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Floodplains, permafrost, cottonwood trees, and peat: What happened the last time climate warmed suddenly in arctic Alaska?

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ABSTRACT

We use the stratigraphy of floodplains on Alaska's North Slope to describe how tundra watersheds responded to climate changes over the last 15,000 calibrated years BP (15 cal ka BP). Two episodes of extremely rapid floodplain alluviation occurred during the Pleistocene–Holocene transition, one between 14 and 12.8 cal ka BP and the other between 11.5 and 9.5 cal ka BP. These aggradation episodes coincided with periods of warming in summer when cottonwood (*Populus balsamifera* L.) expanded its range, peatlands became established, and widespread thermokarst occurred. The two aggradation episodes were separated by a period of floodplain incision during the Younger Dryas under cooler and possibly drier conditions. At times of increasing summer warmth, melting permafrost and enhanced precipitation probably triggered widespread mass wasting on hillslopes that overwhelmed the capacity of streams to transport sediment downstream, and rapid floodplain aggradation resulted. After peatlands became widespread in the early Holocene, rivers slowly incised their valley fills. Because major pulses of sediment input were limited to times of rapid thaw and increasing moisture, many floodplains on the North Slope have been effectively decoupled from upstream hillslopes for much of the past 15,000 years. Our findings: (a) confirm the sensitivity of arctic watersheds to rapid warming in summer, (b) emphasize the importance of hillslope mass wasting in landscape-scale responses to climate change, and (c) suggest that the presence of peatland on this arctic landscape today has raised its geomorphic response threshold to climate warming compared to what it was 14,000 years ago.

1. Introduction

Arctic streams and their floodplains play important roles in local ecosystems, and the freshwater they transport influences high-latitude oceanography (Rouse et al., 1997; Prowse et al., 2006). The geomorphology of arctic watersheds has been little studied compared to those in the temperate zone (Vandenberghe and Woo, 2002; Bridge, 2003; Goudie, 2006). Arctic watersheds possess unique features related to permafrost, extreme seasonality, and tundra vegetation (McNamara et al., 1998, 1999; Beylich et al., 2006). Our knowledge of lower latitude streams may not be a reliable guide in predicting the responses of arctic fluvial systems to future climate changes.

Rapid warming is occurring today in many parts of the Arctic, including northern Alaska (Hinzman et al., 2005; Kaufman et al., 2009). It is generally agreed that global warming will create a wetter Arctic (Walsh et al., 2008, 2010) , both because warmer air can hold more water vapor and because of northward-shifted storm tracks (McClelland et al., 2006). In response, the discharge of arctic rivers is predicted to increase (Arora and Boer, 2001), accompanied by significant increases in sediment fluxes (Syvitski, 2002). Today many arctic rivers carry proportionally less sediment than rivers at lower latitudes (Gordeev, 2006). According to Syvitski (2002), this is because sediment production and transport are increasingly restricted with increasing latitude because of five interrelated phenomena: fewer freeze–thaw cycles, more frozen ground in the watershed, a higher proportion of precipitation falling as snow rather than rain, fewer high-intensity convective storms, and less flood erosion because of frozen channel beds. As climate warms, all these restrictions will be eased, and a surge in sediment flux is predicted. The magnitude of this increase is probably underestimated because Syvitski's (2002) model does not

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account for increased mass wasting (slope movement, mass movement) triggered by warming climate.

On periglacial landscapes, mass wasting involves a diverse set of processes that operate over a wide range of temporal and spatial scales (Woo, 1990). Slow processes of mass wasting include frost creep, gelifluction, and retrogressive-thaw slumping. Rapid mass wasting processes include active-layer-detachment slides, debris flows, and slush flows (French, 2007, p. 224). All of these processes are strongly influenced by the availability of liquid water, which comes from melting snow, summer rainstorms, and/or melting permafrost.

Permafrost is a defining feature of many arctic landscapes. Thermokarst is the collapse, subsidence, and/or mass wasting of the ground surface caused by the thaw of underlying permafrost (French, 2007, p. 186). Because permafrost inflates the ground surface by amounts ranging from centimeters (Pullman et al., 2007) to tens of meters (Sher et al., 2005), its melting can have major geomorphological effects (Murton, 2009; Osterkamp et al., 2009). For instance, thermokarst created the thaw lake basins that now cover some 20% of the Arctic Coastal Plain in northern Alaska (Bockheim et al., 2003a) and it has been a major process shaping the geomorphology of northern Siberia (Grosse et al., 2007). Although thermokarst is recognized as an important cause of slope instability and mass wasting in many periglacial environments (Burn and Lewkowicz, 1990; Bowden et al., 2008; Lacelle et al., 2010), its overall importance in estimates of denudation rates (Rapp, 1960; Beylich et al., 2006; French, 2007, Chapter 9) has probably been greatly underestimated because it occurs sporadically and thus is hard to quantify.

How will the fluvial geomorphology of permafrost landscapes in arctic Alaska respond to rapidly warming climate over the next century? Here we try to answer this question by looking at what happened on floodplains the last time this region experienced rapid warming, which was during the Pleistocene–Holocene transition (Mann et al., 2002a; Kaufman et al., 2004).

2. Regional setting

Alaska's North Slope is the region between the Brooks Range and the Arctic Ocean (Fig. 1). Marked north–south gradients in climate occur across the North Slope today. July is the warmest month, and July mean air temperature increases from 4 °C on the Beaufort Sea coast to 12 °C near the Brooks Range (Zhang et al., 1996). Mean annual precipitation also increases inland from 200 mm at the coast to 320 mm near the mountains. About half this precipitation falls as snow, which persists on the ground for 7–9 months. Rainfall increases over the course of the summer and comes from a combination of convective storms that develop along the crest of the Brooks Range and cyclonic storms that cross the range from the Bering Sea (Kane et al., 1992). Tundra covers the North Slope (Walker et al., 1998), and much of the Arctic Foothills is currently blanketed under 5–30 cm of peat. This peat insulates the ground and maintains seasonally thawed soil layers (active layers) that are 15–40 cm thick (Bockheim and Hinkel, 2005). Trees are absent on the North Slope except for widely scattered groves of cottonwood (*Populus balsamifera* L.) growing in sheltered sites that have unusually warm microclimates (Bockheim et al., 2003b).

The North Slope is divided into two physiographic units: the Arctic Foothills flanking the north side of the Brooks Range, and the Arctic Coastal Plain lying between the Arctic Foothills and the Arctic Ocean (Fig. 1). The Arctic Foothills are east–west trending ridges of sedimentary bedrock that protrude from tundra-covered peneplains (Grantz et al., 1994). Bedrock uplands are surrounded by convexo-concavo, debris-mantled slopes (*sensu* French, 2007, p. 219). Permafrost is continuous north of the Brooks Range and is hundreds of meters thick (Ferrians, 1994).

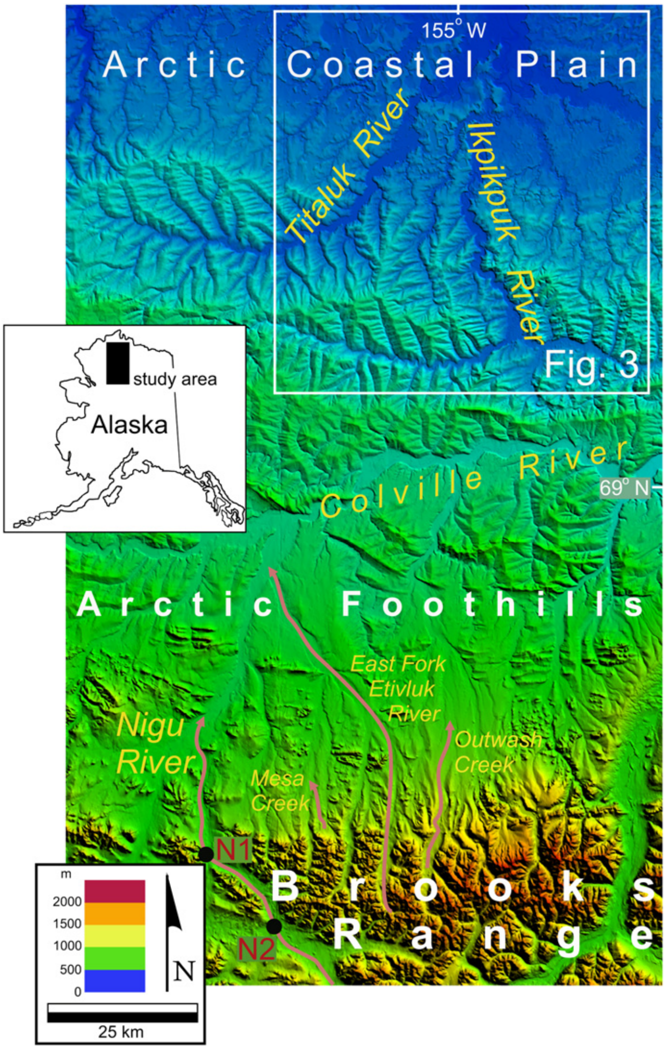

Fig. 1. The study area in northern Alaska showing regional physiographic units, study streams, and stratigraphic sections along the Nigu River.

Much of the Arctic Foothills region has never been glaciated (Kaufman and Manley, 2004). Valley glaciers in the north-central Brooks Range extended only 25–40 km past the range front during the last ice age (Hamilton, 1986; Briner and Kaufman, 2008). Glacier extent was restricted by a lack of precipitation, which came mainly from the North Pacific and was largely blocked by the Brooks Range (Balascio et al., 2005). When the Bering Land Bridge was emergent during Pleistocene ice ages, the North Slope was even farther from the sea and so experienced a climate that was even more continental than today (Mann et al., 2002b). During dry intervals in the Pleistocene, fluvial sediments on the Coastal Plain were reworked by the wind into extensive dune fields (Carter, 1988). One of these dune fields, the Ikpikpuk sand sea, is described below in greater detail because of its possible effect on the base levels of two of the rivers we studied.

Two distinct hydrologic regimes occur in North Slope watersheds. Subnival flow regimes show a peak in discharge during the breakup flood in spring, followed by a generally falling hydrograph as summer progresses; however, this falling trend is frequently interrupted by freshets caused by rainstorms (Kane, 1996). In contrast, nival flow regimes are entirely dominated by the short-lived breakup flood, and stream discharge falls away steadily as the summer progresses. Streams heading in the Brooks Range have subnival flow regimes (McNamara et al., 1998), and those with headwaters in the Arctic Foothills and the Coastal Plain have nival ones (Rovansek et al., 1996).

The Nigu River (Fig. 2) is a wandering, gravel-bed river (Desloges and Church, 1989) that is typical of north-flowing rivers with headwaters in the Brooks Range. The Nigu arises at the crest of the range and drains an area of 1630 km^2. North of the range front, it has a gradient of 0.004. Within the Brooks Range, its gradient is steeper, around 0.007. At present, there are no glaciers in the Nigu watershed, which is covered by tundra with extensive talus slopes on the surrounding mountainsides. The Nigu's bedload is mainly cobbles in steeper reaches and sandy gravel in less-steep ones. This river has little suspended load except during episodes of silt release from several retrogressive-thaw slides that enter the river. No gauging stations exist on the Nigu River but observation of this river over the last 20 summers confirms that it has a marked subnival flow regime. The reaches of the Kuparuk River located 375 km to the northeast on the North Slope that were studied by Lunt and Bridge (2004) and Lunt et al. (2004) have similar plan form, sedimentology, and probably flow regime as the Nigu River. Another arctic river similar to the Nigu whose flow regime and fluvial architecture has been well-described is the Babbage River in the northern Yukon (Forbes, 1983).

The Ikpikpuk River and its tributary the Titaluk (Fig. 3) are low gradient, meandering streams whose headwaters lie 100 km north of the Brooks Range. Both these rivers experience nival flow regimes. The reaches we studied lie within the Arctic Foothills upstream of the Titaluk–Ikpikpuk confluence. In this area, the Arctic Foothills reach 450 m asl and contain abundant sandstone bedrock. The upper Ikpikpuk River has a low gradient of 0.0003, and the Titaluk's gradient is even lower at 0.0002. The Ikpikpuk drainage basin upstream of the Titaluk confluence covers 4400 km^2, and the Titaluk drains an area of 2680 km^2. Hillslope water tracks flowing through peatlands (McNamara et al., 1999) cover large portions of the watersheds of these rivers today. Both the Ikpikpuk and the Titaluk Rivers flow through sinuous, meandering channels lined by willow shrubs. The Ikpikpuk carries a predominately sandy bedload with significant amounts of

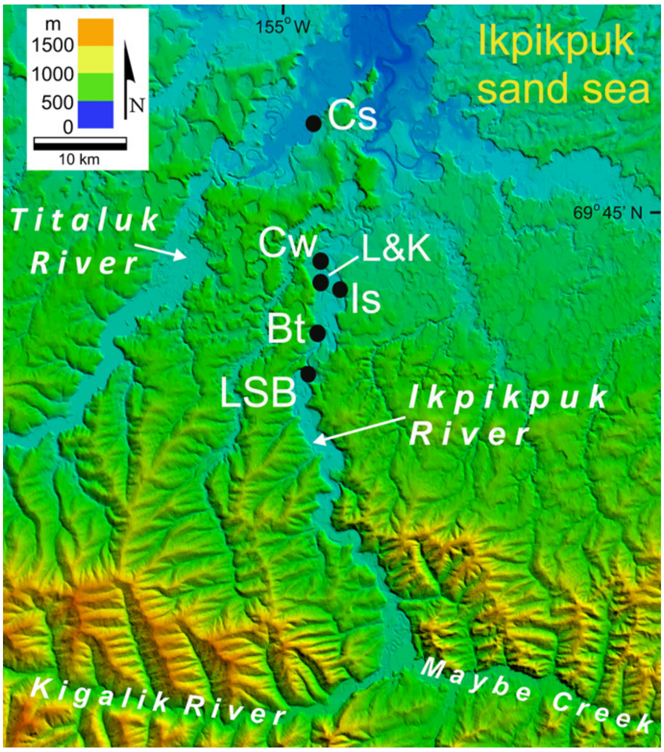

Fig. 3. Location map for the upper Ikpikpuk and Titaluk Rivers. LSB: Little Supreme Bluff, Bt: Bear Tooth Bluff, Is: Island Bluff, L&K: L and K Bluff, Cw: Cottonwood Bluff, and Cs: Corner Section. All these are informal names except Little Supreme Bluff.

Fig. 2. View upstream along the upper Nigu River. Willow shrubs 2 m high on the gravel bar in the middle distance provide scale. In the foreground is a retrogressive-thaw slide several hundred meters wide that has flowed into the river intermittently over the past 20 years.

granule- and pebble gravel in its thalweg. The Titaluk River is finer grained with a predominately sandy bedload and significant amounts of suspended silt derived from the beds of former thaw lakes that the river has breached by lateral erosion.

Near their confluence, the Ikpikpuk and Titaluk Rivers enter a large stabilized dune field, the Ikpikpuk sand sea (Carter, 1981) (Fig. 3). The activity of this sand sea may have affected the base levels of these two rivers in the past. The history of the sand sea is poorly understood. It seems to have been intermittently active between 41 and 16.7 cal ka BP (Carter, 1981). It had stabilized by 13.9 cal ka BP, but resumed activity ca 12.9 cal ka BP around the beginning of the Younger Dryas chronozone and continued until between 9.7 and 8.7 cal ka BP (Carter, 1993). There were at least three episodes of blowout activation later in the Holocene (Galloway and Carter, 1993).

During the Pleistocene, sand supply was probably the main factor that limited the Ikpikpuk sand sea's activity, and most of this sand came from the deltas of the Colville and Ikpikpuk Rivers (Carter, 1993). The presence of extensive sand sheet deposits upwind of the dunes suggests that deflation restricted dune accretion in these upwind areas, and hence that sand was in short supply during the times of most intense dune activity. The presence of large, relict sand wedges (Carter, 1993) in these upwind areas indicates these sand sheets were long-term features of the landscape and probably functioned as sand-transport corridors linking the deltas to the dune field. The geomorphic effects of the Ikpikpuk sand sea on nearby streams are unclear but possibly significant. Migrating dune fields can have dramatic effects on adjacent stream systems (Loope et al., 1995; Mann et al., 2002c). Carter suggested that north-flowing rivers like the Ikpikpuk and the Titaluk were partly blocked at the times of most intense dune activity (Dinter et al., 1990).

Few studies of stream responses to prehistoric climate change have been carried out in arctic Alaska, and existing data are insufficient to develop a regional synthesis. Mann et al. (2002a) studied some of the same stratigraphic sections on the North Slope described here and correlated shifts between floodplain incision and aggradation with changes in effective moisture and vegetation cover. Hamilton (2001, 2009) described the Quaternary stratigraphy of the Noatak River valley where multiple glaciations and ice-dammed lakes interacted with stream systems to create a complicated stratigraphy dominated by glaciogenic features. South of the Brooks Range, Hamilton and Ashley (1993) described the stratigraphy of Epiguruk Bluff in the middle reaches of the Kobuk River. Incision and aggradation at Epiguruk seem to have been closely tied to the activity of the Kobuk sand dunes downstream, with valley-fill aggradation occurring in response to eolian sand overloading the river's transport capacity.

3. Methods

We chose the Nigu, Ikpikpuk, and Titaluk Rivers to study because they provide representative examples of North Slope Rivers and their valley fills contain well-exposed stratigraphic sections. By studying streams possessing different flow regimes, bedloads, and topographic settings, we hoped to identify the environmental drivers whose impacts were so strong that they overwhelmed the individualistic responses (Schumm, 2005) of the different streams. We focused on alluvial deposits within the upland-valley and floodplain-valley reaches of river systems where erosion and deposition are most sensitively coupled to hillslope processes through changes in vegetation cover, surface runoff, and permafrost regime (Church, 2002).

We visited stratigraphic sections in successive years to take advantage of the ever-changing nature of river cutbanks. We visited Little Supreme Bluff, the flagship section in this study, annually over a 15-year period. Sections were prepared by clearing slumped material to expose undisturbed, frozen sediment. Little Supreme Bluff was described by mapping sedimentary units and bounding surfaces onto photographic mosaics of the bluff face. Bedforms and landforms were described using standard methods and terminology (Reineck and Singh, 1980; Miall, 1996; Bridge, 2003). Paleoflow directions were inferred from the orientations of bedform slipfaces, the strike of scour channels, and the orientation of woody debris. We estimate sedimentation rates as the amount of vertical accretion occurring between the youngest-possible, 2δ-calibrated age of the uppermost dated sample and the oldest-possible, 2δ-calibrated age of the lowest sample in the section being considered.

Dating floodplain stratigraphy along the Ikpikpuk and Titaluk Rivers is complicated by the ability of these low gradient, sandy streams to rework even delicate organic material from older, frozen deposits (Nelson et al., 1988). We have found that only four types of plant remains provide precise ^{14}C-age estimates for the fluvial sediment in which they occur: (1) plants like willow shrubs that were buried while living so that their roots and stems show clear evidence of having penetrated the enclosing sediment as it was deposited (Fig. 4), (2) the remains of emergent aquatic plants deposited in oxbow lake basins where a dearth of mineral sediment indicates isolation from the river, (3) completely intact, deciduous leaves (Fig. 5) from laminated back-eddy accumulations of organic debris, and (4) plant leaves that still contain visible chlorophyll. The distinctive hollow, jointed roots of horsetail (*Equisetum* spp.) occur

Fig. 4. Willow shrub in growth position in a Holocene-aged cutbank along the Ikpikpuk River. Baseball cap for scale. Organic debris is often reworked from older frozen deposits in the Ikpikpuk and Titaluk Rivers, so care is required in selecting ^{14}C samples whose ages are coeval with the surrounding sediment.

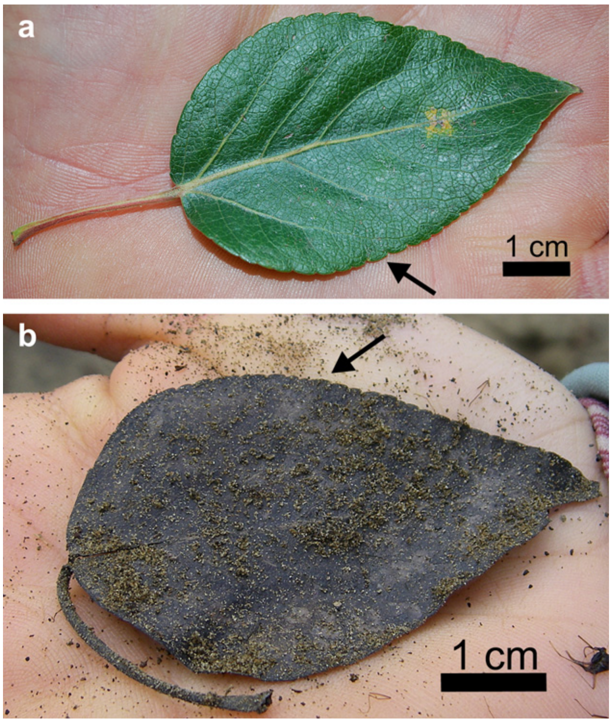

Fig. 5. Living (a) and subfossil leaves (b) of cottonwood (*Populus balsamifera*). The subfossil leaf comes from Little Supreme Bluff on the Ikpikpuk River and dates to ca 10 cal ka BP. Arrows point to crenulate leaf margins.

in some outcrops and comprise a special case as regards dating the sediment they penetrate. Horsetail roots can grow many meters below the ground surface; however, even they cannot grow in permafrost, and observations made along meander-scroll sequences of known age in the Ikpikpuk valley reveal that permafrost rises to within 15–40 cm of the ground surface several centuries after a geomorphic surface stabilizes. Hence the ^{14}C age of a horsetail root recovered >40 cm below the surface probably provides a close, minimum-limiting age on sediment deposition. We calibrated all radiocarbon dates using CALIB 6.0 (Stuiver and Reimer, 1993; Reimer et al., 2009) and used OxCal v4.1.3 (Bronk Ramsey, 2009) to compile the probability-density distributions of calibrated ^{14}C ages.

We use the presence and absence of ^{14}C dated macrofossils of cottonwood (*P. balsamifera* L) as a proxy for summer temperature. Working at the site we call Cottonwood Bluff on the Ikpikpuk River, Nelson and Carter (1987) and Mann et al. (2002a) found extra-limital cottonwood macrofossils dating to the early Holocene. Here we extend this earlier work by ^{14}C dating 23 additional cottonwood macrofossils from the Ikpikpuk and Titaluk valleys. Today the study area lies immediately north of the range limit of cottonwood trees, which have more or less continuously distributed populations in valleys south of the Brooks Range. The presence of small and widely scattered groves of cottonwoods in the Arctic Foothills suggests that the summer climate of this region is presently near the threshold for widespread cottonwood invasion. We assume that the presence of cottonwood macrofossils in the stratigraphic record means that average July temperature was between 10 and 12.5 °C and that their absence means average July temperature was <10 °C (Hopkins et al., 1981; MacDonald et al., 2008).

Because of the uncertainties involved in microscopically distinguishing the wood of cottonwood and willow (*Salix* spp.), we radiocarbon dated only well-preserved cottonwood leaves, bark fragments, and pieces of wood that still retained this species' distinctive, thick-ridged bark. We identified subfossil cottonwood leaves by their large sizes relative to most other plants in the region, their acuminate to subcordate shapes, their crenulate margins, and their robust petiole bases (Fig. 5).

4. Results

4.1. Stratigraphic sections

4.1.1. Nigu River

The N1 section is located near where the Nigu River leaves the Brooks Range (Fig. 1). This section starts at river level with 3.8 m of cobble and boulder gravel containing occasional sandy lenses (Fig. 6). A detrital willow branch 4 m above river level dates to 12,230 ± 50 ^{14}C yr BP (Table 1). At the 8.5-m level, a rooted shrub in growth position dates to 11,360 ± 40 ^{14}C yr BP. At the 9 and 9.6-m levels, detrital wood dates to 11,010 ± 50 and 10,980 ± 40 ^{14}C yr BP, respectively. Near the 10-m level, a layer of sedge peat overridden by soliflucted, pebbly silt dates to 9670 ± 50 ^{14}C yr BP.

The N2 section is exposed along the upper Nigu River 24 km upstream of section N1 (Figs. 1 and 6). The upstream end of this section cuts through a terrace of probable late Pleistocene age that contains boulder gravel devoid of organic material. Section N2 exposes a sandy fluvial terrace inset within this glacial outwash terrace. The section starts at river level with several meters of boulder gravel (Fig. 6). At 3.7 m above the river, a willow shrub in growth position dates to 11,370 ± 50 ^{14}C yr BP (Table 1). A nearby detrital twig dates to 11,380 ± 60 ^{14}C yr BP. This is overlain by 12 m of water-lain sand, most of it horizontally stratified. Numerous branches and twigs of shrubs are interbedded, along with occasional lenses of caribou fecal pellets and strands of caribou hair. At 15 m above river level, another rooted willow shrub dates to 10,920 ± 50 ^{14}C yr BP (Fig. 6). At the 16-m level, a layer of sedge peat dates to 8080 ± 50 ^{14}C yr BP. This peat is overlain by a meter of highly deformed silt and peat associated with solifluction lobes descending from the riser of the higher terrace.

We interpret these sections as indicating that by 13.1–13.4 cal ka BP (section N2) and possibly as early as 13.9–14.3 cal ka BP (section N1), the Nigu River was depositing sediment of similar particle sizes and bedforms as those being deposited today. By ca 14 cal ka BP, the Nigu River probably flowed through a wandering, gravel-bedded channel similar to its present one. One striking thing about both these sections is how fast sedimentation occurred between 14.3 and 12.7 cal ka BP (section N1) and between 13.4 and 12.6 cal ka BP (section N2). In section N1 this amounted to about 4 mm yr^{-1}, while in section N2 it amounted to about 14 mm yr^{-1}. Concerted search has failed to find any younger valley fills along the Nigu River.

4.1.2. Ikpikpuk River

4.1.2.1. Little Supreme Bluff. Little Supreme Bluff lies on the Ikpikpuk River 34 km downstream of the Kigalik–Maybe Creek confluence (Fig. 3). It consists of a 2 km-long cut bank that exposes the interiors of two river terraces (Fig. 7). Our work concentrated on the junction between Terraces 1 and 2 where the bed of an oxbow lake is exposed. Four major sedimentary units are distinguishable in the section as a whole based on age, particle sizes, and bedforms (Fig. 8). At river level, several meters of indurated, iron-stained, pebbly gravel contain rooted willow shrubs dating to >42,000 ^{14}C yr BP (Table 1). Much of this Purple Gravel unit was deposited as plane beds, though there are occasional scour infillings containing peat clasts as well as occasional cosets of high-angle cross-beds. Epsilon cross-beds and the casts of contraction cracks filled by pebbles and sand record the levels of former point-bar surfaces. Accretion surfaces in the Purple Gravel are oriented

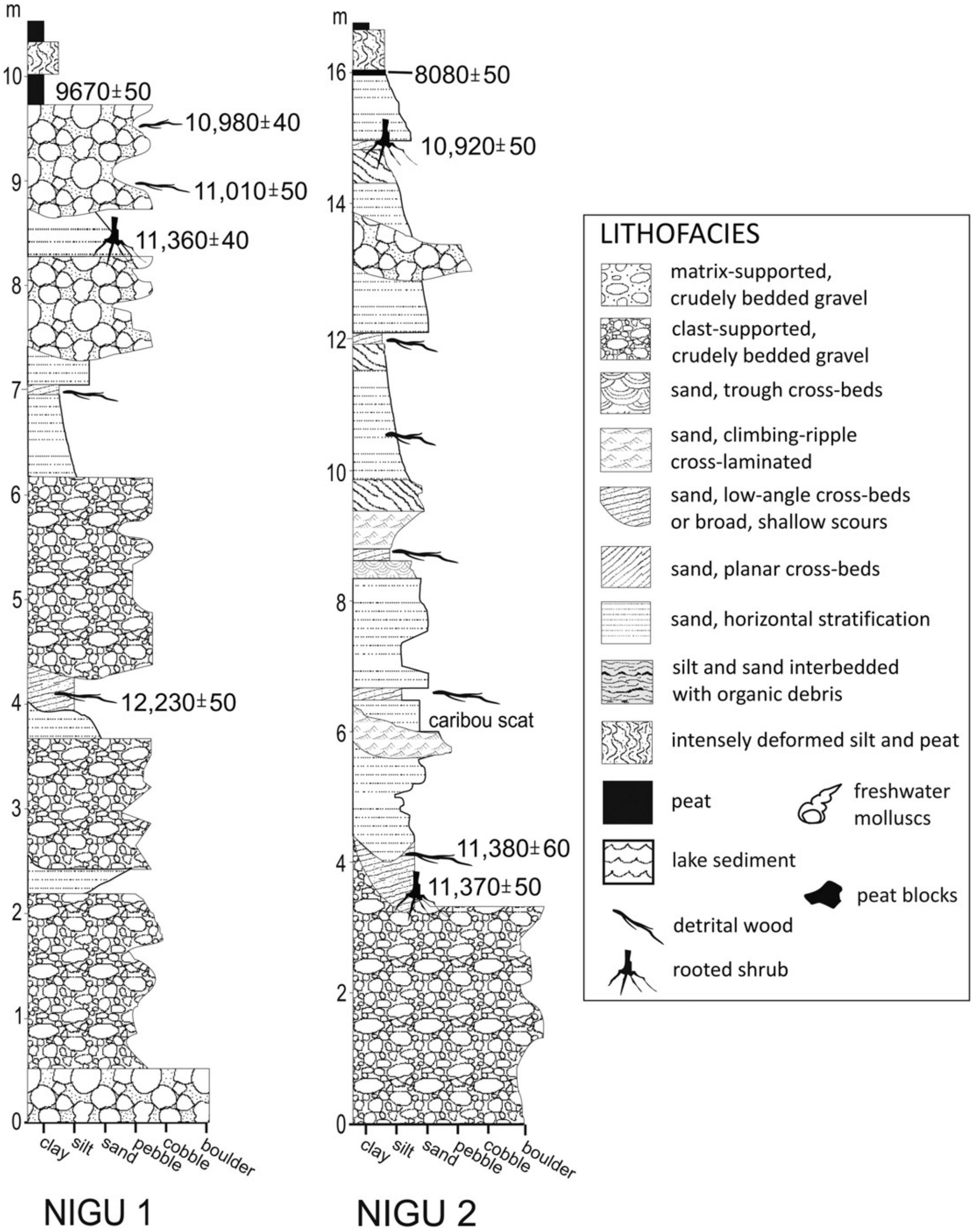

Fig. 6. Stratigraphic sections along the Nigu River. Radiocarbon ages in uncalibrated years BP. See Table 1 for calibrated ages.

roughly at right angles to the current directions indicated by the cross-bedding (Fig. 8), suggesting deposition by meandering channels (Miall, 1996).

Overlying the Purple Gravel along an erosional boundary is a sandy unit ranging in thickness from several meters at its upstream end to 20 m farther downstream (Fig. 8). We call this unit, which composes the bulk of Terrace 1, the Peregrine Sand after the falcons that typically nest at this end of the bluff. Channel-fill deposits predominate, and common bedforms including climbing ripples, scour-hollow infillings, plane beds, and high-angle trough cross-beds. The flow directions recorded by cross-stratification roughly parallel the strikes of former channels in this unit, suggesting that the Ikpikpuk River had a braided channel while depositing the Peregrine Sand. Organic detritus is common, especially in the infilled of scour hollows and channels, but woody debris >1 cm in diameter is rare. This organic detritus includes twigs, branches, willow leaves, rootlets, occasional peat clasts, and moss fragments. In situ, rooted willow shrubs are abundant only in the upper levels of this unit and these date to between 11,600 ± 50 and 11,340 ± 40 ^{14}C yr BP (Fig. 8). Alluviation occurred at a rate of approximately 8 mm yr^{-1} while the Peregrine Sand was being deposited.

The upstream portion of the Peregrine Sand is overlain above an erosional unconformity by another sandy unit called the Rough-Legged Sand after the hawks that typically nest on this part of the

Table 1
Radiocarbon ages from fluvial sections. Ages previously reported in Mann et al. (2002a) are italicized.

Sample/Location[a]	Laboratory #	Lat. (°N)	Long. (°W)	Dated material	$\delta^{13}C$ (‰)	^{13}C-normalized age (years before 1950 AD)	1 std dev	2δ-calibrated age range (cal yr before 1950)	Median probable calibrated age (cal yr BP)
Nigu River									
N2: *24June98f*	*Beta-120020*	*68° 08′*	*156° 01′*	*sedge stem*	*−26.8*	*8080*	*50*	*8770–9130*	*9010*
N1: *9June97kin-d*	*Beta-124782*	*68° 17′*	*156° 24′*	*detrital twig*	*−27.5*	*9670*	*50*	*10,790–11,210*	*11,090*
N2: *24June98e*	*Beta-121110*	*68° 08′*	*156° 01′*	*Salix in growth position*	*−26.1*	*10,920*	*50*	*12,630–12,940*	*12,790*
N1: 19July2002E	GX-29707-AMS	68° 17′	156° 24′	detrital twig	−27.1	10,980	40	12,670–13,070	12,840
N1: *9June97kinC*	*Beta-111127*	*68° 17′*	*156° 24′*	*detrital twig*	*−28.0*	*11,010*	*50*	*12,700–13,080*	*12,880*
N1: 19July2002F	GX-29708-AMS	68° 17′	156° 24′	*Salix* in growth position	−26.7	11,360	40	13,130–13,340	13,240
N2: 17July2002G	GX-29706-AMS	68° 08′	156° 01′	*Salix* in growth position	−28.0	11,370	50	13,120–13,360	13,240
N2: *24June98a*	*Beta-120019*	*68° 08′*	*156° 01′*	*detrital twig*	*−30.1*	*11,380*	*60*	*13,120–13,380*	*13,250*
N1: *7-13-98b*	*Beta-120537*	*68° 17′*	*156° 24′*	*detrital twig*	*−29.2*	*12,230*	*50*	*13,880–14,260*	*14,080*
Ikpikpuk River									
MISC: 4July2006F	Beta-222488	69° 39′	154° 50′	*Salix* in growth position	−29.1	2310	70	2130–2500	2330
MISC: *7-12-97a*	*Beta-111035*	*69° 25′*	*154° 47′*	*Salix in growth position*	*−30.7*	*5430*	*60*	*6000–6400*	*6230*
MISC: *7-16-99a*	*Beta-132694*	*69° 39′*	*154° 50′*	*Salix in growth position*	*−26.1*	*6070*	*80*	*6740–7160*	*6940*
L&K:7-14-2008ff	Beta-256523	69° 41′	154° 52′	*Equisetum* roots in situ	−25.2	7560	50	8210–8450	8380
LSB: *7-13-99a*	*Beta-132631*	*69° 36′*	*154° 55′*	*seeds of Menyanthes trifoliata*	*−25.4*	*8720*	*40*	*9550–9820*	*9670*
CotB: 7-14-99Q1	*Beta-132693*	*69° 43′*	*154° 52′*	*seeds of Menyanthes trifoliata*	*−27.1*	*8770*	*40*	*9560–10,110*	*9770*
CotB: 16 July 2008C2	Beta-256533	69° 43′	154° 52′	detrital trunk fragment w/bark	−27.7	8810	50	9670–9970	9853
BearT: 7-14-2008	Beta-256522	69° 38′	154° 54′	*Salix* in growth position	−27.2	9050	60	9930–10,390	10,220
IslandB: 4July2006A	Beta-222489	69° 39′	154° 51′	*Salix* in growth position	−29.1	9230	60	10,250–10,520	10,400
LSB: 22July2002Up	GX-29711-AMS	69° 36′	154° 55′	*Populus* leaf	−30.1	9250	70	10,250–10,580	10,420
IslandB: 6Jul05IK21	Beta-215208	69° 39′	154° 51′	*Populus* stump in situ	−26.0	9290	60	10,270–10,650	10,480
LSB: 22July2002Mid	GX-29710-AMS	69° 36′	154° 55′	*Populus* leaf	−29.5	9310	40	10,300–10,650	10,520
Island B: 4Jul2006D-1	Beta-222490	69° 39′	154° 51′	leaves of *Populus*, *Salix*, *Vaccinium*	−29.5	9330	60	10,300–10,700	10,540
CotB: 17July2005K	Beta-217270	69° 43′	154° 52′	detrital *Salix* branch	−27.8	9340	60	10,300–10,710	10,550
LSB: 22July2002A	GX-29709-AMS	69° 36′	154° 55′	*Populus* log	−27.0	9370	40	10,500–10,700	10,600
CotHP: 5July2006C	Beta-222493	69° 43′	154° 52′	*Salix* in growth position	−27.0	9480	50	10,580–10,830	10,740
CotHP: 16July2008B	Beta-256527	69° 43′	154° 52′	*Equisetum* roots in situ	−25.6	9490	60	10,580–10,880	10,770
CotHP: 16July2008B	Beta-256528	69° 43′	154° 52′	*Equisetum* roots in situ	−25.6	9700	60	10,790–11,240	11,120
CotB: *Ikpikpuk 2*	*Beta-111032*	*69° 43′*	*154° 52′*	*Populus leaf*	*−31.8*	*9720*	*50*	*10,870–11,240*	*11,160*
LSB: 13July2008	Beta-256538	69° 36′	154° 55′	freshwater bivalve	−5.0	9930	50	11,230–11,420	11,340[b]
LSB: 22July2002L	GX-29712-AMS	69° 36′	154° 55′	*Populus* leaf	−30.2	10,190	80	11,400–12,200	11,870[b]
CotB: *Ikpikpuk1*	*Beta-109676*	*69° 43′*	*154° 52′*	*Populus leaf*	*−29.2*	*10,940*	*50*	*12,640–12,970*	*12,800*
LSB: 23July2002A	GX-29724-AMS	69° 36′	154° 55′	*Salix* in growth position	−29.5	11,340	40	13,120–13,320	13,220
LSB: 17July2002G	GX-29706-AMS	69° 36′	154° 55′	detrital twig	−28.0	11,370	50	13,120–13,360	13,240
LSB: *7-14-99d*	*Beta-132692*	*69° 36′*	*154° 55′*	*Salix in growth position*	*−27.3*	*11,520*	*80*	*13,210–13,590*	*13,370*
LSB: *7-14-99a*	*Beta-132632*	*69° 36′*	*154° 55′*	*Salix in growth position*	*−28.3*	*11,540*	*50*	*13,260–13,520*	*13,380*
LSB: 7-13-2008	Beta-256520	69° 36′	154° 55′	twigs in peat block	−26.7	11,580	60	13,280–13,610	13,420
LSB: *7-1-98c*	*Beta-120023*	*69° 36′*	*154° 55′*	*Salix in growth position*	*−26.4*	*11,600*	*50*	*13,300–13,620*	*13,430*
LSB: *7-1-98a*	*Beta-120022*	*69° 36′*	*154° 55′*	*detrital branch in peat block*	*−27.4*	*11,640*	*50*	*13,330–13,660*	*13,480*
LSB: *7-1-98q*	*Beta-120024*	*69° 36′*	*154° 55′*	*detrital branch in peat block*	*−29.1*	*11,730*	*70*	*13,400–13,760*	*13,580*
LSB: *7-1-98x*	*Beta-120025*	*69° 36′*	*154° 55′*	*detrital branch in peat block*	*−27.8*	*11,860*	*50*	*13,490–13,850*	*13,720*
CotHP: 16July2008A	Beta-256524	69° 43′	154° 52′	sediment block w/rooted *Salix*	−27.8	>42,500	–	–	–
LSB: 7-13-2008	Beta-256521	69° 36′	154° 55′	*Salix* in growth position	−28.3	>42,500	–	–	–
CotHP: 16July2008C1	Beta-256532	69° 43′	154° 52′	detrital *Populus* stump w/bark	−23.4	>43,500	–	–	–
LSB: 7-18-98c	Beta-123316	69° 36′	154° 55′	*Salix* in growth position	−29.0	>47,770	–	–	–
Titaluk River									
Crner: 25July2008D	Beta-256526	69° 52′	154° 50′	*Salix* in growth position	−27.3	9450	60	10,520–10,820	10,690
Crner: 25July2008C	Beta-256525	69° 52′	154° 50′	rootlets, probably *Menyanthes*, in growth position	−24.7	9510	60	10,590–11,090	10,830

[a] Abbreviations of stratigraphic sections: **Ikpikpuk River**: Little Supreme Bluff: LSB; Bear Tooth Bluff: BearT; Island Bluff: IslandB; L and K Bluff: L&K; Cottonwood Bluff, High Point: CotHP; Cottonwood Bluff, Section A: CotA; Cottonwood Bluff, Section B: CotB; miscellaneous cutbanks: MISC. **Titaluk River**: Corner Section: Crner. **Nigu River**: Section 1: N1; Section 2: N2.

[b] Dates not plotted in Fig. 10 either because their 2δ-age range is unusually large or because they are likely to be contaminated with old carbon.

bluff. The unconformity between the Peregrine and Rough-Legged units is marked by a concentration of peat clasts (Fig. 8). Similar concentrations of peat clasts occur today in the river's thalweg where the channel is eroding into high bluffs. The undercut vegetation mat growing on top of these bluffs tumbles into the river and remains there as a lag. Based on this modern analogy, the ages of these peat blocks in section provide maximum-limiting ages on channel incision. We dated five detrital peat blocks from the Peregrine/Rough-Legged boundary and obtained ^{14}C ages between 11,860 ± 50 and 11,370 ± 50 ^{14}C yr BP (Fig. 8, Table 1).

In contrast to the Peregrine Sand, the Rough-Legged Sand consists largely of lateral accretion deposits marked by sweeping epsilon cross-strata whose predominant strike is oriented roughly perpendicular to the flow directions inferred from smaller bedforms. Other than epsilon cross-strata, bedforms in the Rough-Legged Sand resemble those in the Peregrine Sand. We found no rooted plants within the Rough-Legged Sand, though the leaves of cottonwood and willow are abundant, along with occasional woody debris of these same taxa. Cottonwood leaves from a height of 6 to 8 m above river level dated to between 10,190 ± 80 and

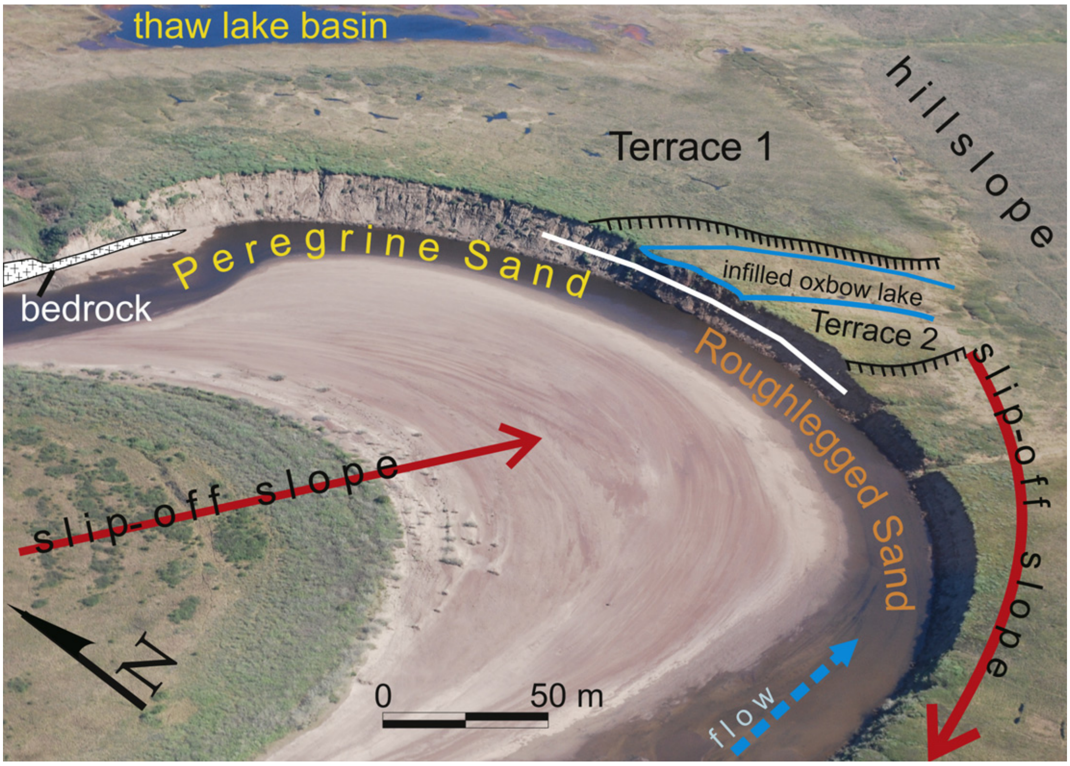

Fig. 7. Oblique aerial photograph of Little Supreme Bluff on the Ikpikpuk River. The white line on the bluff face shows the extent of the cross section in Fig. 8.

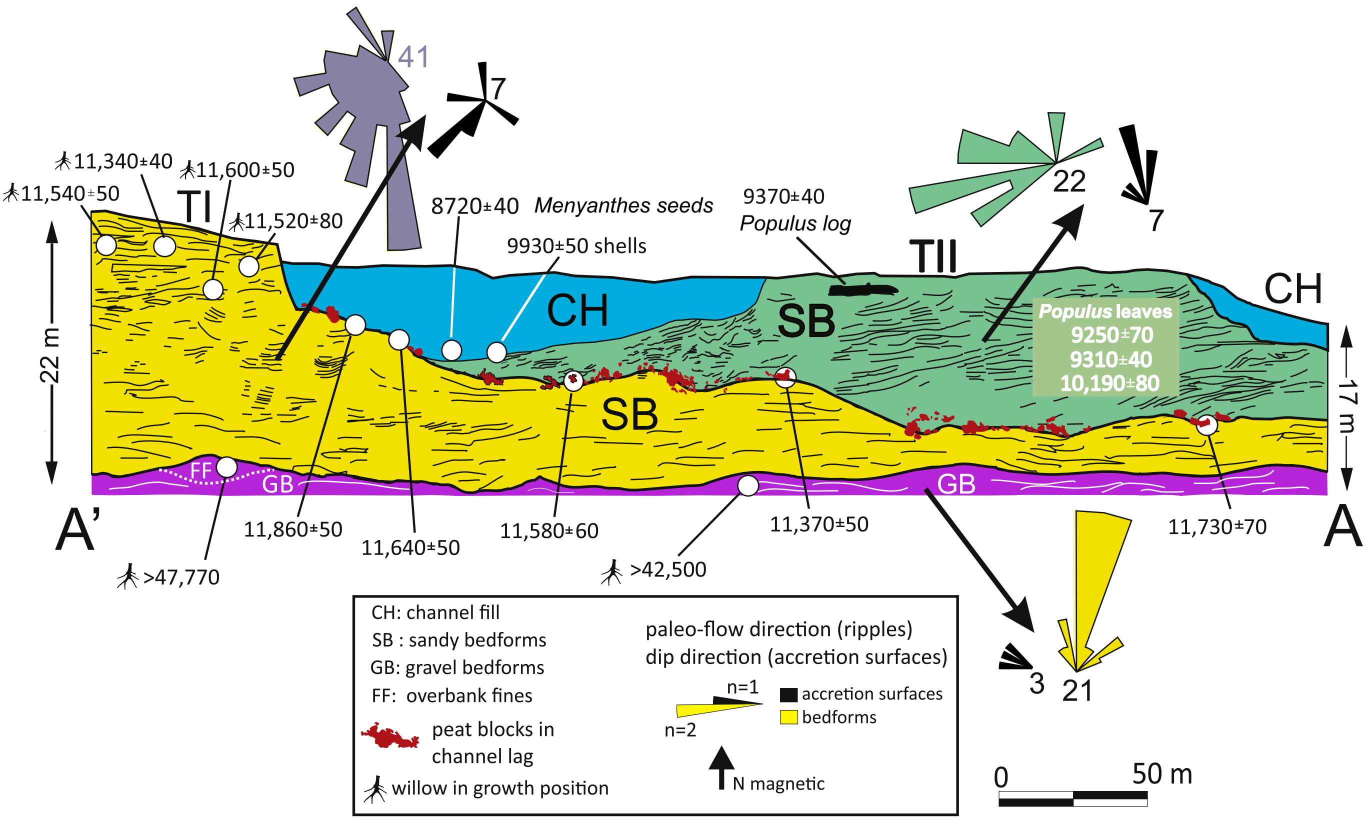

Fig. 8. Stratigraphic section in the central part of Little Supreme Bluff, Ikpikpuk River.

9250 ± 70 ^{14}C yr BP, and a cottonwood log 1.5 m below the surface of Terrace 2 dated to 9370 ± 40 ^{14}C yr BP (Table 1, Fig. 8). Because these samples may have been reworked from older deposits, their ages are maximum-limiting dates only.

At the downstream end of the Rough-Legged unit, a prominent infilled channel lies along the base of the riser of Terrace 1 (Fig. 7). This oxbow lake represents one of the last positions of the meandering channel that deposited the Rough-Legged Sand. The bottom layers of this channel-fill consist of several meters of organic-rich, laminated silt with occasional freshwater mollusks, fish bones, and the distinctive seeds of the emergent aquatic plant, *Menyanthes trifoliata*. The gastropod shells date to 9930 ± 50 ^{14}C yr BP, and the *Menyanthes* seeds date to 8720 ± 40 ^{14}C yr BP (Table 1; Fig. 8). The upper portion of the oxbow lake is filled with a massive deposit of peat comprised mostly of the aquatic moss, *Scorpidium scorpioides*.

We interpret the stratigraphy of Little Supreme Bluff as follows. Sometime before 48 cal ka BP (possibly during the height of the Last Interglacial, MIS 5e), the Ikpikpuk flowed in a meandering, gravel-bedded channel at an elevation similar to today. The Ikpikpuk's bedload was more gravelly then, possibly because the river had a higher annual discharge or because its flow regime was more subnival in character than it is today. The presence of fossil sand wedges in the Purple Gravel implies that snow cover was sparse in winter and that there were strong winds. It is interesting that sand wedges are rare in Holocene deposits along the upper Ikpikpuk today. The unconformity represented by the eroded surface of the Purple Gravel probably represents a lengthy period of time. The overlying Peregrine Sand records very rapid aggradation on the floodplains of braided channels. This period of aggradation lasted from sometime before 13.6 cal ka BP to ca 13.1 cal ka BP (Table 1). A period of incision followed that was accompanied by the erosion of river bluffs capped by peat that had accumulated between 13.8 and 13.1 cal ka BP. A second aggradation episode then occurred, depositing the Rough-Legged Sand on the floodplain of a meandering channel. A channel was abandoned high above present river level sometime before 9.5–9.8 cal ka BP, the age of the *Menyanthes* seeds in the basal sediment of the oxbow lake. The 11.2–11.4 cal ka BP age of shells from the same deposit provide only a maximum-limiting date because it is likely they took up older dissolved carbon. Sometime after the oxbow lake formed, the Ikpikpuk began to incise back down towards the level of the Purple Gravel.

4.1.2.2. Bear Tooth Bluff. Bear Tooth Bluff is located 5 km downstream of Little Supreme Bluff (Fig. 3). A prominent strath terrace standing 7 m above river level is overlain by 50 cm of angular talus and then by 5.6 m of fluvial sand. In the uppermost 25 cm of this sand is an in situ rooted willow dating to 9050 ± 60 ^{14}C yr BP (Table 1). Capping the section is a meter of bluff-top loess containing several buried soils. We interpret this section as indicating aggradation ended here ca 9.9–10.4 cal ka BP and that the river then downcut.

4.1.2.3. Island Bluff. Island Bluff is located 7.5 km downstream of Little Supreme Bluff (Fig. 3). On the east side of the river, a narrow channel is actively eroding a 16-m high cut bank (Fig. 9). A

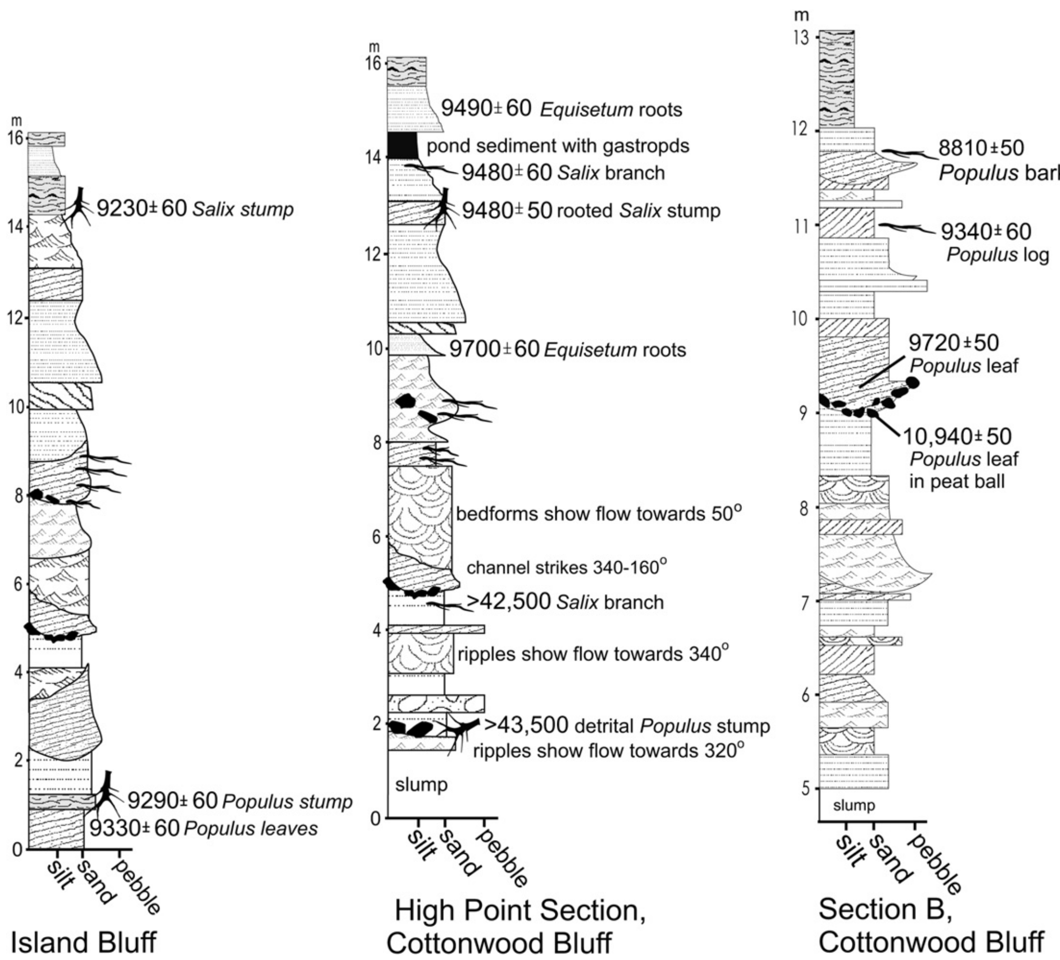

Fig. 9. Stratigraphic sections at Island Bluff and Cottonwood Bluff, Ikpikpuk River.

cottonwood stump with intact bark and rooted in overbanks silts 1 m above present river level dates to 9290 ± 60 ^{14}C yr BP (Table 1). Near present river level, intact cottonwood leaves in a channel-fill deposit of silty sand date to 9330 ± 60 ^{14}C yr BP. Above the dated stump are 13 m of medium and coarse sand deposited as scour fills, and epsilon cross-beds, climbing ripples, and plane beds. At a height of 14.2 m above river level, a unit of organic-rich silty sand contains abundant, rooted willows, one of which dates to 9230 ± 60 ^{14}C yr BP. These willows are buried by sandy plane beds and climbing ripples, and the section is capped by bluff-top silts, peat lenses, and buried soils (Fig. 9). We interpret this section as recording floodplain aggradation between 10.6 and 10.2 cal ka BP (Table 1) at a rate of 33 mm yr^{-1}.

4.1.2.4. Cottonwood Bluff. Cottonwood Bluff is a 2-km long cut bank located 30 km downstream of Little Supreme Bluff and 64 km below the Kigalik–Maybe Creek confluence (Fig. 3). We studied the downstream 1 km of this bluff where it exposes the interior of a terrace whose surface altitude ranges from 13 to 16 m above river level (Fig. 9). Two sections were previously described here by Mann et al. (2002a); we describe Section B again because we have added several new ^{14}C dates.

The High Point section is farthest upstream (Fig. 9). The lowest 5–6 m of this section consist of climbing ripple cross-stratification in sand, plane beds in sand and pebble gravel, scour hollows infilled with peat clasts, and detrital stumps and branches. An uprooted cottonwood stump with intact bark dated to >43,500 ^{14}C yr BP. At the 4.5 m level, a detrital branch dated to >42,500 ^{14}C yr BP. A major erosional unconformity exists somewhere between the 5 and 10 m levels. At the 10-m level, *Equisetum* roots in growth position date to 9700 ± 60 ^{14}C yr BP (Fig. 9). At the 13-m level, a willow shrub in growth position dates to 9480 ± 50 ^{14}C yr BP. More *Equisetum* roots penetrating intact plane beds of sand at the 15-m level date to 9490 ± 60 ^{14}C yr BP.

We interpret the High Point section as indicating that sometime before 42.5 ^{14}C ka BP the Ikpikpuk had incised its valley fill down to near the level where it flows today. Bedforms and plant remains in this older unit are indistinguishable from those in younger deposits. The more recent aggradation that built the 16-m high terrace was in progress 10.6–11.2 cal ka BP (Table 1). Between 11.2 and 10.6 cal ka BP, around 5 m of sandy sediment aggraded here, averaging 8 mm yr^{-1} over this 600-year period.

Cottonwood Section B is located near the downstream end of the bluff and consists of 13 m of waterlaid sand. Bedforms include trough cross-beds, climbing ripples, scour-infilling plane beds, and high-angle cross-beds (Fig. 9). At the 9 m level, we found an intact cottonwood leaf within a block of detrital peat and sand. This leaf dated to 10,940 ± 50 ^{14}C yr BP (Appendix A). Another cottonwood leaf slightly higher in the section dated to 9720 ± 50 ^{14}C yr BP. Samples of detrital cottonwood wood and bark from the 11 m and 11.8 m levels, respectively, date to 9340 ± 60 and 8810 ± 50 ^{14}C yr BP. Because they are not in growth positions, these dates provide only maximum-limiting ages on depositional events. We conclude that rapid aggradation began here sometime after 11.2 cal ka BP.

Together with the stratigraphy previously described at Cottonwood Bluff by Nelson and Carter (1987) and Mann et al. (2002a), these sections record the same early Holocene aggradation episode that occurred upstream at Island, Bear Tooth, and Little Supreme Bluffs. Abandonment of an oxbow lake now perched on the terrace surface at Cottonwood Bluff (Mann et al., 2002a; Section A) occurred after 8770 ± 40 ^{14}C yr BP (9.6–10.1 cal ka BP) (Table 1).

4.1.2.5. Other Ikpikpuk River sections. L and K Bluff is located 4 km upstream of Cottonwood Bluff (Fig. 3). This section exposes the interior of a terrace standing 15 m above present river level. Several meters of purple, pebbly gravel near river level are overlain by river-deposited medium and coarse sand. *Equisetum* roots in a lense of silty sand 2.3 m below the bluff top dated to 7560 ± 50 ^{14}C yr BP (Table 1). This suggests the river was >10 m above its present level ca 8.2–8.5 cal ka yr BP.

We dated three willows in growth position within three different cutbanks in the Ikpikpuk valley upstream of Cottonwood Bluff (Table 1). All date to the mid- and late Holocene and record the formation of the extensive meander-scroll plain that now fills much of the Ikpikpuk valley.

4.1.3. Titaluk River

4.1.3.1. Corner Section. The Corner Section is located 27 km upstream of the Titaluk–Ikpikpuk confluence (Fig. 3). This section exposes the interior of a terrace that stands 18 m above present river level. Above 3.6 m of slump near river level, there are 7 m of fluvial sand, which in turn are overlain by 7 m of peat that has infilled an oxbow lake. Rooted willows from the basal layers of this lake date to 9450 ± 60 ^{14}C yr BP and 9510 ± 60 ^{14}C yr BP (Table 1). We interpret this section as indicating the aggradation that built the terrace occupied by the oxbow lake occurred shortly before about 10.6–11.1 cal ka BP and was followed by downcutting.

4.2. Extralimital cottonwood ages

Macrofossils of cottonwood trees and shrubs are common in stratigraphic sections along the Ikpikpuk and Titaluk Rivers. Logs of cottonwood up to 20 cm in diameter are occasionally encountered as driftwood on point bars. Bark fragments and leaves occur in some sections. At the 2δ level of uncertainty, the 23 cottonwood macrofossils that we dated in the present study range in age from 11.6 to 9.3 cal yr BP (Appendix A). Four additional ages on extralimital cottonwood come from Mann et al. (2002a), four from Nelson and Carter (1987), ten from Hopkins et al. (1981), and one from Kaufman and Hopkins (1985).

5. Discussion

5.1. Timing

The first of two episodes of rapid floodplain aggradation in the Arctic Foothills began ca 14 cal ka BP and ended ca 12.75 cal ka BP (Fig. 10). Evidence for the first episode comes from the Nigu and Ikpikpuk valleys (this study) as well as from the East Fork of the Etivluk valley, and the valley of Mesa Creek (Fig. 1) (Mann et al., 2002a). The second aggradation episode began ca 11.5 and ended ca 9.5 cal ka BP. The clearest records of this second aggradation episode come from the Ikpikpuk and Titaluk valleys. The lack of evidence for this early Holocene aggradation event in the Nigu valley is probably the result of chance, since terrace exposures there are rare.

The two aggradation episodes that occurred during the Pleistocene–Holocene transition were separated by a period of valley-fill incision that lasted from ca 12.75 to 11.5 cal ka BP during the Younger Dryas chronozone (Fig. 10). Floodplain incision is inherently more difficult to date than aggradation because it involves a net loss of sediment downstream. Only at Little Supreme Bluff on the Ikpikpuk River do we have a clear picture of what happened during the Younger Dryas (Fig. 8). Sometime after 13.1 cal ka BP (11,340 ± 40 ^{14}C yr BP), the Ikpikpuk River downcut through the Peregrine Sand to near its present level. Numerous blocks of bluff-top peat were left as lag deposits in the thalweg as the river cut laterally into the valley fill left during the 14–12.75 cal ka BP aggradation episode. No ^{14}C ages closely limit

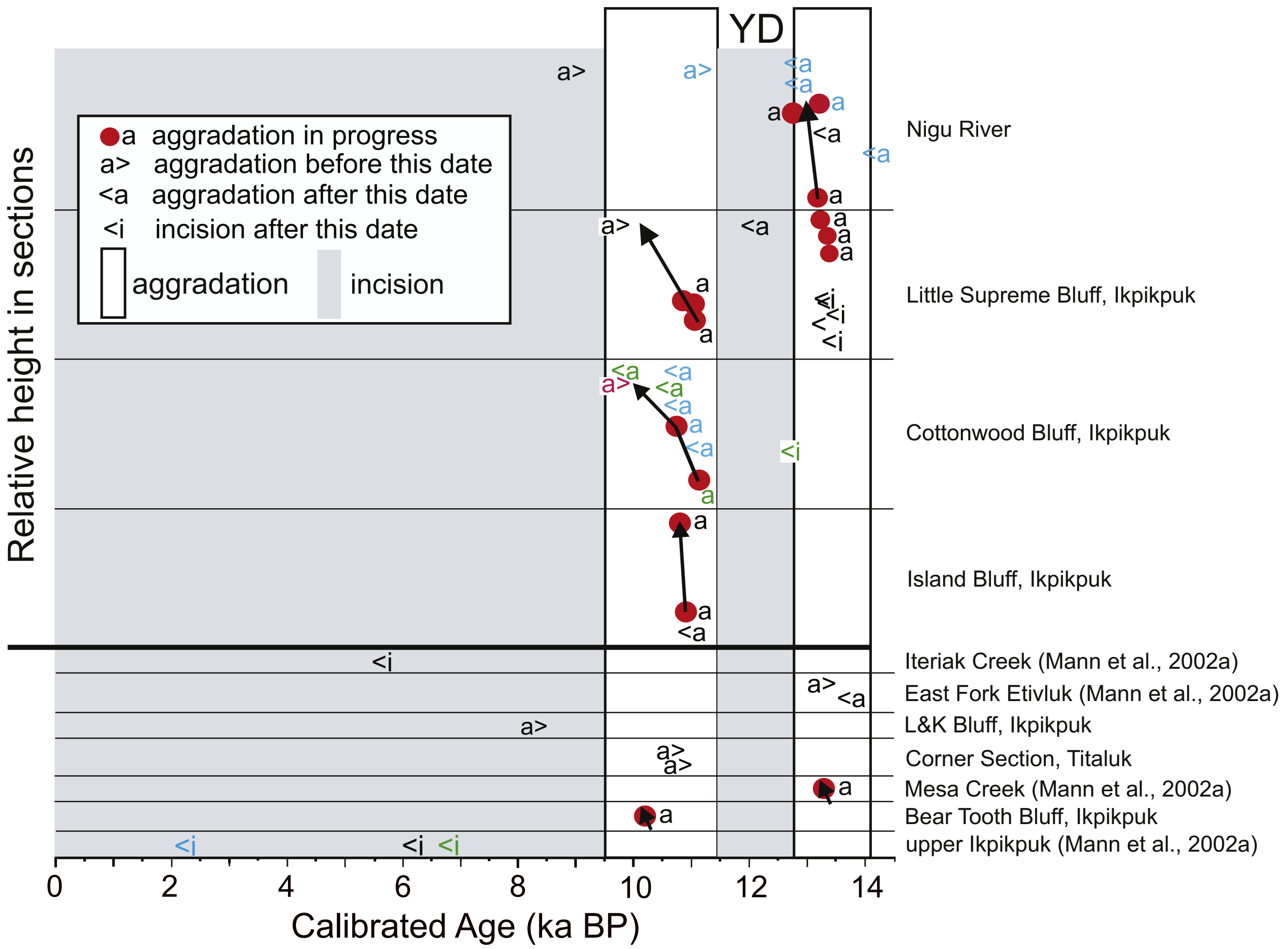

Fig. 10. Synthesis of post-14,000 cal yr BP aggradation and incision along the study rivers. Two episodes of rapid floodplain alluviation preceded and followed the Younger Dryas (YD) chronozone. Different colored letters at the same bluff locality indicate ^{14}C ages from different stratigraphic sections. Median probable calibrated age is plotted for each dated sample.

the time when aggradation resumed at Little Supreme Bluff, but we do know the floodplain was aggrading there after about 10.5 cal ka BP (9310 ± 40 ^{14}C yr BP). Downstream at Island Bluff, the Ikpikpuk's floodplain was aggrading near present river level ca 10.5 cal ka BP (9290 ± 60 ^{14}C yr BP). At Cottonwood Bluff, aggradation was underway ca 11.1 cal ka BP (9700 ± 60 ^{14}C yr BP). After ca 9.5 cal ka BP, net incision occurred in the Ikpikpuk and Titaluk valleys (Fig. 10) as meandering channels left descending, unpaired, meander-scroll terraces. A trend of slow downcutting over the last 9000 years is consistent with the geomorphology of post-glacial fluvial terraces in other valleys in region (Mann et al., 2002a).

5.2. Correlations

5.2.1. Extralimital cottonwoods, thermokarst, and peat formation

Prehistoric episodes of rapid floodplain aggradation in the Arctic Foothills occurred at times when summers were warmer than today. This conclusion is based on the fact that cottonwood trees expanded their range into tundra regions where they do not grow today at the same times that floodplains were aggrading rapidly there (Fig. 11). Range expansions of cottonwoods into areas that are now treeless occurred when July temperatures were warmer than today (Hopkins et al., 1981; Kaufman and Hopkins, 1985; Nelson and Carter, 1987; Mann et al., 2002a; Kaufman et al., 2004). The probability-density distribution of 39 ^{14}C ages of extralimital cottonwood from northwestern North American Arctic (Appendix A) cluster into two groups, one centered on 13.1 cal ka BP and the other on 10.6 cal ka BP (Fig. 11). Kaufman et al. (2004) described a broad peak in extralimital cottonwood ages between 11 and 9 cal ka BP using some of the same data; the difference is that they used a 500-year bin size to sort the calibrated ages, which obscures the earlier 13.1 cal ka BP peak in the age distribution.

Other proxy data support the interpretation that episodes of rapid floodplain aggradation occurred at times when climate was rapidly warming. Numerous thaw lakes developed in northwestern Canada during the first millennium of the Holocene, most likely in response to warmer summers (Burn, 1997). In the Alaskan Arctic Foothills, Mann et al. (2002a) noted the occurrence of widespread thermokarsting around the time of the Pleistocene–Holocene transition. Near the Lena River delta, thermokarst may have begun as early as 12.5 cal ka BP and was widespread by 11.5 cal ka BP, with thermokarst lakes reaching their maximum extents ca 7–5 cal ka BP (Grosse et al., 2007). In Siberia and Alaska, the frequency of thermokarst basin formation shows a small, initial

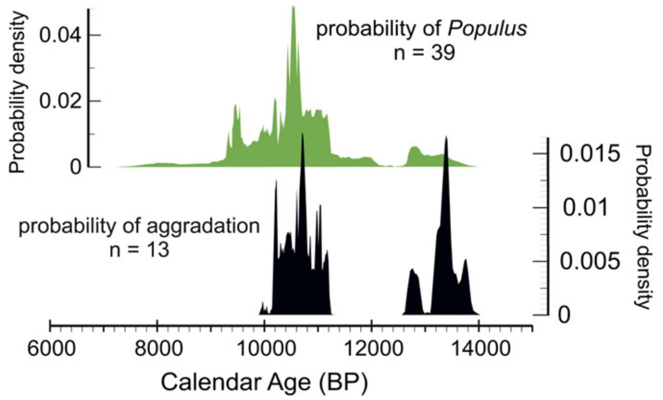

Fig. 11. Probability-density curves (Bronk Ramsey, 2009) for the ^{14}C ages of cottonwoods (*Populus balsamifera*) in northwestern North America at localities beyond their present range limits (above) and for ^{14}C ages describing floodplain aggradation in the Arctic Foothills (below). Cottonwood ages come from Appendix A. The ^{14}C ages of aggradation-in-progress are shown as red dots in Fig. 10 (Table 1). There were two periods during the Pleistocene to Holocene transition when summer temperatures warmed enough to allow cottonwood trees to spread past their current range limits and this expansion coincided with floodplain aggradation.

peak ca 13.5 cal ka BP and a larger one ca 10.5 cal ka BP (Walter et al., 2007).

Additional evidence for the timing of post-glacial warming in the Arctic comes from the timing of peatland establishment. In many parts of the Arctic, peatlands expanded rapidly between 11.5 and 8 cal ka BP (Smith et al., 2004; MacDonald et al., 2006; Korhola et al., 2010), though near the Lena River delta in Siberia, peat formation seems to have begun earlier around 14.4 cal ka BP (Grosse et al., 2007). Basal peat dates from the Arctic Foothills suggest there were two intervals of widespread paludification in the Arctic Foothills: one between 15.5 and 13 cal ka BP and the other between 11.5 and 8 cal ka BP (Mann et al., 2002a). Interestingly, this double-peak pattern does not appear in the recent synthesis of Jones and Yu (2010). The timing of paludification was probably triggered by increased effective moisture that accompanied warming summer climate (Mann et al., 2002b; Grosse et al., 2007).

5.2.2. *Were there two post-glacial thermal maxima in northern Alaska?*

Both of the pre- and post-Younger Dryas episodes of rapid floodplain aggradation on the North Slope occurred within the broad, Milankovitch-driven maximum in summertime insolation that occurred in the Arctic between 12 and 10 cal ka BP (Kaufman et al., 2004). We suggest that summer climate started to warm rapidly on the North Slope ca 14 cal ka BP, but then was interrupted by the onset of the Younger Dryas ca 12.7 cal ka BP. As the Younger Dryas ended, the effects of the high-latitude insolation maximum reasserted themselves and caused the second peak in summer warmth centered on 10.6 cal ka BP. It is well known that the climatic effects of the Younger Dryas varied geographically (Kokorowski et al., 2008; Meltzer and Holliday, 2010). Within Alaska, the Younger Dryas affected coastal regions more strongly than interior ones (Bigelow and Edwards, 2001; Briner et al., 2005; Kaufman et al., 2010). Given this geographic complexity, it is unlikely this double-peaked thermal maximum occurred in all sectors of the Arctic.

5.3. *Rates*

During both the pre- and post-Younger Dryas aggradation episodes, stream valleys filled with sediment at rapid rates. Along the Nigu River between 13.5 and 12.5 cal ka BP, aggradation occurred at between 4 and 14 mm yr^{-1}. During this same interval, the Ikpikpuk valley at Little Supreme Bluff aggraded at approximately 8 mm yr^{-1}. In the first millennium of the Holocene, the Ikpikpuk valley at Island and Cottonwood Bluffs aggraded at 8–33 mm yr^{-1}.

Incision rates are not as securely dated. At Little Supreme Bluff, incision amounting to 8 m occurred sometime after 13.3 cal ka BP, the upper limiting age on the youngest in situ willow in the Peregrine Sand. Assuming the cottonwood leaf comprising sample GX-29710 (9310 ± 40 ^{14}C yr BP, Fig. 8) in the overlying Rough-Legged Sand was not redeposited, then this incision episode was completed before ca 10.3 cal ka BP. This implies that the Ikpikpuk incised its floodplain at this location at a rate of at least 3 mm yr^{-1} during the Younger Dryas.

It is difficult to define what typical floodplain aggradation and incision rates are on a global basis. For one thing, aggradation and incision tend to be episodic, so records that span short time intervals sometimes show anomalously slow or rapid rates. This is especially true in watersheds where human activities have recently triggered severe erosion (Knox, 2006; Trimble, 2009). A geographically random review of alluviation rates along streams with drainage basins <200,000 km^2 (Table 2) suggests that recent, human-aggravated aggradation rates typically fall between 2 and 140 mm yr^{-1}. Longer-term, pre-anthropogenic rates tended to be much lower, between 0.1 and 10 mm yr^{-1}. In a relative sense then, aggradation rates between 4 and 33 mm yr^{-1} that occurred along the Nigu and Ikpikpuk Rivers during the Lateglacial and early Holocene were extremely rapid.

5.4. *Causes*

We have correlated episodes of rapid floodplain aggradation during the Pleistocene/Holocene transition with warming summer temperatures. But what exactly was the connection between the two? Warmer summers in the Arctic Foothills probably caused active layers to deepen and more rain and/or more intense rainstorms to occur (Mann et al., 2002a). Warmer summers imply warmer winters as well, which means snowfall probably increased. Increased precipitation in both summer and winter makes sense with the rapid decline in climatic continentality that resulted from the flooding of the Bering Land between 14 and 8 cal ka BP (Mann et al., 2002b).

How could deeper thaw and increased soil moisture have caused such a radical increase in sediment delivery from hillslopes to floodplains compared to today? The answer is probably two-fold. First, increased precipitation very likely triggered an abrupt increase in surface-wash erosion. Runoff from snowmelt is the major cause of surface erosion in the High Arctic today, where the vegetation cover is <30% and summer rainfall is rare. Measurements of suspended sediment on hillslopes at 80° north on Ellesmere Island (Lewkowicz and Kokelj, 2002) suggest that an abrupt increase in erosion occurs when effective precipitation rises to 50 mm, followed by a decline as the vegetation cover thickens in response to wetter conditions. Just like in semiarid regions at lower latitudes today (Dendy and Bolton, 1976), a threshold in surface-wash erosion probably existed in the Arctic Foothills during the late Pleistocene. If both snowmelt and summer rainfall increased suddenly on a sparsely vegetated, formerly summer-dry landscape, they would probably have triggered a pulse of surface erosion. Perhaps this is what caused development of the extensive rill systems that persist today in the Arctic Foothills as peat-covered water tracks (McNamara et al., 1999).

The second way that warmer, wetter summers might have triggered a surge in hillslope erosion causing rapid alluviation on floodplains was through enhanced landsliding. More precipitation

Table 2
A Geographically Random and Incomplete Survey of Floodplain Aggradation Rates Worldwide. The Nigu, Ikpikpuk, and Titaluk rivers drain watersheds of 1630, 4400, and 2680 km^2, respectively. Aggradation on the Nigu and Ikpikpuk floodplains occurred at rates between 4 and 33 mm yr^{-1} during warm periods in the Lateglacial and early Holocene.

Vertical aggradation (mm yr^{-1})	Stream	Location and Drainage Area (km^2)	Channel type	Time period	Reference
0.1–10	tributaries of Republican River	Nebraska, USA: <400	arroyos	last several millennia	Daniels (2003)
0.2	tributaries of Mississippi	Wisconsin, USA: 0.5–500	incised, meandering	10,000–200 ^{14}C yr BP, prior to European agriculture	Knox (2006)
0.2–1.3	Meuse-Rhine River	The Netherlands: 198,700	meandering, anthropogenic	last 1500 years	Törnqvist and Bridge (2002)
0.3–4	Brazos River	Texas, USA: 118,000	meandering	Holocene	Taha and Anderson (2008)
0.5–6	Macdonald and Tuross Rivers	Australia: 1920 & 2150	incised, meandering,	last 8000 years	Rustomji et al. (2006)
1	Archuleta Creek	New Mexico, USA: 240	meandering, intermittent	10,200–7000 ^{14}C yr BP	Mann and Meltzer (2007)
1.4	Dry Cimarron River	New Mexico, USA: 270	meandering, intermittent	4700–2200 ^{14}C yr BP	Mann and Meltzer (2007)
1.75	Columbia River	BC, Canada: 6700	anastamosing	last 4500 years	Makaske et al. (2002)
2 to 20	tributaries of Mississippi	Wisconsin, USA: 0.5–500	incised, meandering	post-1800 AD, after European agriculture began	Knox (2006)
2.5	Rhone River	France: 97,800	meandering, delta distributaries	5700 BC to AD 270	Arnaud-Fassetta (2004)
4.2–6.3	Coon Creek	Wisconsin, USA: 360	meandering	AD 1975–1993	Trimble (2009)
6.5–24	Ain River	France: 3630	wandering gravel-bed	last 10–40 years	Piégay et al. (2008)
20–50	Coon Creek	Wisconsin, USA: 360	meandering	AD 1853–1958	Trimble (2009)
140	Rhone River	France: 97,800	anthropogenic	AD 1950–2003	Provansal et al. (2010)

and deeper thaw would have acted in concert to increase the frequency of slush flows, debris flows, active-layer-detachment slides, and thermokarst-driven retrogressive-thaw slides (Fig. 2). These processes of mass wasting are often interconnected (Lewkowicz, 1988). Active-layer-detachment slides, which are usually triggered by increased pore–water pressures at the base of the active layer, can develop into retrogressive-thaw slides involving large-scale thermokarst (Lewkowicz, 1990). Together with slope-wash erosion, these mass-wasting processes would have overwhelmed the limited sediment-transport capacities of the streams, leading to the rapid aggradation of valley fills. Cooler temperatures during the Younger Dryas probably caused precipitation to decline and active layers to become thinner again. This would have stabilized hillslopes, reduced sediment input, and allowed streams to begin downcutting and transporting away the backlog of sediment.

There is a slight possibility that rapid alluviation at sections N1 and N2 could have been related to a glacial advance upstream. In the higher peaks of the central Brooks Range 250 km east of the Nigu, a glacier readvance of limited extent occurred sometime between 15.1 and 13.3 cal ka B.P. (Hamilton, 2003). For several reasons, we think it unlikely that a glacial advance was involved in depositing the Nigu sections. First, they post-date 14.3 (N1) and 13.4 (N2) cal ka BP. Second, these two sections contain abundant plant material, which is in stark contrast to the sterile, glacial outwash terraces present at higher elevations in the Nigu valley. Third, both these sections record deposition by a wandering, gravel-bedded river similar to the modern Nigu rather than by braided channels carrying glacial outwash.

5.5. *Sand dunes and river base levels*

The causal chain of warming climate – widespread mass wasting – floodplain aggradation may have been more complicated in the cases of the Ikpikpuk and Titaluk Rivers upstream of the Ikpikpuk sand sea. Too little is known about the timing of this dune field to exclude the possibility that aggradation and incision in the upper reaches of the Ikpikpuk and Titaluk were influenced by changes in base level caused by dune activity. There are suggestions this was the case. The stabilized surface of the sand sea now lies at an altitude of 60–65 m along the hill front near the Ikpikpuk–Titaluk confluence. Upstream, the fluvial terraces representing valley fills deposited after 14 cal ka BP lie within this same altitudinal range (Fig. 12), suggesting they were graded to the surface of the active sand sea.

Even if the sand sea did partly control floodplain dynamics in the upper Ikpikpuk and Titaluk valleys, climate probably remained the ultimate control. In Section 2 we noted that the activity and extent of the Ikpikpuk sand sea was likely limited by its sand supply. The Colville River was the main source of sand for the dunes, and the sediment load of the Colville River was controlled by the same factors affecting the sediment loads of other rivers in the region. Further support for the inference that aggradation and incision along the Ikpikpuk and Titaluk Rivers were primarily a response to the changing inputs of sediment from local hillslopes comes from three sources: (1) The timing of incision and aggradation was similar in valleys distant from the Ikpikpuk sand sea. Pre-Younger Dryas aggradation also occurred along the Nigu River (Fig. 6), as well as along Mesa Creek and the East Fork of the Etivluk River (Mann et al., 2002a). These streams did not flow through dune fields. (2) There is evidence for widespread mass wasting at the time of the Pleistocene–Holocene transition. We previously interpreted six exposures in the Arctic Foothills that contain flow-deformed peats as indicating a period of heightened solifluction occurring between 14 and 9.5 cal ka BP (Fig. 6 in Mann et al., 2002a). It seems likely that some of these deposits were the result of active-layer-detachment slides or retrogressive-thaw slides. (3) Floodplain incision occurred along the Ikpikpuk during the Younger Dryas despite the fact that the Ikpikpuk sand sea was still active at that time (Carter, 1993). Our conclusion is that the waxing and waning of dune activity probably amplified the responses of the Ikpikpuk and Titaluk floodplains to changes in sediment input but did not interfere with what was mainly a signal of changes in hillslope mass wasting.

5.6. *Decoupling streams and hillslopes*

Floodplain stratigraphy suggests that for most of the last 14,000 years the upper reaches of the Titaluk and Ikpikpuk Rivers

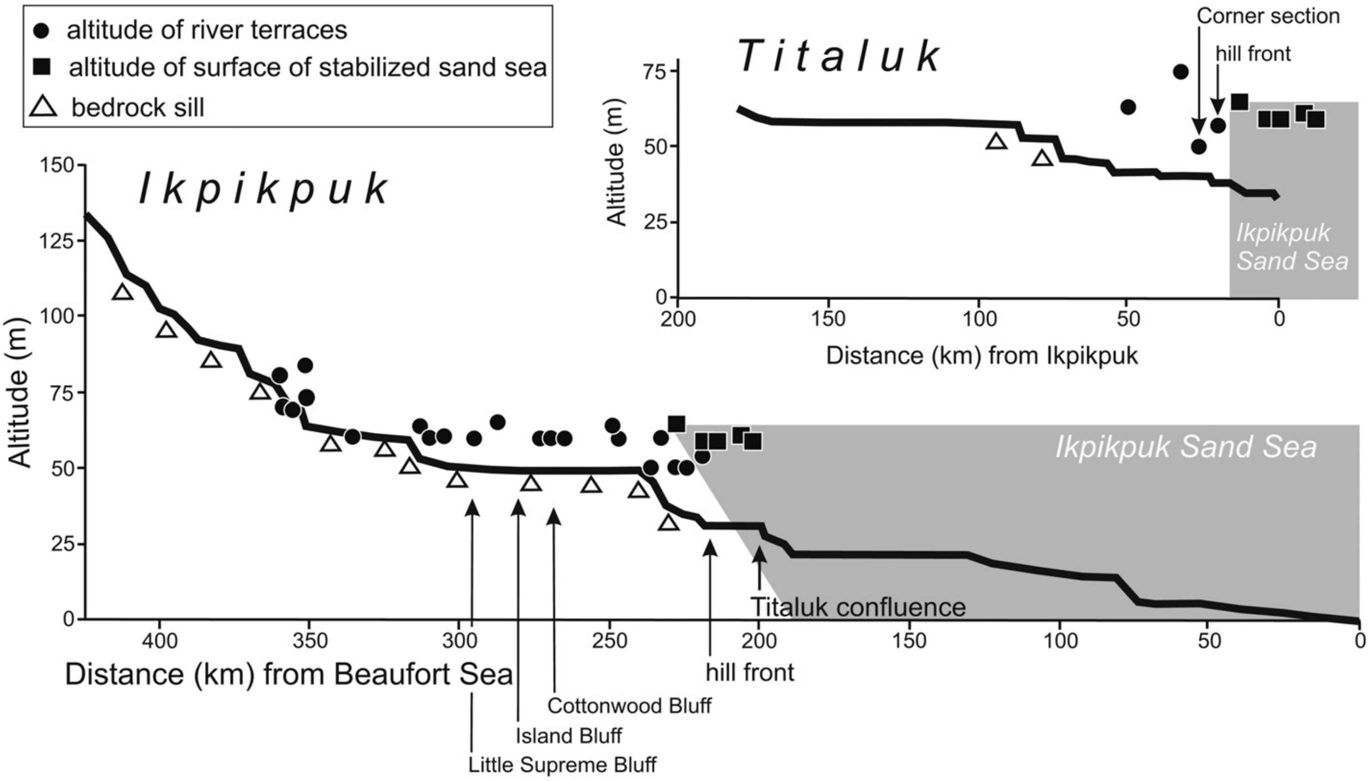

Fig. 12. Topographic cross-sections through the southern margin of the Ikpikpuk sand sea and adjacent parts of the Ikpikpuk and Titaluk valleys. Terraces in the river valleys appear to be graded to the former surface of the sand sea. The rivers have since downcut through the dunes.

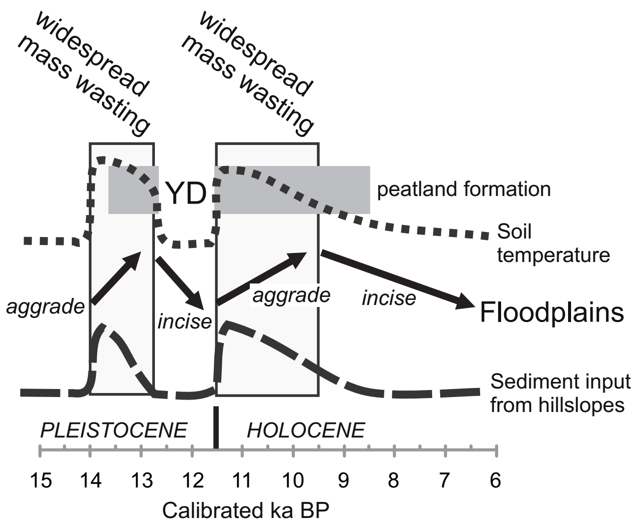

Fig. 13. Inferred interactions between hillslope erosion, floodplains, soil temperature, and peatland in the Arctic Foothills over the last 15 cal ka. Two prehistoric episodes of rapid summertime warming between ca 14 and 9.5 cal ka BP probably triggered widespread mass wasting on hillslopes. The resulting sediment may have overwhelmed the transport capacity of streams, and floodplains aggraded rapidly. These warmer, wetter periods were interrupted by cooling and drying during the Younger Dryas (YD), which probably restabilized the permafrost landscape and allowed streams to incise their floodplains. The second episode of warming and aggradation ended as peat spread across the uplands. This peat would have lowered soil temperatures again and restabilized the permafrost. Since the early Holocene, floodplains have been largely decoupled from sediment inputs from hillslopes, which has resulted in long-term, slow incision as streams carried away the sediment legacy of the Pleistocene–Holocene transition.

have been largely isolated from inputs of mineral sediment coming from their headwater hillslopes (Fig. 13). This inference is based on several observations. Only twice over the last 14,000 years has sufficient sediment reached the floodplains of the Ikpikpuk and Titaluk Rivers to leave a stratigraphic record of widespread valley-fill aggradation (Fig. 10). Each of these aggradation episodes lasted only ca 1000 years. Most of the remaining 12,000 years has seen slow incision as rivers transported away the sediment accumulated during these two brief but massive pulses of sediment input. The Nigu River is probably not so extreme a case because of its subnival flow regime and because many of its tributaries drain steep, rubble slopes. Nonetheless, the lack of lower terraces along the Nigu suggests that the pre-Younger Dryas aggradation episode was the most significant alluvial event of the last 14,000 years.

The second observation supporting the lengthy isolation of rivers in the Arctic Foothills from inputs of mineral sediment from surrounding hillslopes is that large parts of their watersheds have been covered by peat since the early Holocene (Mann et al., 2002a). Surficial organic soil horizons (peat) are highly effective at preventing sheetwash, rill, and channel-bed erosion (McNamara et al., 1999). Besides protecting mineral soils from water erosion, the thermal properties of peat tend to stabilize permafrost across entire landscapes by causing long-term cooling of the ground (Williams and Smith, 1989, p. 112; Hinzman et al., 1996).

Finally, long-term decoupling of valley fills from hillslope erosion is consistent with the presence of extensive, down-stepping flights of meander scrolls in the Ikpikpuk and Titaluk valleys. These meander-scroll plains reflect slow incision that began in the early Holocene after peatlands became widely established.

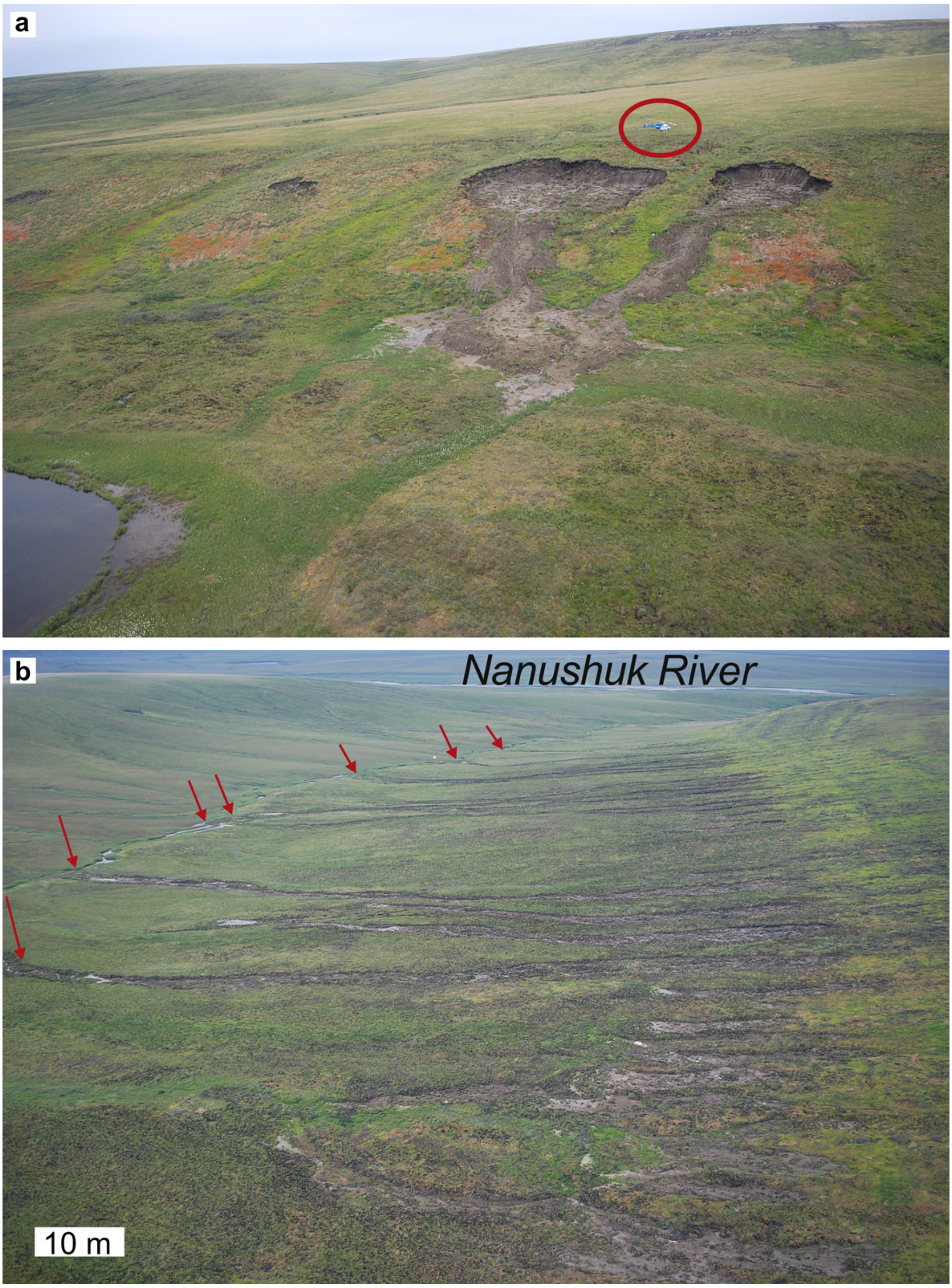

Fig. 14. The future? Two views of mass wasting triggered by the 2007 Anaktuvuk River fire 175 km east of the upper Ikpikpuk River. This fire burned in late summer across a tussock tundra landscape (Jones et al., 2009) and caused numerous active-layer-detachment slides. Some of these slides triggered thermokarst and developed into retrogressive-thaw slides. These photographs were taken in July 2010, and much of the vegetation cover has reestablished itself. The orange patches are early successional *Marchantia* liverworts growing where mineral soil was exposed by intense burning. As summer temperatures continue to warm and late summer droughts increase in frequency, tundra fires may be of key importance in disrupting the organic soil horizons that now blanket much of the Arctic Foothills. Disrupting this peat cover is probably necessary before climate warming can reactivate the mass wasting processes that transported large amounts of sediment from hillslopes to floodplains during the Pleistocene–Holocene transition. (a) Retrogressive-thaw slides on a southwest-facing slope in the Nanushuk valley (68° 55′N, 150° 40′W). Helicopter (red circle) for scale. These landslides are still growing rapidly. (b) View west down an unnamed tributary of the Nanushuk River showing numerous landslides on a south-facing slope. At least 25 slides are visible here. Red arrows mark slides that have reached the creek. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Rivers draining the Arctic Foothills have spent most of post-glacial time in states of geomorphic somnolence compared with the two episodes of extremely rapid sedimentation that occurred during the Pleistocene–Holocene transition. Although localized deposition and erosion occurs every year in these valleys as meanders shift and floods occur, at the scale of valley fills very little has happened since the early Holocene. Most of the last 10,000 years has been spent slowly removing the sedimentary legacy of just two, short-lived warming events (Fig. 13).

5.7. The peat threshold

Because peat is now widespread in the Arctic Foothills and because it inhibits soil erosion and stabilizes the permafrost, the threshold for geomorphic change on this landscape is probably much higher today than it was at the beginning of any other warming episode during the last 100 ka. The adverb "probably" is used here because there is no systematic data describing the extent and timing of peat cover in the Arctic during interstadial periods within the last glacial cycle. Looking into the future, the peat cover that is now widespread on the North Slope landscape would probably have to be disrupted in order for the climate warming now in progress to be able to trigger hillslope erosion as extreme as what occurred during the Pleistocene/Holocene transition. How could a blanket of peat of regional extent be disrupted?

The most likely way that the hillslope–floodplain linkage will be reawakened in the Arctic Foothills is by burning (Fig. 14). Tundra fires remove soil organic horizons and expose mineral soil, which can trigger rapid thawing and mass wasting (French, 2007, p. 191; Liljedahl et al., 2007). Such fires are predicted to become more frequent on the North Slope as summers become warmer and drier and as fire-prone shrubs invade the tundra in response to these warmer conditions (Tape et al., 2006; Higuera et al., 2008; Jones et al., 2009). We speculate that as summer climate continues to warm, more frequent tundra fires will be the proximate trigger for a new outbreak of mass wasting on hillslopes in the Arctic Foothills. If this happens, the result could be an episode of extremely rapid hillslope erosion and rapid floodplain alluviation after a hiatus of some 9000 years.

6. Conclusions

What can the prehistoric responses of arctic watersheds to changing climate tell us about their responses in the future? Floodplain stratigraphy on Alaska's North Slope records two episodes of extremely rapid floodplain alluviation ca 14–12.8 cal ka BP and again ca 11.5–9.5 cal ka BP. Both these aggradation episodes coincided with periods of summertime warming evidenced by range expansions of cottonwood trees and episodes of peatland initiation and thermokarst. Warmer summers imply increased soil moisture. We suspect that deeper thaw and increased soil pore–water pressure triggered widespread mass wasting on hillslopes. This surge in erosion probably overwhelmed the transport capacity of streams, resulting in rapid alluviation on floodplains. Valley-fill incision occurred during the Younger Dryas, probably as a result of cooler, drier conditions that restabilized the hillslopes. Renewed warming in the earliest Holocene again caused widespread mass wasting and rapid alluviation. Since ca 9 cal ka BP, valley fills have experienced slow incision, probably because spreading peatlands have thermally stabilized the permafrost and shielded mineral soils from erosion. Left largely uncoupled from sediment inputs from their adjacent hillslopes, rivers have spent the last 9000 years transporting away the legacies of sediment deposited during these two earlier pulses of sedimentation. We speculate that the widespread presence of peat in the Arctic Foothills today has raised the threshold for climatically driven geomorphic change to a much higher level than it was at the end of the Pleistocene when peatlands were scarce. This peat cover would have to be disrupted – probably by wildland fires – before the rapid warming that is now occurring can trigger any significant geomorphic changes in the watersheds of rivers on Alaska's North Slope.

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Appendix A

Radiocarbon ages of cottonwood (*Populus balsamifera* L.) macrofossils.

Laboratory Number	Latitude (°N)	Longitude (°W)	Dated Material	$\delta^{13}C$ (‰)	C13-normalized Age	2σ calibrated age range (cal yr before 1950)	
						Lower range	Upper range
Populus ages reported in this paper							
Ikpikpuk River, Cottonwood Bluff							
Beta-215205	69° 42.673′	154° 49.931′	log with bark	−28.3	8430 ± 50	9310	9360
Beta-217268	69° 42.960′	154° 52.322′	leaf	−28.6	8830 ± 60	9690	10,170
Beta-217266	69° 42.966′	154° 51.733′	stump w/bark	−26.5	9000 ± 60	9920	10,090
Beta-222494	69° 42.942′	154° 52.443′	bark	−23.8	9010 ± 60	9920	10,090
Beta-217269	69° 42.928′	154° 52.495′	leaf	−28.4	9320 ± 60	10,300	10,330
Beta-217270	69° 42.980′	154° 52.501′	log with bark	−27.8	9340 ± 60	10,300	10,320
Beta-222495	69° 42.942′	154° 52.443′	leaf	−27.6	9390 ± 60	10,420	10,470
Beta-215204	69° 42.978′	154° 51.931′	log with bark	−28.8	9550 ± 50	10,700	10,470
Beta-217267	69° 42.978′	154° 51.931′	log with bark	−30.6	9550 ± 70	10,670	11,160
Beta-215209	69° 42.640′	154° 50.250′	bark	−28.7	9610 ± 70	10,740	11,180
Beta-256532	69° 42.926′	154° 52.479′	stump w/bark	−23.4	>43,500	–	–
Ikpikpuk River, Island Bluff							
Beta-215208	69° 38.767′	154° 50.799′	stump w/bark	−26.0	9290 ± 60	10,270	10,600
Beta-222490	69° 38.767′	154° 50.799′	leaves	−29.5	9330 ± 60	10,300	10,330
Upper Ikpikpuk River							
Beta-215206	69° 22.087′	154° 40.745′	log with bark	−27.0	8580 ± 60	9470	9680

(continued on next page)

Appendix (*continued*)

Laboratory Number	Latitude (°N)	Longitude (°W)	Dated Material	$\delta^{13}C$ (‰)	C13-normalized Age	2σ calibrated age range (cal yr before 1950)	
						Lower range	Upper range
Beta-215207	69° 35.505′	154° 56.623′	log with bark	−26.7	8890 ± 70	9740	10,200
Beta-217271	69° 22.053′	154° 41.275′	log with bark	−29.8	9570 ± 60	10,710	11,140
Beta-215203	69° 22.352′	154° 40.466′	log with bark	−26.3	>47,090	–	–
Ikpikpuk River, Little Supreme Bluff							
GX-29711-AMS	69° 35.550′	154° 54.816′	leaf	−30.1	9250 ± 70	10,250	10,580
GX-29710-AMS	69° 35.550′	154° 54.816′	leaf	−29.5	9310 ± 40	10,300	10,320
GX-29709-AMS	69° 35.553′	154° 54.825′	log with bark	−27.0	9370 ± 40	10,500	10,700
GX-29712-AMS	69° 35.550′	154° 54.816′	leaf	−30.2	10,190 ± 80	11,400	11,570
Titaluk River							
Beta-215210	69° 43.770′	155° 16.983′	log with bark	−27.9	8380 ± 50	9280	9500
Beta-217272	69° 42.603′	155° 12.908′	log with bark	−26.0	>46,500	–	–
Populus ages reported in Mann et al. (2002a)							
Cottonwood Bend							
Beta-121113	69° 43.000′	154° 52.55′	log	−29.6	9270 ± 60	10,250	10,590
Beta-111032	69° 43.000′	154° 52.55′	leaf	−31.8	9720 ± 50	10,870	10,950
Beta-109676	69° 43.000′	154° 52.55′	leaf	−29.2	10,940 ± 50	12,640	12,970
Dune Bend							
Beta-120018	69° 46.50′	154° 48.30′	log	−26.9	9350 ± 60	10,300	10,310
Ikpikpuk River (Nelson and Carter, 1987)							
I-13324	69° 17.5′	154° 42.5′	wood	–	8710 ± 140	9500	10,170
I-11282	69° 35.8′	154° 54.5′	wood	–	9380 ± 150	10,250	11,090
I-13174	69° 43′	154° 53′	wood	–	9430 ± 160	10,280	11,160
I-11280	69° 48.9′	154° 24.73′	Peat w/leaves	–	9540 ± 160	10,410	11,240
Northern Alaska and Northwestern Canada (Hopkins et al., 1981)							
W-1250	N. side Cape Blossom, Kotzebue Sound		wood	–	7270 ± 350	7440	7450
W-1249	E. shore Kotzebue Sound at Arctic Circle		wood	–	8550 ± 400	8550	10,560
W-1993	Sagavanirktok River, N. Alaska		wood	–	8400 ± 300	8630	10,170
W-1255	E. side Cape Blossom, Kotzebue Sound		wood	–	9020 ± 350	9320	9340
W-2620	between Rex Point and Cape Deceit, S. shore Kotzebue Sound		wood	–	9625 ± 350	9930	9990
I-11073	Ikpikpuk River, Arctic Foothills		wood	–	9670 ± 130	10,600	10,620
GSC-2022	Coastal bluffs SE Sabine Point, Yukon Territory		wood	–	9940 ± 90	11,210	11,750
W-1254	E. shore Kotzebue Sound, southeast Riley's Wreck		wood	–	11,340 ± 400	12,220	12,260
I-10274	W. bank Nigu River, 11 km N of Inyorurak Pass (this paper's Nigu 1 section)		wood	–	11,100 ± 170	12,650	13,290
GSC-1514	Twin Lakes near Inuvik, Northwest Territories		wood	–	11,500 ± 160	13,090	13,740
Seward Peninsula and Baldwin Peninsula (Kaufman and Hopkins, 1985)							
L-117F	65° 31′	164° 12′	log	–	8800 ± 1000	7790	12,580

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