lacustrine and glacio-lacustrine sediments with similar cryostructures

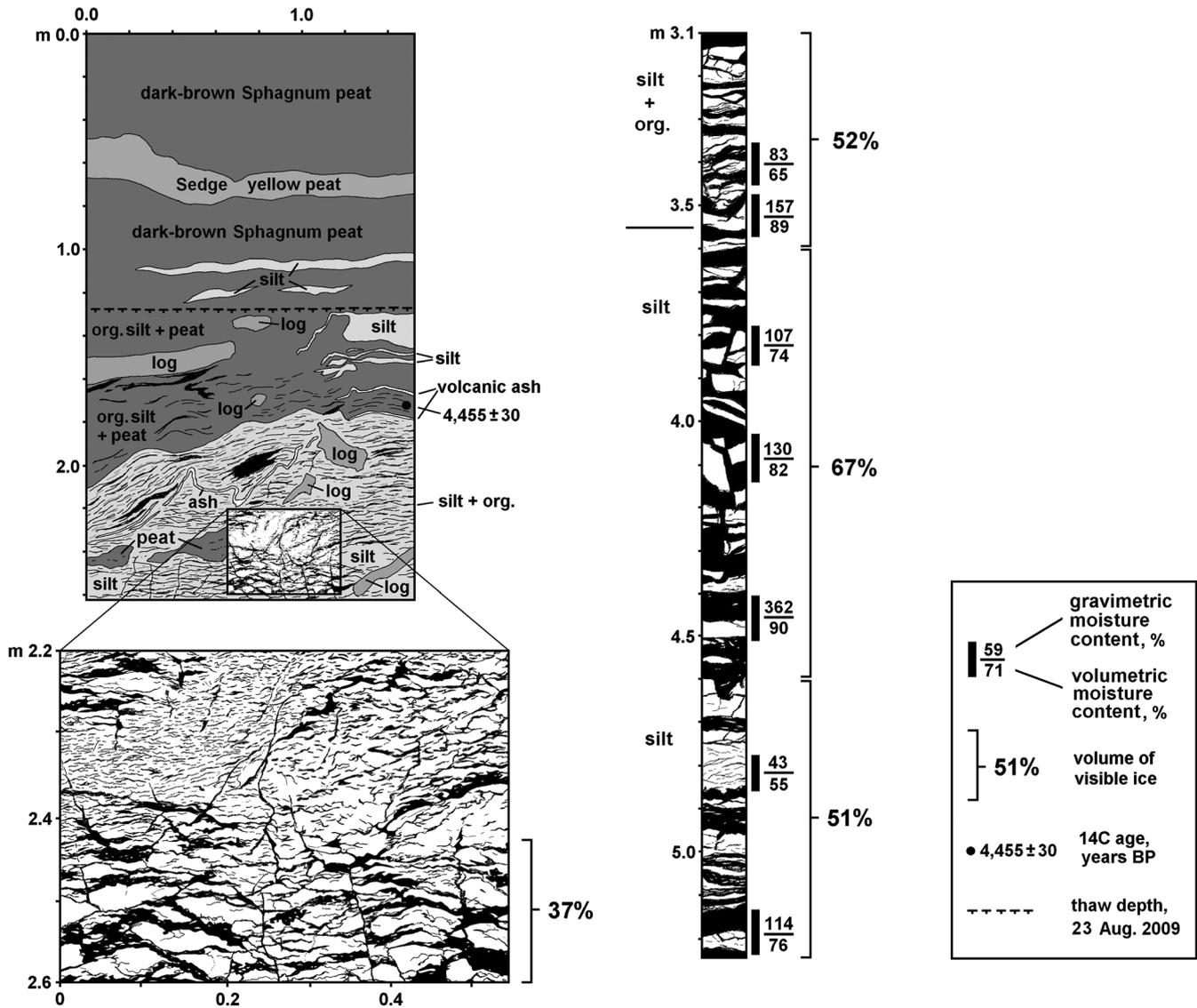


Figure 9 Cryostratigraphy (ice is black) and moisture content of frozen soils, Innoko Flats: exposure (left) and borehole IFEX-2 (right).

from different permafrost regions of Russia, Alaska and Canada (Kanevskiy *et al.*, 2013b, and citations therein). A difference in the elevations of permafrost plateaus and modern thermokarst bogs of up to 5 m (Figure 3) corresponds to a thaw settlement of the surface due to thawing of the ground ice (mainly within ice-rich silt) under the bogs.

Formation and Permafrost History of the Lacustrine Plains

Based on evidence from the three study areas and our studies of permafrost in other regions of Alaska, we have developed a conceptual model with nine stages to synthesise the depositional and permafrost processes that affected evolution of the lacustrine-loess landscape on the

Koyukuk and Innoko Flats from the end of Pleistocene to the present day (Figure 10).

Koyukuk-Innoko Region Prior to Formation of the Lacustrine Plains.

By the end of the Pleistocene, the accumulation of silt in extremely cold periglacial environments had formed yedoma (Figure 10A). In Alaska, numerous sections of yedoma have been observed in the vast areas which were unglaciated in the Late Pleistocene (Kanevskiy *et al.*, 2011, and citations therein). The volumetric content of wedge ice in Alaskan yedoma has been estimated to be up to 70 per cent in the East Oumalik area, northern Alaska (Lawson, 1983), 57 per cent at the Itkillik River exposure, northern Alaska (Kanevskiy *et al.*, 2011), 61 per cent in

the Devil Mountains area, Seward Peninsula (Shur *et al.*, 2012), and 47 per cent in the Livengood area, interior Alaska (Kanevskiy *et al.*, 2012). Yedoma sections with a very high content of segregated ice and a relatively small volume of wedge ice have also been described (Kanevskiy *et al.*, 2008, 2012). Thaw strain values of yedoma silt in interior Alaska generally vary from 20 per cent to 60 per cent (Kanevskiy *et al.*, 2012). Complete thawing of 30-m thick yedoma with a typical wedge-ice content of 30 per cent to 50 per cent can result in a thaw settlement exceeding 20 m.

In the Koyukuk and Innoko Flats, the existence of yedoma in the Late Pleistocene is suggested by the widespread occurrence of wind-blown silt (Péwé, 1975; Muhs *et al.*, 2003; Muhs and Budahn, 2006) and the absence of glaciation (Péwé, 1975; Hamilton, 1994). Bones of Pleistocene mammals (mammoth) typical of yedoma were discovered in the Yukon-Koyukuk lowland (Weber and Péwé, 1961). In adjacent regions, ice-rich silts with large ice wedges occur on the Seward Peninsula (von Kotzebue, 1821; Quackenbush, 1909; Taber, 1943; Hopkins, 1963; Hopkins and Kidd, 1988; Höfle and Ping, 1996; Shur *et al.*, 2012), the lower Kobuk River (Cantwell, 1887) and the Palisades exposure in the central Yukon River valley (Maddren, 1905; Matheus *et al.*, 2003; Reyes *et al.*, 2010; Jensen *et al.*, 2013). Within the Koyukuk Flats, at the Finger Lake site and from aeroplane flights, we have observed rare isolated hills that are remnants of the old surface and which occasionally contained thermokarst features indicative of yedoma, including tall conical thermokarst mounds formed as a result of ice-wedge degradation and deep thermokarst lakes on the tops of the hills. Thus, we conclude that yedoma was widespread in the Koyukuk and Innoko Flats during the Late Pleistocene.

Stages 1 to 3 – Thaw Lake Formation and Yedoma Degradation.

Since the end of the Pleistocene, a significant portion of the yedoma, particularly in the discontinuous permafrost zone, has been lost by thermokarst and thermal erosion. The stages of formation of thermokarst lakes in yedoma terrain were described by Soloviev (1962) and Shur *et al.* (2012). Thaw lake development starts with partial thaw of the upper ice wedges and the formation of small shallow ponds in the troughs above the ice wedges, especially at their intersections (stage 1). Deepening and widening of the water-filled troughs results in the initial formation of a shallow thermokarst lake above the polygons (stage 2). When the lake water depth exceeds a critical value, which corresponds to the mean annual bottom temperature at the freezing point (Kudryavtsev, 1959; Shur and Osterkamp, 2007), thawing of yedoma beneath the lake accelerates (Figure 10B, stage 3). The early stages of lake development can be interrupted by drainage, the development of floating mats, or the accumulation of organic matter on the sinking soil surface (Shur *et al.*, 2012).

alternative scenario for these stages of terrain evolution infers that the formation of small ponds (stage 1) or shallow lakes (stage 2) was triggered by water accumulating in topographic depressions (Katasonov, 1979; Jorgenson and Shur, 2007) as a result of increasing atmospheric precipitation during the transition from the Late Pleistocene to Holocene. Such wetter conditions were probably more important to thermokarst development than increasing air temperatures (Katasonov, 1979; Gravis, 1981; Shur, 1988a). Under this scenario, thermokarst starts as a result of thawing of the ice-rich soils beneath small ponds or lakes only at stages 2 or 3. Yedoma thawing could also be triggered by thermal erosion, which increased substantially during the Pleistocene-Holocene transition (Mann *et al.*, 2002).

Degradation of ice-rich yedoma occurs rapidly beneath deep lakes. During this process, a layer of thawed silt accumulates at the lake bottom. This layer completely loses its original structure, and its thickness can be very small compared with the original thickness of undisturbed yedoma because of the thaw settlement of ice-rich soils and melting of ice wedges (Shur *et al.*, 2012). The layer of thawed silt is covered with lacustrine deposits associated with thermal erosion of the lake shores. The boundary between yedoma soils thawed *in situ* and retransported yedoma soils deposited at the lake bottom as a result of shore erosion, slope processes and currents is not always clear. Thus, in Figure 10 we combined these deposits into one type: 'thawed and partially reworked yedoma'.

Thaw lake development in the region started before 10 435 ¹⁴C yr BP (KFUW-2), which is the oldest age for terrestrial peat overlying lacustrine organic silt. The age range of 7830 ¹⁴C yr BP to 3270 ¹⁴C yr BP for lacustrine organic silt (Table 2) indicates that it took thousands of years for the thaw lakes to develop and reduce the yedoma to small isolated hills within the flats. Kaplina (2009) analysed more than 100 radiocarbon dates from thaw lake basins developed in yedoma terrain in northern Yakutia, and concluded that lake thermokarst began 13 000 ¹⁴C yr BP to 12 000 ¹⁴C yr BP, and peat formation in drained lake basins began 11 000 ¹⁴C yr BP to 10 000 ¹⁴C yr BP. Stabilisation of thermokarst terrain started from 10 000 ¹⁴C yr BP to 8500 ¹⁴C yr BP. Similar dates were reported by Katasonov (1979) and Gravis (1981) for central and northern Yakutia, respectively. But there are few radiocarbon dates related to yedoma degradation in Alaska. Lawson (1983) sampled a peat layer from the bottom of a thaw lake basin in the Oumalik area (northern Alaska) and concluded that the lake activity started before 7500 yr BP and continued for at least 1500 years. Jones *et al.* (2012) reported that basal peat ages from thaw lake basins on the northern Seward Peninsula were within the last 4000 yr BP, and only one date exceeded 9000 cal. yr BP. These dates are consistent with an analysis of 1516 radiocarbon dates in a circumarctic database that showed rapid peatland development between 12 000 yr BP and 8000 yr BP, followed by lower rates of peatland

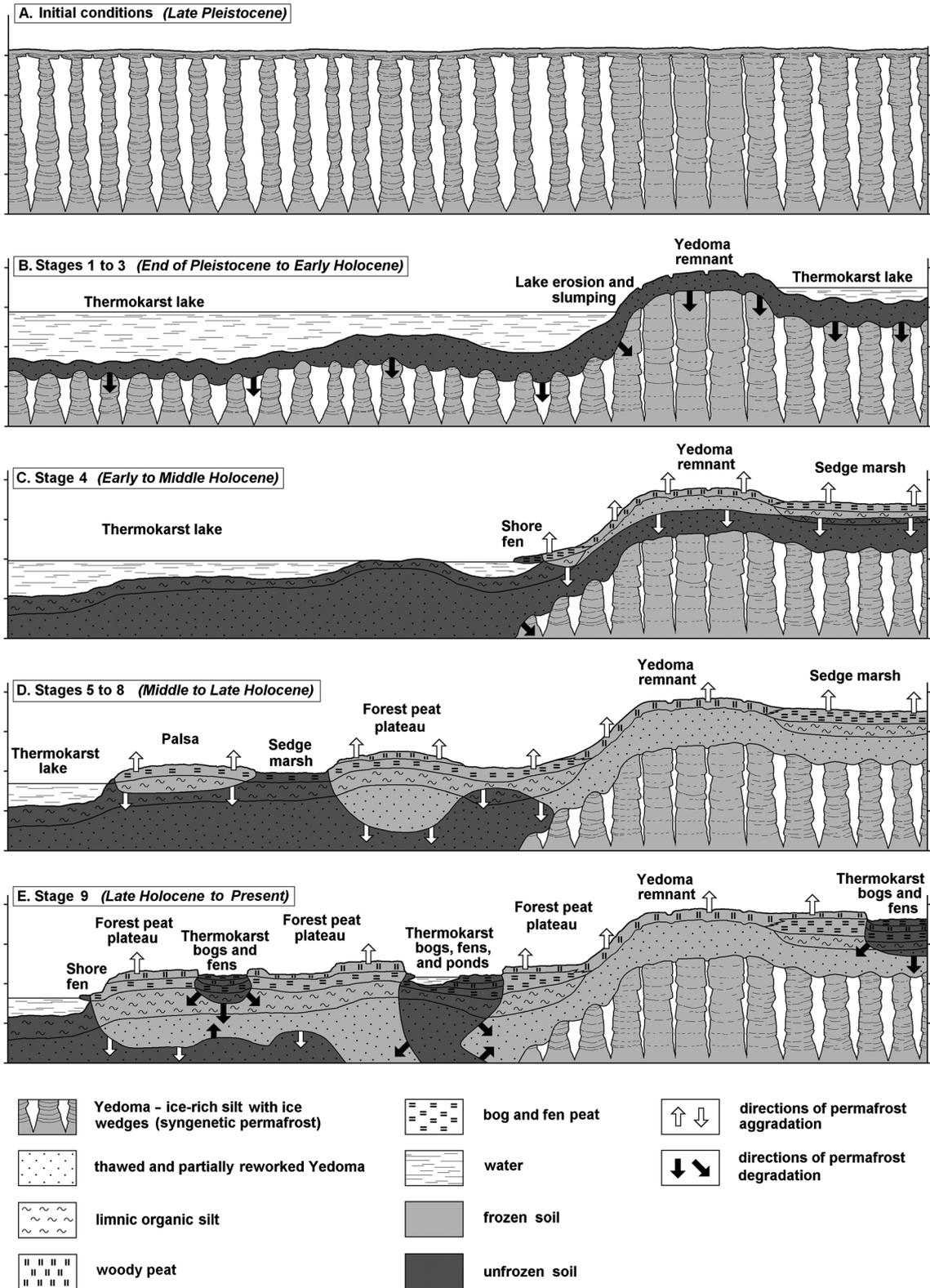


Figure 10 (A)–(E) Conceptual model showing the stages of terrain development from the Late Pleistocene to the present (not to scale).

initiation during the middle Holocene (MacDonald *et al.*, 2006). A high frequency of thermokarst lake formation in Beringia during the same period was also reported by Brosius *et al.* (2012).

Stage 4 – Complete Thawing of Yedoma Beneath the Lakes.

Under favourable conditions, the development of thermokarst lakes results in their expansion due to thermal erosion, complete degradation of yedoma beneath the lakes and the formation of deep taliks (Figure 10C). In areas of cold continuous permafrost, lake thermokarst usually leads to the formation of closed taliks, but in areas with higher temperatures, thawing completely penetrates the permafrost and open taliks develop. During this stage, lacustrine sediments incorporate mixed colluvial material from the eroding banks, algal remains from the water column, and mixed silt and detrital organic fragments distributed by currents throughout the lake, forming heterogeneous organic-mineral deposits (lacustrine organic silt). These combined processes make dating of lacustrine deposits problematic (Hopkins and Kidd, 1988).

The surface of yedoma remnants also experienced changes. The steppe grasslands typical of yedoma terrain during the dry Late Pleistocene were replaced by forests with thick mosses and shallow bogs (Shur and Jorgenson, 2007), which favoured peat formation. For example, at Finger Lake, a layer of the ice-rich syngenetically frozen peat > 2.5 m thick was observed on the yedoma hill where the surface silts had thawed (Figure 7). Formation of the thick peat resulted in a new cycle of permafrost aggradation. The climate cooling which followed the early Holocene climate optimum probably contributed to this peat accumulation and permafrost aggradation. Permafrost aggraded in two directions: upwards (syngenetic freezing of organic soils accompanying moss accumulation on the surface) and downwards (epigenetic refreezing of previously thawed silt) (Figure 10C).

Most isolated yedoma remnants that survived the Holocene climate optimum probably contain relatively ice-poor deposits in which deep thawing did not result in a significant subsidence (Figure 10B). Ice-rich yedoma survived at sites that were well drained before the beginning of the large-scale yedoma degradation, usually adjacent to rivers or foothills. Generally, large areas in the discontinuous permafrost zone of Alaska have been affected by deep thawing during the Holocene, as indicated by a layer of ice-poor reworked soils on top of many yedoma sections (Péwé, 1975; Kanevskiy *et al.*, 2012), but the development of thaw lake basins has been strongly controlled by topography. As in all yedoma regions, drained lake basins in interior Alaska are abundant on the flat plains and relatively rare in the foothills. Formation of yedoma remnants eventually led to terrain stabilisation. The remaining yedoma hills within and surrounding the flats became more stable because the well-drained, sloping surfaces are less likely to impound water, and thus reduce the likelihood of positive feedback promoting the development of new thermokarst lakes (Shur, 1988a; Jorgenson *et al.*, 2012; Shur *et al.*, 2012).

Stages 5 to 8 – Lake Drainage, Peat Accumulation and Formation of Permafrost Plateaus in Drained Lake Basins.

Lakes breach and drain (stage 5) when they expand and connect to drainages (Walker, 1978). Drainage in yedoma terrain results in deep drained lake basins (alases), and basins coalescing in areas of widespread lake thermokarst can form alas valleys or even alas plains with rare remnants of the original yedoma surface (Soloviev, 1962; Shur *et al.*, 2012). We consider the Innoko and Koyukuk Flats to be large thaw lake (alas) plains.

After drainage, the basins are complex environments with spatially heterogeneous hydrologic conditions. The lake basins may be partially drained with a deeper central lake or many remnant ponds, or completely drained while retaining many wet depressions interspersed with better-drained mounds. This mosaic of drainage conditions typically leads to a mosaic of ecosystem types that include shallow ponds, marshes, wet meadows and better-drained areas that support a successional sequence from grass meadows to shrublands to forest. These differing ecological conditions set the stage for differing successional development. Lake drainage generally creates optimal conditions for peat accumulation (stage 6), which starts in a semi-aquatic environment and leads eventually to terrestrialisation and the development of forested ecosystems.

Stage 7 is characterised by the initial freezing of taliks which existed beneath thermokarst lakes before they drained (Figure 10D). Under cold climatic conditions (usually in the continuous permafrost zone), freezing of the talik starts immediately after lake drainage or even before it, when the water depth decreases below its critical value. In the latter case, a fresh deposit that accumulated under shallow water (lacustrine peat or organic silt) freezes syngenetically. Formation of syngenetic permafrost starts simultaneously with freezing of the talik (Figure 11A), and stages 5 to 7 combine and proceed in a single stage.

In the discontinuous permafrost zone, where bogs with water are usually permafrost-free, permafrost cannot form immediately after lake drainage (Shur and Jorgenson, 2007). Freezing of taliks starts with the development of palsas in areas of fast peat accumulation where moss surfaces rise above the water level (Seppälä, 1986, 2011; Kuhry, 2008; Shur *et al.*, 2011). The main reason that permafrost forms under these conditions is the difference in thermal conductivity of peat in frozen and unfrozen states, which creates a thermal offset (Kudryavtsev, 1959; Burn and Smith, 1988; Osterkamp and Romanovsky, 1999). As a result, the mean annual temperature under the layer of peat can be several degrees (°C) less than that at the soil surface (Osterkamp and Romanovsky, 1999). At the Koyukuk Flats study area, a thermal offset within permafrost plateaus varies from -2.4°C to -3.0°C (O'Donnell *et al.*, 2012). Eventually, the depth of seasonal freezing exceeds the depth of seasonal thawing, causing permafrost to form. Permafrost formation in drained lake basins within the discontinuous or sporadic permafrost zones is a typical example of ecosystem-driven permafrost (Shur and Jorgenson, 2007).

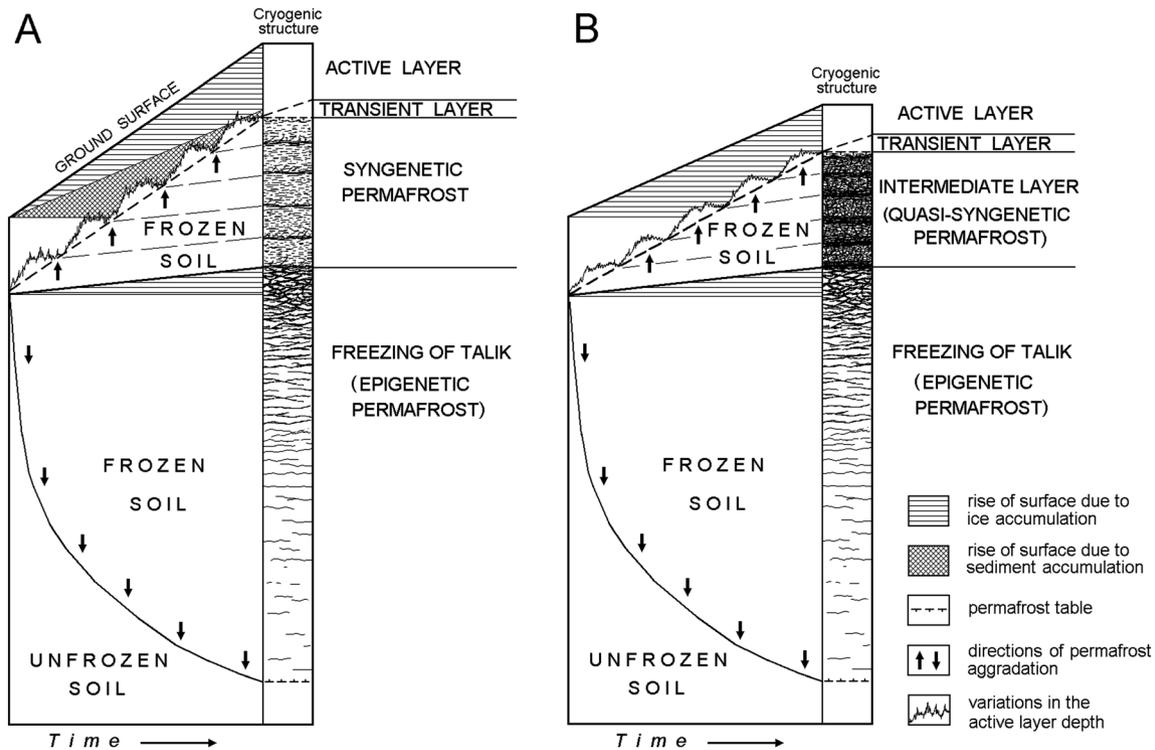


Figure 11 Mechanisms of permafrost formation triggered by lake drainage: freezing of the talik is accompanied by the formation of (A) syngenetically frozen sediments or (B) an intermediate layer. The scheme of syngenetic freezing is based upon Popov (1967), and the scheme of quasi-syngenetic freezing is based upon Kanevskiy (2004).

Individual palsas formed during stage 7 eventually merge to form continuous permafrost plateaus (stage 8). Permafrost aggradation in drained lake basins caused significant heave of the ground surface because of the freezing of water-saturated deposits in taliks. The resulting elevated permafrost plateaus, covered with black spruce forests, occupy large areas of the Innoko and Koyukuk Flats. The surface of forested permafrost plateaus is characterised by an uneven topography related to differential heaving and their complex history. In some situations, several levels (generations) of permafrost plateaus were distinguished. Such plateaus have different ages because lake drainage and peat formation started at different times in different locations. We attribute large-scale freezing of peatlands to cooling during the middle Holocene (Zoltai, 1993; Sannel and Kuhru, 2008; Fritz *et al.*, 2012; Marcott *et al.*, 2013). A significant decline in the initiation of new peatlands in the entire circumarctic region has also occurred since the middle Holocene (MacDonald *et al.*, 2006).

During stages 7 and 8, a quasi-syngenetically frozen intermediate layer (Shur, 1988a, 1988b; French and Shur, 2010) forms on top of epigenetic permafrost as the active layer thins in response to vegetation growth and peat accumulation. Upward aggradation of quasi-syngenetic permafrost starts simultaneously with the downward freezing of the talik that forms epigenetic permafrost (Figure 11B). In many cases, quasi-syngenetically frozen lacustrine

sediments are overlain by syngenetically frozen terrestrial peat. Because the cryostructures of syngenetic and quasi-syngenetic permafrost are similar, the boundary between them can be difficult to distinguish. Complex sequences of epigenetic, syngenetic and quasi-syngenetic permafrost can form after lake drainage. The occurrence of residual ponds within drained lake basins and the possibility of secondary thermokarst with subsequent freezing of taliks can significantly obscure an interpretation of the permafrost sequence.

Stage 9 – Formation and Expansion of a New Generation of Thermokarst Features.

The high ice content of soils of permafrost peat plateaus makes them vulnerable to thermokarst. At the present time, peat plateaus in the Koyukuk and Innoko Flats are subject to widespread thermokarst, which includes the initiation of thermokarst pits and their transformation into shallow thermokarst bogs and fens. As a result, permafrost plateaus are interspersed with growing bogs, ponds and fens in various stages of development (Figure 10E).

Some new thermokarst pits have formed in areas where the organic soil is relatively thin, thus providing little thermal protection for the ice-rich silt, while in adjacent areas with thick peat (up to 4 m) above ice-rich silt no thermokarst features were observed. Another factor is the uneven microtopography of the peat plateaus (Figure 3) that allows water to impound in small depressions after snowmelt

and heavy rains. The change in albedo, heat gain and thermal properties provides a strong positive feedback, where increased thaw creates deeper pits in which deeper water enhances degradation (Shur, 1977; Jorgenson *et al.*, 2010).

Thaw of ice-rich soil with a high visible ice content can cause surface settlement of up to 50 per cent of the original thickness of frozen silt. Starting with small pits, the development of thermokarst bogs continues due to lateral enlargement of thaw bulbs and the collapse of peat plateau margins. With further expansion, the bogs can coalesce and drainage becomes better integrated, contributing to the formation of more minerotrophic fens. The full sequence of landscape evolution is reflected in an upward stratigraphic sequence of reworked yedoma silt, lacustrine organic silt, bog peat, woody peat that accumulated under forests during the permafrost plateau stage and topped by semi-aquatic sphagnum bog peat that accumulated after collapse. Radiocarbon dates for unfrozen semi-aquatic peat show that the oldest collapse-scar bogs at the Koyukuk Flats (Two Lakes) started forming not later than 1200 ¹⁴C yr BP (O'Donnell *et al.*, 2012).

Permafrost in the study area continues to evolve. Under conditions of relatively warm discontinuous permafrost, the degradation of perennially frozen peat plateaus and aggradation of permafrost in palsas can occur simultaneously.

CONCLUSIONS

Perennially frozen organic and fine-grained mineral soils of forested peat plateaus containing abundant ground ice comprise a significant part of the upper permafrost of the Koyukuk and Innoko Flats. The volume of visible segregated ice in mineral soils locally reaches 50 per cent. A method for estimating the moisture content of frozen silt from the volume of visible ice corresponds well with laboratory measurements and can reduce the need for sample processing.

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Permafrost dynamics have strongly affected terrain development in the lacustrine-loess lowlands of west-central Alaska from the Late Pleistocene to the present day. Through sediment and peat cryostratigraphy and radiocarbon dating, the present patchy mosaic of ecosystem types can be related to environmental changes indicative of permafrost degradation and aggradation. The fine-grained and organic-rich soils are susceptible to an accumulation of excess ground ice and substantial heave during permafrost formation that strongly affect ecosystem development and establish the conditions for 2–4.5 m of subsidence upon thawing. Thus, ground ice dynamics are fundamental to the evolution of the broader landscape.

We consider the Innoko and Koyukuk Flats to be large thaw lake (alas) plains. Nine stages of their formation are identified, including four stages of yedoma degradation and five stages of subsequent permafrost aggradation-degradation. The complex spatial pattern of terrain conditions associated with alternating periods of permafrost aggradation and degradation in response to both climatic and ecological changes complicates predictions of landscape response to future climatic changes or human impact.

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