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CROSS-BEDDED WOODY DEBRIS FROM A PLIOCENE FORESTED RIVER SYSTEM IN THE HIGH ARCTIC: BEAUFORT FORMATION, MEIGHEN ISLAND, CANADA

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ABSTRACT: **Cross-bedding, the inclined internal stratification that records the migration of certain transverse sedimentary bedforms, is nearly ubiquitous in current-transported bedload sediments. Although examples of the structure are known from inorganic clastic sediments and sedimentary rocks from practically all depositional environments and intervals of geologic history, here we report cross-bedded lenses that are composed wholly or significantly of woody debris, in Pliocene alluvium of the Beaufort Formation in the Canadian High Arctic. The uniqueness of cross-bedded woody debris has hitherto been overlooked, but we demonstrate that, in the entire Phanerozoic record, it is apparently restricted to alluvium deposited during a warm climatic interval that permitted the growth of boreal-type forests within 10° latitude of the North Pole. The marked spatiotemporal restriction of cross-bedded woody debris implies that there may be environmental factors, unique to polar forests, which promote the subaqueous transport of large amounts of fine woody debris as fluvial bedload. We propose a non-uniformitarian conceptual model for the formation of cross-bedded woody debris in forested polar rivers whereby an exceptional abundance of woody debris could accumulate, and become saturated and denser than water, due to reduced decomposition on forest floors that were subject to prolonged periods of darkness and subzero temperatures.**

THE BEAUFORT FORMATION

The purpose of this short paper is to briefly describe and discuss apparently unique sedimentary features, namely cross-bedded deposits of woody debris, which record the transport of significant amounts of sorted woody debris as fluvial bedload, and are apparently restricted to Pliocene polar river systems. The described deposits were discovered during field-based sedimentological investigations into the Beaufort Formation on Meighen Island, Nunavut, Canada (79.9° N, 99.5° W). The Beaufort Formation is an extensive clastic wedge preserved in a 1200 km outcrop belt (Fig. 1) that consists of unconsolidated alluvial gravels, sands, and silts, and minor peat horizons, deposited by a braided river system that flowed in an overall westward direction across a contiguous landmass (Fyles 1990). Under the circumstances of a particularly warm Pliocene climate, the alluvial wedge gradually filled pre-existing valleys to form a broad coastal plain that was later incised by Quaternary rivers and glaciers to reopen the large channels that currently divide the Canadian Arctic Archipelago (Rybczynski et al. 2013). In the Pliocene, global mean annual temperature was 2 to 3 °C warmer than present and mean annual ground temperature in the Canadian High Arctic was 14 to 22 °C warmer (Csank et al. 2011). These elevated temperatures sustained a latitudinal paleo-treeline at least as far north as 80° N approximately 3.5 Ma ago (Fyles 1990; Elias and Matthews 2002).

On Meighen Island, the Beaufort Formation is apparently the only non-Quaternary unit exposed as outcrop, with an apparent thickness of 220 m (Thorsteinsson 1960; Matthews 1987; Fyles et al. 1991). This estimated thickness is effectively only a representation of the topographic relief of the island, and borehole data suggest that undifferentiated unconsolidated sediments of the Beaufort Formation and underlying Eureka Sound Group reach a thickness of up to 2575 m (Brent and Embry 1995). Despite this, exposure of the Beaufort Formation is relatively poor on Meighen Island due to the gentle topography and blanketing of much of the island by multiple Quaternary deposits and an ice cap. Outcrops are typically restricted to isolated valley walls, escarpments, and stream cuts that expose continuous vertical sections of no more than 27 m height. Exposures and the colluvium that cover them are frozen within 1 m of the surface. As such, without detailed geological mapping, it is hard to determine exact stratigraphic relationships on the island.

EVIDENCE FOR POLAR FORESTS

Organic horizons in the Beaufort Formation on Meighen Island provide a large repository of paleoecological information. These comprise both the horizons of transported woody debris that are the focus of this paper, in addition to isolated mossy peat lenses (Kuc 1973; Matthews and Ovenden 1990). Outcrop restrictions reduce the ability to establish whether the peats were autochthonous or whether they represent significant rafts of transported overbank material or material carried frozen in stream ice. Despite this, the peaty lenses contain abundant significantly or partially decomposed wood, moss, leaves, needles, nuts, cones, and other humus material that permit the reconstruction of the Pliocene plant communities from which the woody debris described here was derived. The recorded vascular-plant fossils are typical of a boreal-type forested peatland setting, and include species of pine, birch, poplar, alder, spruce, and larch, in both shrub and tree form, as well as eastern cedar, which at present is a more southerly taxon not found in boreal forests (Matthews and Ovenden 1990).

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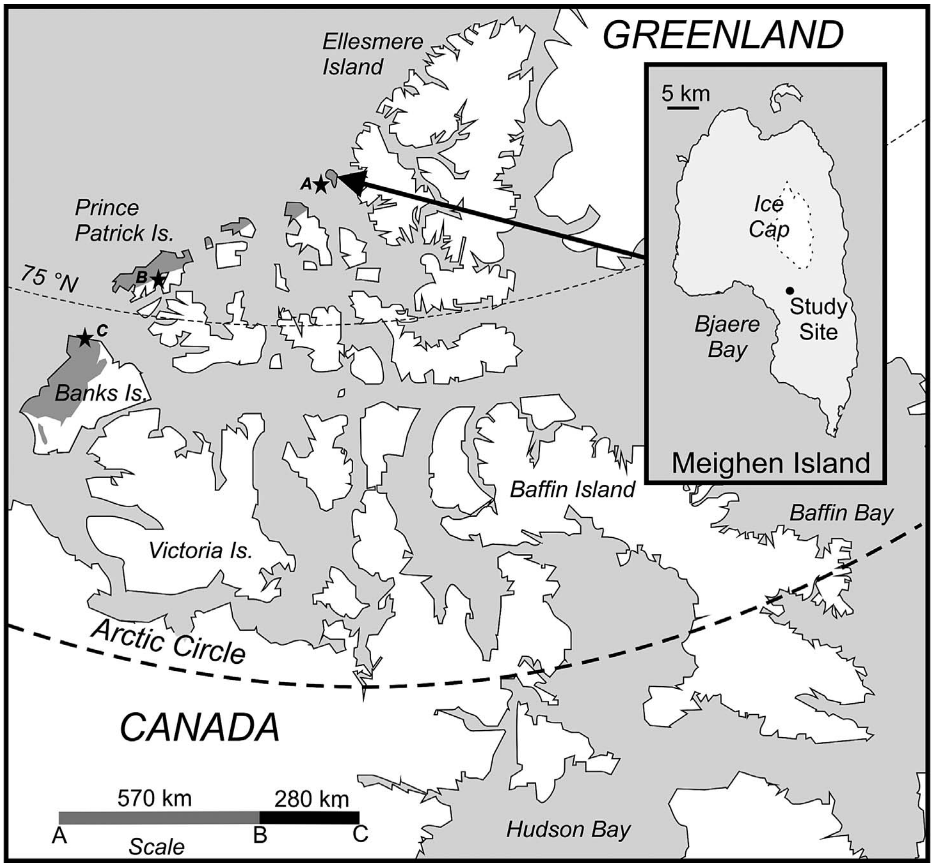

FIG. 1.—Beaufort Formation outcrop in the Canadian High Arctic, with location of Meighen Island shown in inset. Map shows the approximate extent of the Pliocene Beaufort Formation relative to the study area on Meighen Island. Lettered localities refer to examples of cross-bedded woody debris recorded in this (A) and previous (B, C) studies (Devaney 1991; Murphy 2006).

The peat lenses also contain a diverse assemblage of insect fossils (Elias and Matthews 2002). *In situ* fossil forests of a similar boreal-type composition are known from a number of Neogene localities in the Canadian High Arctic (Matthews and Ovenden 1990), including in the Miocene Ballast Brook Formation on Banks Island (Williams et al. 2008) and the terrace gravels hosting the mid-Pliocene Beaver Pond and Fyles Leaf Bed localities at Strathcona Fiord, Ellesmere Island (Matthews and Fyles 2000; Csank et al. 2011; Rybczynski et al. 2013).

There are no standing fossil trees as yet known from the Beaufort Formation, but well-preserved and abundant woody debris from these forests has long been recognized as a conspicuous sedimentary characteristic of the formation across its outcrop belt (Tozer 1956; Devaney 1991; Fyles et al. 1994; Murphy 2006). On Meighen Island, woody debris is common and distributed throughout the Beaufort Formation, often forming distinct stratigraphic horizons with little clastic material: of particular note, one (apparently non-cross-bedded) woody debris horizon at the main study site is at least 48 m wide and 30 to 50 cm thick (Fig. 2A, B). The vast majority of the material is fine woody debris (FWD), defined as being less than 2.5 cm diameter (Harmon et al. 1986), but very rare isolated logs (coarse or large woody debris) are also present (Fig. 2C). Some of the coarse woody debris exhibits preserved articulated branches, little evidence of abrasion in moving water, and, rarely, the presence of bark (Fig. 2D). Such deposits are unlikely to have been transported far by the Beaufort Formation river system and may have entered channels through windthrow, toppling deadwood, or due to bank collapse and floodplain erosion (Braudrick et al. 1997).

CROSS-BEDDED WOODY DEBRIS

The cross-bedded woody debris described herein comes from the most well-exposed section of the formation on Meighen Island: two vertical outcrops of approximately the same 27-m-thick stratigraphic level, which form opposite valley walls to a recent stream incision, located in the southwest of the island approximately 2 km east of Bjaere Bay (Fig. 1), and previously referred to as "The Gap" (Fyles et al. 1991). Other localities across the island contain lenses or horizons of woody debris, which, due to exposure constraints, are less well defined in terms of their geometry and internal structure. Although some of these are suspected to be cross-bedded (perhaps not obvious in exposures cut across the strike of paleoflow), due to their inferior preservation and the uncertainty of their stratigraphic relationship to the main study site, they are not discussed in this paper. Seven specific lenses of cross-bedded woody debris thus form the focus of the following description, four of which (I–IV) are located on the eastern valley wall (Fig. 3A), and three of which (V–VII) are located on the western wall of The Gap (Fig. 2A). All the lenses occur encased in sand-dominated facies, interpreted to have been deposited by the downstream migration of mid-channel bars within braided fluvial channels (Fig. 3A), and the deposits of woody debris typically extend laterally for 3 m or less within these before they pass abruptly or gradationally into cross-stratified sands. The true width:depth ratio of the lenses is hard to determine, because the cross-bedding is clearly apparent only in profiles that happen to be cut almost parallel to paleoflow direction.

The woody debris that constitutes the cross-bedded debris horizons is typically smaller and less well preserved than in most of the non-cross-bedded wood accumulations, and appears more water-worn and often blackened. The blackened color appears to be a result of partial decomposition; we saw no evidence of charcoal or burning in any of the lenses. The FWD is composed entirely of mechanically broken twigs with no articulated branches, bark, or log material: terminations of the twigs in both cross-bedded and non-cross-bedded accumulations of

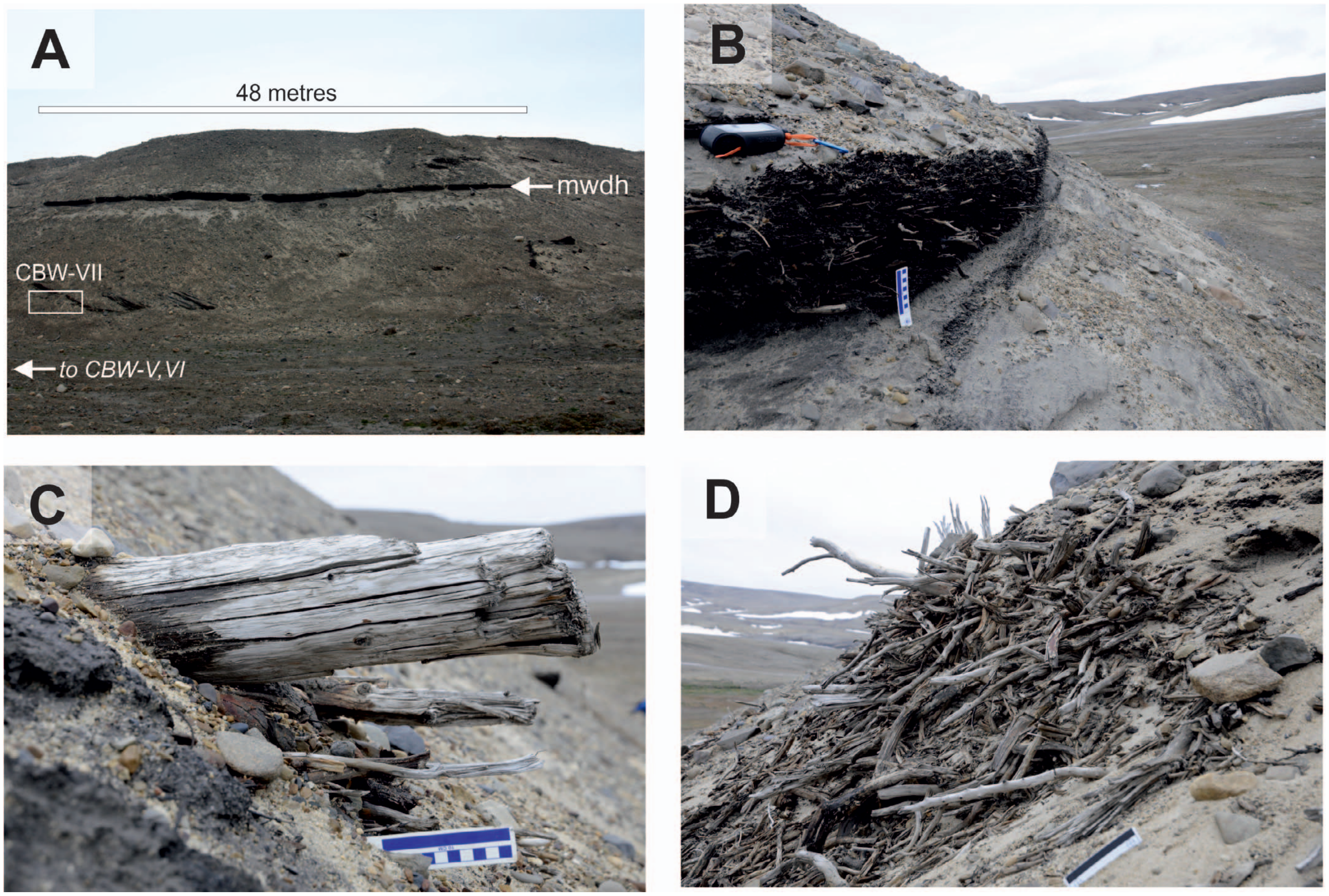

FIG. 2.—Woody debris from polar forests. **A)** Major (48 m wide, 0.5 m thick) horizon consisting entirely of fine woody debris (mwdh) in braided alluvium of the Beaufort Formation on Meighen Island. Photograph taken looking towards western side of The Gap; also shown are relative locations of cross-bedded horizons of woody debris (see Fig. 3). **B)** Detail of the horizon in Part A, showing it to be completely composed of water-worn fine woody debris. Scale is 10 cm. **C)** Rare instance of isolated coarse woody debris, bark partially preserved. Scale is 10 cm. **D)** Accumulation of apparently randomly oriented woody debris exhibiting some branch articulation. Scale is 10 cm.

woody debris were routinely and thoroughly checked for evidence of beaver-cutting (Rybczynski 2008), but none was witnessed. The major 48-m-long, 50-cm-thick woody horizon (Fig. 2B), located on the western wall of the main study site, could not be conclusively determined to be cross-bedded, though it is composed of the same type of woody debris as the cross-bedded lenses.

There is some variation in the lenses of cross-bedded woody debris, notably in the ratio of actual wood material to sand that comprises them, the size of the constituent woody debris, and the geometry of the lenses. Brief descriptions of each of the examples follow:

CBW-I (Fig. 3B): 50 cm of apparently planar cross-bedded woody debris extending laterally for 3 m, with a minor component ($< 5\%$) of sand across some foresets. The debris horizon has an unscoured base, resting on top of a thin rippled silt horizon, which itself marks the fining upwards of a series of cross-bedded sands, with occasional pebbly foresets. The sandy cross-strata show a northwards paleoflow direction, slightly oblique to the orientation of the long axes of the woody debris. As with all the cross-bedded woody debris horizons, it proved impossible to excavate a measurable foreset surface in the more woody cross-strata, but the apparent dip of the foresets was accordant with the underlying sands. Woody particles were mostly 1 to 5 cm in length, though isolated twigs up to 30 cm were also present.

CBW-II (Fig. 3C): 50 cm at its deepest point, this 3-meter-long lens seemingly filled a gentle scour hollow. The horizon contained 5–10% sand across its foresets, and wood particles averaged 3 cm in length, with some up to 7 cm. Above CBW-II, a 2-m-thick cross-bedded sand unit contains isolated woody fragments and passes upwards into an 80-cm-thick scour filled with very fine (< 2 cm) fragments of wood, peat, and comminuted vegetative matter, with no evident cross-bedding.

CBW-III (Fig. 3D): 2.5-m-long by 80-cm-thick lens of larger wood fragments (typically 4 to 10 cm, up to 38 cm) filling a discrete scour and with almost no sand. The lens is scoured into a pebbly sand with reworked mudclasts. The woody debris is oriented in the same direction as CBW-I.

CBW-IV (Fig. 3E): Approximately 1 m below CBW-III, here woody debris foresets alternate with sandy foresets (accounting for 50%) of the cross-bedded unit. Down-dip, woody debris becomes more infrequent, and the horizon passes laterally into cross-bedded sands with very little woody material.

CBW-V (Fig. 3F): Low-angle planar cross-bedded woody debris, comprising two distinct foresets (< 20 cm total thickness) in cross-bedded sands.

CBW-VI (Fig. 3G–H): 60 cm thickness of cross-bedded woody debris with no sand present. Woody debris ranged in length from 1 to 44 cm,

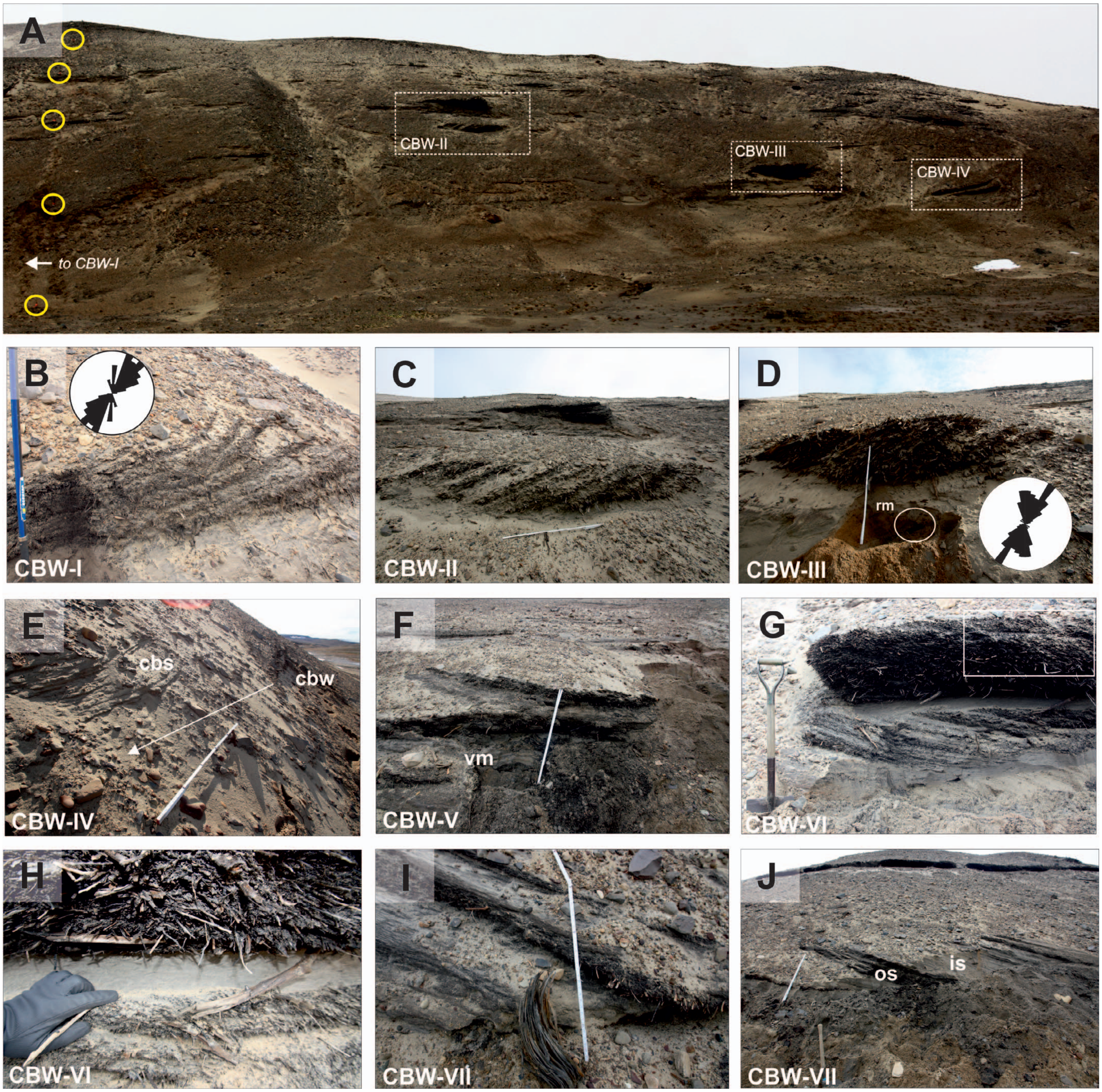

FIG. 3.—Cross-bedded woody debris in the Beaufort Formation. **A)** Photograph of outcrop of braided alluvium in the Beaufort Formation on Meighen Island (marker ribbons, highlighted, are spaced at 5 m vertical intervals; photograph was taken looking towards east side of The Gap). Relative location of cross-bedded woody debris horizons are highlighted. **B)** CBW-I: Cross-bedded woody debris with accessory sand (contrast the fresh cut in the left of the image with the wash-covered surface) showing axial orientation of individual twigs in the cross-beds (rose diagram: n96). **C)** CBW-II: Cross-bedded woody debris with some sand along foresets (appearing exaggerated in this image due to wash from above layers). Measuring stick is 1 meter. **D)** CBW-III: Scour fill of cross-bedded woody debris with very little inorganic material; underlying layers contain reworked muds (rm) (rose diagram [n100] records axial orientation of individual twigs in the cross-beds, slightly oblique to apparent northwards flow direction). Measuring stick is 1 meter. **E)** CBW-IV: Example of cross-bedded woody debris (cbw) that apparently passes into typical cross-bedded sand (cbs) down-dip along its apparent paleoflow direction (arrowed). Measuring stick is 1 m. **F)** CBW-V: Two low-angle foresets composed entirely of woody debris, in sandy cross-bedding rich in comminuted vegetative matter (vm). Measuring stick is 80 cm. **G)** CBW-VI: Lower unit exhibits sandy cross-bedding with a subsidiary component of woody debris along foresets, while upper cross-bedded unit consists entirely of wood debris; seen best in the highlighted area where sand wash from above has picked out the foresets. **H)** CBW-VI: Detail of base of unit shown in Part G, showing how cross-bedding in the overlying wood-rich unit is not apparent where washed sand has not picked out foresets. **I)** CBW VII: Thick forest composed almost entirely of woody debris, similar to CBW-V. Lower part of measuring stick is 80 cm. **J)** CBW-VII: Detail of cross-bedded sands passing down-dip from foreset shown in Part I, showing cross-bedded inorganic sands (is) alternating with cross-bedded sands rich in comminuted organic detritus (os). Measuring stick is 80 cm.

TABLE 1.—*Air-dry densities of the wood genera that constituted the Beaufort Formation boreal-type forest, relative to water density at 4 °C (wood data from Zanne et al. 2009).*

	Density (kg/m^3)
WATER	*1000*
Birch	450–660
Larch	389–599
Pine	370–680
Alder	350–459
Poplar	310–494
Eastern Cedar	290
Spruce	266–455

with a mean length of 10 cm. No scouring evident; its tabular base rests on top of cross-bedded sand that is rich in woody debris (30–40%).

CBW-VII (Fig. 3I–J): Isolated pronounced foresets of pure woody debris, in cross-bedded sands that exhibit a black color due to extensive organic content.

The woody debris in all of the lenses is well sorted, and there appears to be a correlation between the proportion of sand in the woody cross-strata and the "grain size" (i.e., length, diameter) of the woody debris. Samples of twigs from the sand-poor cross-bedded lenses (CBW-I, -II, -III, -VI) ranged in length from 1 to 44 cm, whereas sand-rich cross-bedded lenses (CBW-IV, -V, -VII) yielded twigs that ranged in length from 1 to 30 cm.

All of the cross-bedded lenses described above are interpreted to record the shallow subaqueous migration of small, two-dimensional bedforms (transversely oriented dunes) within a distal braided stream setting. However, because cross-bedding records the current deposition of bedload sediments (Allen 1984), its formation requires that the sedimentary particles involved were denser than the fluid which transported them. The presence of cross-bedded sets that are entirely or partially composed of FWD particles is therefore indicative of an abundance of woody debris material that was denser than the moving water in which it was deposited. The density of water (at a temperature of 4° C) is 1000 kg/m^3, and this density only ever decreases slightly, to 958 kg/m^3, when it reaches 100 °C or approximately 917 kg/m^3 when in the form of ice. No density within this range of water phases would be sufficient for air-dry wood from a boreal-type forest to be transported as bedload (Table 1) (Chave et al. 2009; Zanne et al. 2009). Because the formation of cross-bedding requires subaqueous bedload transport, it seems apparent that the woody debris in the Beaufort Formation must have become denser than water before or during its entrainment as sedimentary particles. Cross sections of the woody fragments are generally circular and exhibit no indication of strain due to extension (due to freezing) or compression prior to deposition, and no mineral replacement is evident—the wood is burnable. Ruling out physiological and mineral-replacement hypotheses, it seems most likely that densification was achieved by saturation, because saturated wood has an effective density that is greater than water and can sometimes remain as intact particulate sediment even when submerged (Montgomery et al. 2003).

GLOBAL STRATIGRAPHIC DISTRIBUTION OF CROSS-BEDDED WOODY DEBRIS

Woody debris has been a sizeable sediment component and a significant geomorphic agent in many pristine fluvial systems since the Devonian, and fossil wood material is a commonly recorded feature in worldwide alluvial facies of late Paleozoic, Mesozoic, and Cenozoic age (Gibling and Davies 2012; Davies and Gibling 2013). Subsequent to the discovery of cross-bedded woody debris on Meighen Island, an intensive search of databases of published (English-language) literature was conducted in order to find analogous reports of the bedform from elsewhere in the stratigraphic record (using Web of Science [http://wok.mimas.ac.uk/] and online search engines). Remarkably, however, the results of this literature search have shown that the only other recorded observations of cross-bedded fine woody debris, in the entire global Phanerozoic sedimentary record, have been independently made from other more southerly Beaufort Formation exposures elsewhere in the Canadian Arctic. Devaney (1991, p. 210) reported that "one example of a cross-bedded wood bed was seen" in the Beaufort Formation on Prince Patrick Island, c. 570 km southwest of Meighen Island, while Murphy (2006, p. 22) recorded three lenses of woody debris with "internal layering which separates lenses into separate beds that dip approximately 15–30° downstream in paleoflow" from Banks Island, c. 840 km southwest of Meighen Island (Fig. 1). The significance of the rarity of these instances has not previously been noted, but taken together with the Meighen Island examples they demonstrate that while patches of cross-bedded woody debris were evidently extensively distributed across the Beaufort alluvial plain in the Pliocene High Arctic, particularly so in its more northern portion, there has seemingly been no other recorded occurrence of the bedform in the entire worldwide stratigraphic record. The structure is even currently unknown from other Cenozoic North American Arctic polar forest-bearing formations (e.g., Francis 1988; Fyles et al. 1994; Williams et al. 2008); such units may contain cross-bedding with foreset drapes of comminuted organic matter (Fig. 4), but none, to date, have been recorded which are composed solely or largely of fine woody debris.

FIG. 4.—Typical cross-bedded vegetative matter from the Miocene Ballast Brook Formation, Banks Island. Foresets are draped with flakes of comminuted organic material, but fine woody debris is absent or occurs only as isolated very small diameter individual twigs or stems. Pen for scale is 16 cm.

Further illustrating the exceptional nature of the deposits, modern occurrences of cross-bedded woody debris are also unknown. In present-day freshwater settings, woody debris in cross-strata is usually comminuted and restricted to drapes on toesets and topsets (Spicer and Wolfe 1987), and any saturated plant debris in alluvium is typically isolated within sand, with twigs oriented oblique to flow (Alexander et al. 1999). Furthermore, most fluvial wood is destroyed by decomposition or abrasion within years (Melillo et al. 1993; Hyatt and Naiman 2001), with longer residence times permitted only where wood pieces are large enough to become lodged within channels and avoid being flushed from the system (Collins et al. 2012). Saturated woody debris is sometimes preserved as sunken wood in marine settings in the geological record, but it tends to have little depositional fabric and is typically found in association with marine fossils or wood borings (Kaim 2011).

To our knowledge, there is thus no material in either the stratigraphic record or modern sedimentary environments that is comparable to the cross-bedded woody debris in the Beaufort Formation. It is arguable that this spatiotemporal restriction is an artifact of such deposits being overlooked or underreported in previous studies, but the fact that the only previously recorded instances have transpired to have been made independently from other Beaufort Formation localities is striking.

DISCUSSION AND POTENTIAL IMPLICATIONS

In light of the present absence of evidence for cross-bedded woody debris in strata from other climatic zones or ages, an explanation is proposed that could account for both the geographic extent and stratigraphic restriction of bedload transported, saturated, cross-bedded woody debris, deposited in the Pliocene across at least 840 km of the Canadian Arctic (with most of the examples being recorded from the northernmost locality on Meighen Island). The issue of apparent spatiotemporal uniqueness, combined with the fact that wood is acting as an unusually abundant and dense sedimentary particle, strongly intimates that an explanation might be found in the non-uniformitarian nature of the extreme high-latitude forests that existed in the northern polar region during the Pliocene. Such biomes endured hostile photosynthetic conditions during winter darkness, incomparable to those imposed on extant boreal forests at more southern latitudes. During a present-day annual cycle, for example, Meighen Island receives 134 days of persistent light and 119 days of persistent darkness (there would have been minor deviation from this during the Pliocene, but imprecise dating of the succession means that accounting for Milankovitch cyclicity is not currently possible). This light and temperature regime may have promoted a rapid turnover of tree populations in forests. Short growing seasons would have limited photosynthetic carbon acquisition and reserves, and this could possibly have reduced the percentage of trees that survived each long polar winter (Creber and Challinor 1985; Beerling and Osborne 2002). In subsequent spring seasons, new trees could have occupied the space previously utilized by the previous winter's deadfall, resulting in relatively young forests with a large amount of litter on forest floors. Although this possibly enhanced mortality of trees remains uncertain, the decay and recycling of detrital wood in the polar forests would certainly have been severely inhibited. Mechanical breakdown (e.g., by wind) of any standing deadwood in the polar forests would have provided a constant and elevated supply of woody debris onto floodplains. Perhaps most significantly, the persistent winter darkness and resulting cold, damp conditions would together have minimized the efficacy of bacterial decomposition (Heal et al. 1981; Berg et al. 1998), thus enabling uniquely exceptional quantities of detrital wood to temporarily accumulate and then become saturated on floodplains. This could potentially explain how there could be mass saturation of woody debris in the system, with less of the attendant decay (and subsequent biological or mechanical destruction) that usually limits the contribution of submerged woody debris as particulate matter in the preserved sedimentary record (Spänhoff et al. 2001). Subsequent entrainment of these exceptional accumulations by incision and bank collapse of floodplain storage areas would have ensured a sizeable supply of fine woody debris, often with a density greater than water, into the Beaufort Formation river channels.

This interpretation potentially explains a type of woody sedimentary structure that is, at present, apparently unique to forested Arctic river systems. A better understanding of the stratigraphic distribution of cross-bedded woody debris is necessary. If cross-bedded woody debris is truly indicative of polar forest alluvium, then it should arguably be expected to be found in some of the many other sedimentary successions that record the intermittent emergence of polar forest biomes throughout the Mesozoic and early Cenozoic (Spicer and Chapman 1990; Abbott 2008). The sedimentological signature of the bedform in older strata will potentially be less obvious than in the Beaufort Formation due to the effects of diagenetic compaction and the limited long-term preservation potential of buried woody debris in the rock record (Davies and Gibling 2013), and such features may thus have potentially been overlooked in previous studies. Alternatively, the anomalously large amount of undecomposed wood in the Beaufort Formation may reflect a genuine peak in preserved polar woody debris in the Pliocene, potentially reflecting a marked contrast in decomposition when compared to polar forests from exceptionally warm intervals (e.g., of the Eocene), where mean annual temperature was significantly above freezing and sufficient to sustain high rates of methanogenesis (Jahren 2007), removing woody debris from the sedimentary system. If this is true, then the Beaufort Formation may record an interval where polar forests operated within a narrow window of conditions pertaining to cold temperatures, darkness, and a lack of decomposition, distinguishing it from other Cenozoic North American Arctic polar forest-bearing formations where elevated temperatures, such as for the Eocene Strathcona Fiord section of the Eureka Sound Group (Francis 1988), or light regimes, such as for the Miocene Ballast Brook Formation (Williams et al. 2008; Fig. 4), promoted the advanced decomposition of fine woody debris before it could become saturated and transported as bedload.

If it is truly as restricted as seems apparent, cross-bedded woody debris may potentially be able to provide insights into particular conditions of limited decomposition and natural carbon burial during warm Arctic conditions. Further observations are encouraged to test the apparent geographic and stratigraphic restriction of a sedimentary structure which could potentially have relevance to improving our understanding of the dynamics and nutrient cycling of past (and future) polar-latitude forests.

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REFERENCES

Abbott, R.J., 2008, History, evolution and future of arctic and alpine flora: overview: Plant Ecology and Diversity, v. 1, p. 129–133.

Alexander, J., Fielding, C.R., and Jenkins, G., 1999, Plant-material deposition in the tropical Burdekin River, Australia: implications for ancient fluvial sediments: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 153, p. 105–125.

Allen, J.R.L., 1984, Sedimentary Structures: Their Character and Physical Basis: Amsterdam, Elsevier, 663 p.

Beerling, D.J., and Osborne, C.P., 2002, Physiological ecology of Mesozoic polar forests in a high CO_2 environment: Annals of Botany, v. 89, p. 329–339.

Berg, B., Johansson, M.-B., Meentemeyer, V., and Kratz, W., 1998, Decomposition of tree root litter in a climatic transect of coniferous forests in Northern Europe: a synthesis: Scandinavian Journal of Forest Research, v. 13, p. 402–412.

Braudrick, C.A., Grant, G.E., Ishikawa, Y., and Ikeda, H., 1997, Dynamics of wood transport in streams: a flume experiment: Earth Surface Processes and Landforms, v. 22, p. 669–683.

Brent, T.A., and Embrv, A.F., 1995, Stratigraphy and structure of Meighen Island, Canadian Arctic Archipelago: Geological Survey of Canada, Proceedings of the Oil and Gas Forum, Open File, v. 3058, p. 163–168.

Chave, J., Coomes, D., Jansen, S., Lewis, S.L., Swenson, N.G., and Zanne, A.E., 2009, Towards a worldwide wood economics spectrum: Ecology Letters, v. 12, p. 351–366.

Collins, B.D., Montgomery, D.R., Fetherston, K.L., and Abbe, T.B., 2012, The floodplain large-wood cycle hypothesis: a mechanism for the physical and biotic structuring of temperate forested alluvial valleys in the North Pacific coastal ecoregion: Geomorphology, v. 139–140, p. 460–470.

CREBER, G.T., AND CHALLINOR, W.G., 1985, Tree growth in the Mesozoic and early Tertiary and the reconstruction of palaeoclimates: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 52, p. 35–60.

CSANK, A.Z., PATTERSON, W.P., EGLINGTON, B.M., RYBCZYNSKI, N., AND BASINGER, J.F., 2011, Climate variability in the Early Pliocene Arctic: annually resolved evidence from stable isotope values of sub-fossil wood, Ellesmere Island, Canada: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 308, p. 339–349.

DAVIES, N.S., AND GIBLING, M.R., 2013, The sedimentary record of Carboniferous rivers: continuing influence of land plant evolution on alluvial processes and Palaeozoic ecosystems: Earth-Science Reviews, v. 120, p. 40–79.

DEVANEY, J.R., 1991, Clastic sedimentology of the Beaufort Formation, Prince Patrick Island, Canadian Arctic islands: late Tertiary sandy braided river deposits with woody detritus beds: Arctic, v. 44, p. 206–216.

ELIAS, S.A., AND MATTHEWS J.V., JR., 2002, Arctic North American seasonal temperatures in the Pliocene and early Pleistocene, based on mutual climatic range analysis of fossil beetle assemblages: Canadian Journal of Earth Sciences, v. 39, p. 911–920.

FRANCIS, J.E., 1988, A 50-million-year-old fossil forest from Strathcona Fiord, Ellesmere Island, Arctic Canada: evidence for a warm polar climate: Arctic, v. 41, p. 314–318.

FYLES, J.G., 1990, Beaufort Formation (late Tertiary) as seen from Prince Patrick Island, Arctic Canada: Arctic, v. 43, p. 393–403.

FYLES, J.G., MARINCOVICH, L., JR., MATTHEWS, J.V., JR., AND BARENDREGT, R., 1991, Unique mollusk find in the Beaufort Formation (Pliocene) on Meighen Island, Arctic Canada: Geological Survey of Canada, Current Research, Part B, v. 91-1B, p. 105–112.

FYLES, J.G., HILLS, L.V., MATTHEWS, J.V., JR., BARENDREGT, R., BAKER, J., IRVING, E., AND JETTÉ, H., 1994, Ballast Brook and Beaufort formations (Late Tertiary) on northern Banks Island, Arctic Canada: Quaternary International, v. 22–23, p. 141–171.

GIBLING, M.R., AND DAVIES, N.S., 2012, Palaeozoic landscapes shaped by plant evolution: Nature Geoscience, v. 5, p. 99–105.

HARMON, M.E., FRANKLIN, J.F., SWANSON, F.J., SOLLINS, P., GREGORY, S.V., LATTIN, J.D., ANDERSON, N.H., CLINE, S.P., AUMEN, N.G., SEDELL, J.R., LIENKAEMPER, G.W., CROMACK, K., JR., AND CUMMINS, K.W., 1986, Ecology of coarse woody debris in temperate ecosystems: Advances in Ecological Research, v. 15, p. 133–301.

HEAL, O.W., FLANAGAN, P.W., FRENCH, D.D., AND MACLEAN, S.F., JR., 1981, Decomposition and accumulation of organic matter, *in* Bliss, L.C., Heal, O.W., and Moore, J.J., eds., Tundra Ecosystems: A Comparative Analysis: Cambridge, Cambridge University Press, p. 127–134.

HYATT, T.L., AND NAIMAN, R.J., 2001, The residence time of large woody debris in the Queets River, Washington, USA: Ecological Applications, v. 11, p. 191–202.

JAHREN, A.H., 2007, The Arctic forest of the Middle Eocene: Annual Review of Earth and Planetary Sciences, v. 35, p. 509–540.

KAIM, A., 2011, Non-actualistic wood-fall association from Middle Jurassic of Poland: Lethaia, v. 44, p. 109–124.

KUC, M., 1973, Bryogeography of Expedition Area, Axel Heiberg Island, N.W.T., Canada: Lehre, J. Cramer, 120 p.

MATTHEWS, J.V., JR., 1987, Plant macrofossils from the Neogene Beaufort Formation on Banks and Meighen islands, District of Franklin: Geological Survey of Canada, Paper 87-1A, p. 73–87.

MATTHEWS, J.V., JR., AND FYLES, J.G., 2000, Late Tertiary plant and arthropod fossils from the high-terrace sediments on the Fosheim Peninsula of Ellesmere Island (Northwest Territories, District of Franklin): Geological Survey of Canada, Bulletin 529, p. 295–317.

MATTHEWS, J.V., JR., AND OVENDEN, L.E., 1990, Late Tertiary plant macrofossils from localities in arctic/subarctic North America: a review of the data: Arctic, v. 43, p. 364–392.

MELILLO, J.M., NAIMAN, R.J., ABER, J.D., AND ESHLEMAN, K.N., 1983, The influence of substrate quality and stream size on wood decomposition dynamics: Oecologia, v. 38, p. 281–285.

MONTGOMERY, D.R., COLLINS, B.D., BUFFINGTON, J.M., AND ABBE, T.B., 2003, Geomorphic effects of wood in rivers, *in* Gregory, S.V., Boyer, K.L., and Gurnell, A.M., eds., The Ecology and Management of Wood in World Rivers: American Fisheries Society, Symposium 37, p. 21–48.

MURPHY, J., 2006, Woody debris lenses: paleoenvironmental archives: Keck Symposium, v. 19, p. 20–25.

RYBCZYNSKI, N., 2008, Woodcutting behavior in beavers (Castoridae, Rodentia): estimating ecological performance in a modern and a fossil taxon: Paleobiology, v. 34, p. 389–402.

RYBCZYNSKI, N., GOSSE, J.C., HARINGTON, C.R., WOGELIUS, R.A., HIDY, A.J., AND BUCKLEY, M., 2013, Mid-Pliocene warm-period deposits in the High Arctic yield insight into camel evolution: Nature Communications, v. 4, doi: 10.1038/ncomms2516.

SPÄNHOFF, B., ALECKE, C., AND MEYER, E.I., 2001, Simple method for rating the decay stages of submerged woody debris: Journal of the North American Benthological Society, v. 20, p. 385–394.

SPICER, R.A., AND CHAPMAN, J.L., 1990, Climate change and the evolution of high-latitude terrestrial vegetation and floras: Trends in Ecology and Evolution, v. 5, p. 279–284.

SPICER, R.A., AND WOLFE J.A., 1987, Plant taphonomy of late Holocene deposits in Trinity (Clair Engle) Lake, northern California: Paleobiology, v. 13, p. 227–245.

THORSTEINSSON, R., 1960, The History and Geology of Meighen Island, Arctic Archipelago: Geological Survey of Canada, Bulletin 75, p. 1–19.

TOZER, E.T., 1956, Geological reconnaissance of Prince Patrick Island, Eglinton and western Melville Islands, Arctic Archipelago, Northwest Territories: Geological Survey of Canada, Paper, v. 55-5, p. 1–32.

WILLIAMS, C.J., MENDELL, E.K., MURPHY, J., COURT, W.M., JOHNSON, A.H., AND RICHTER, S.L., 2008, Paleoenvironmental reconstruction of a Middle Miocene forest from the western Canadian Arctic: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 261, p. 160–176.

ZANNE, A.E., LOPEZ-GONZALEZ, G., COOMES, D.A., ILIC, J., JANSEN, S., LEWIS, S.L., MILLER, R.B., SWENSON, N.G., WIEMANN, M.C., AND CHAVE, J., 2009, Data from: Towards a worldwide wood economics spectrum: Dryad Digital Repository, doi: 10.5061/dryad.234.

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