WOOD JAMS OR BEAVER DAMS? PLIOCENE LIFE, SEDIMENT AND LANDSCAPE INTERACTIONS IN THE CANADIAN HIGH ARCTIC

NEIL S. DAVIES[1], JOHN C. GOSSE[2], ALEXANDRA ROUILLARD[3,4], NATALIA RYBCZYNSKI[5,6], JIN MENG[7], ALBERTO V. REYES[8] and JARLOO KIGUKTAK[9]

[1]Department of Earth Sciences, University of Cambridge, Downing Street, Cambridge CB2 3EQ, United Kingdom.

[2]Department of Earth and Environmental Sciences, Dalhousie University, Halifax, Nova Scotia B3H 4R2, Canada.

[3]Lundbeck Foundation GeoGenetics Centre, GLOBE Institute, University of Copenhagen, Copenhagen, Denmark.

[4]Department of Geosciences, UiT—The Arctic University of Norway, Tromsø, Norway.

[5]Department of Palaeobiology, Canadian Museum of Nature, Ottawa, Ontario K1P 6P4, Canada.

[6]Department of Biology & Department of Earth Sciences, Carleton University, Ottawa, Ontario K1S 5B6, Canada.

[7]Division of Paleontology, American Museum of Natural History, New York, NY, USA.

[8]Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, T6G 2E3, Canada.

[9]Grise Fiord, Nunavut, X0A 0J0, Canada.

RRH: PLIOCENE HIGH ARCTIC LIFE-SEDIMENT INTERACTIONS

LRH: DAVIES ET AL.

ABSTRACT

During the mid-Pliocene (Zanclean, ca. ~3.9 Ma), parts of the Canadian High Arctic experienced mean annual temperatures that were 14-22°C warmer than today and supported diverse boreal-type forests. The landscapes of this vegetated polar region left behind a fragmented sedimentary record that crops out across several islands in the Canadian Arctic Archipelago as the Beaufort Formation and correlative strata. Paleoecological information from these strata provides a high-fidelity window onto Pliocene environments, and prominent fossil sites yield unparalleled insights into Cenozoic mammal evolution. Significantly, many of the strata reveal evidence for life-sediment interactions in a warm-climate Arctic, most notably in the form of extensive woody debris and phytoclast deposits. This paper presents original field data that refines the sedimentological context of plant debris accumulations from the anactualistic High Arctic forests, most notably at the 'Fyles Leaf Beds' and 'Beaver Pond' fossil-bearing sites in the 'high terrace deposits' of central Ellesmere Island. The former is a remarkably well-preserved, leaf-rich deposit that is part of a complex of facies associations representing lacustrine, fluvio-deltaic and mire deposition above a paleotopographic unconformity. The latter yields tooth-marked woody debris within a peat layer that also contains a rich assemblage of vertebrate and plant fossils including abundant remains from the extinct beaver-group *Dipoides*. Here we present sedimentological data that provide circumstantial evidence that the woody debris deposit at Beaver Pond could record dam-building in the genus, by comparing the facies motif with new data from known Holocene beaver dam facies in England. Across the Pliocene of the High Arctic region, woody debris accumulations are shown to represent an array of biosedimentary deposits and landforms including mires, driftcretions, woody bedforms, and possible beaver dams, which help to contextualize mammal fossil sites, provide facies models for

high-latitude forests, and reveal interactions between life and sedimentation in a vanished world that may be an analogue to that of the near-future.

INTRODUCTION

The Pliocene (5.3-2.6 Ma) is a phase of geological history that has strong potential analogue for near-future Earth climate (Burke et al., 2018). The epoch witnessed analogous CO_2 concentrations to present (365 to 415 ppm; Pagani et al., 2010) and was the most recent interval during which global temperatures exceeded those of today for a sustained interval (Ballantyne et al. 2010), with a similar continental geography to modern-day Earth (Torsvik and Cocks, 2016). Elevated global temperatures were exacerbated in Arctic regions due to an asymmetrical latitudinal temperature gradient that developed as the result of increased poleward heat transport and decreased albedo (Ballantyne et al., 2010). Mean annual temperature was likely particularly amplified in the region corresponding to the present-day Canadian Arctic Archipelago because the Pliocene landmass was mostly contiguous. The lack of inter-island channels and lower sea-ice cover would have collectively resulted in a more continental climate (Ballantyne et al., 2010; Fletcher et al., 2017; Gosse et al., 2017). Accordingly, Pliocene paleo-MAT (mean annual temperature) in the Canadian High Arctic has been estimated at 14-22°C warmer than present (Ballantyne et al. 2006, 2010; Csank et al. 2011; Fletcher et al., 2017), and a latitudinal paleo-treeline was sustained at least as far north as 80°N (Fyles 1990; Elias and Matthews 2002; Fletcher et al., 2017).

There has been a wealth of paleontological investigation into the fossil flora and fauna of High Arctic Pliocene strata. Reported plant fossils include those typical of boreal-type forest settings, and include species of pine, fir, birch, hazel, willow, poplar, alder, hemlock, spruce, larch, oak, elm, hornbeam and hickory in both shrub and tree form, as well as eastern juniper, which at present is a more southerly taxon not found in boreal forests (Matthews and Ovenden 1990;

Fletcher et al., 2021a). Faunal assemblages are known to include a variety of terrestrial and aquatic invertebrate species (Fyles et al., 1991; Elias and Matthews, 2002), vertebrate fossils of teleost fish, scaup duck and frog (Murray et al., 2009; Gosse et al., 2017), and a particularly diverse and striking mammal fauna that includes bear, horse, deerlet, badger, rabbit, shrew, beaver and camel fossils (Hutchison and Harington, 2002; Tedford and Harington, 2003; Dawson and Harington, 2007; Murray et al., 2009; Rybczynski et al., 2013).

While the plants, insects and larger vertebrates of the Pliocene Arctic boreal forests are well known, comparatively little work has been completed on sedimentological aspects of the fossil sites (Davies et al., 2014; Mitchell et al., 2016; Barendregt et al., 2021), which has the potential to inform on both paleohydraulic conditions and the nature of organism-sediment and organism-organism interactions in this anactualistic (i.e., without modern analogue) ecosystem. In this paper we describe the sedimentological context of a number of woody debris and phytoclast deposits that occur at two sites within the 'high terrace deposits' of Ellesmere Island in the Canadian Arctic Archipelago. We first discuss the geological context of the study sites ('Fyles Leaf Beds' and 'Beaver Pond') before cataloguing characteristics of plant debris accumulations, including phytoclast-lined clinoforms and laminated organic-rich deposits, which frequently reveal evidence of interactions between different types of organisms. Individually, these instances provide snapshots of interactions between organisms and Earth surface processes. We subsequently present evidence from woody debris accumulations suggesting a variety of formational origins. We assess evidence that suggests that beaver-cut wood at the Beaver Pond site may represent constructional behaviour by the extinct genus *Dipoides* (Rybczynski, 2008). Such evidence has previously been considered underdetermined (Mitchell et al., 2016) or unlikely (Plint et al., 2020), but we compare sedimentary facies evidence with new data from a case study of definitive Holocene beaver dam facies (Skipsea Withow, NE England) and suggest a suite of circumstantial sedimentological evidence that may support convergent evolution of dam-building behaviour in *Dipoides* and *Castor*. Finally, we synthesize the reported observations to demonstrate how the suite of snapshots of life-sediment interaction can be combined to refine the paleoenvironmental context of key Pliocene fossil sites in the region.

THE HIGH TERRACE DEPOSITS OF ELLESMERE ISLAND

The strata described here belong to the 'high terrace deposits' of Ellesmere Island, an informal stratigraphic term for scattered Pliocene sedimentary outcrops in the eastern Canadian Arctic Archipelago (Fyles, 1989) (Figure 1). Pliocene strata in the Canadian Arctic Archipelago have been described and studied since the 19th century (Mecham 1855, Heer 1868), but their stratigraphic framework was not delineated until Tozer (1956) defined the Beaufort Formation to account for distinct fluvial strata in the region. The definition of the Beaufort Formation was subsequently modified by Fyles et al. (1994) to specifically refer to outcrops along the western Canadian Arctic, which constitute a suite of coastal plain fluvial facies (Devaney, 1991). The Beaufort Formation remains a key reference anchor for Pliocene stratigraphy in the region, correlating north-westwards to equivalent marine strata within the offshore Iperk Sequence in the Canada Basin (Fyles, 1990; Stashin, 2021), and eastwards to the 'high terrace deposits', which are differentiated from the Beaufort Formation *sensu stricto* by containing non-coastal plain facies (Gosse et al., 2017). The similarity of age indicators and fossil flora and fauna have resulted in the high terrace deposits frequently being considered as 'Beaufort Formation *sensu lato*' or 'Beaufort Formation equivalent' – coeval strata that are differentiated only by recording slightly different paleoenvironmental facies (Rybczynski et al. 2013, Fletcher et al. 2019; Stashin, 2021).

Recent geochronological analysis of the Beaufort Formation and equivalents has yielded a range of ages that show the succession is diachronous across the High Arctic. Isochron and

simple burial ages show that the oldest part of the succession dates from c. 6.2 Ma and occurs at the Beaufort Formation type section on Prince Patrick Island (Stashin, 2021; Gosse et al., 2021). The high terrace deposits discussed here are amongst the youngest strata of the regional succession, dating to c. 3.9 Ma (Rybczynski et al. 2013, Fletcher et al. 2019), and near-contemporaneous with the northernmost Beaufort Formation *sensu stricto*, that crops out on Meighen Island (Fyles et al., 1991; Braschi, 2015; Barendregt et al., 2021).

Two localities within the high terrace deposits have yielded the observations described in this paper (Figure 1). Both localities have informal names in common usage, after key fossil finds in the vicinity of each (Gosse et al., 2017): the Fyles Leaf Beds site (078° 29' N, 082° 38' W), named for the discovery of abundant leaf litter and plant remains at the site by Fyles (1989; "Site A" therein), and the Beaver Pond site (078° 33' N, 082° 22' W) named for an abundance of beaver-cut sticks discovered in peat layers (Harington, 1978; Matthews and Fyles, 2000).

Fyles Leaf Beds site

The high terrace deposits at Fyles Leaf Beds crop out over an area of c. 1 km^2 on top of an unnamed 360 m asl mesa, located 12 km southwest of the head of Strathcona Fiord. The summit of the mesa is capped by Quaternary till and outwash sediment and the high terrace deposits are best exposed in a series of cliffs and gullies on its eastern flank (Figure 2). Here the Pliocene deposits can be seen to infill a pre-existing paleotopography developed within underlying strata (Eocene Eureka Sound Group and Cretaceous Isachsen Formation) and can be grouped into two main facies, each consisting of two sub-facies. The lowest part of the succession (Facies 1; c. 15-70 m thick) comprises continuous thin (1-10 cm thick) horizontal layers of sand and silt that have a superficial varve-like appearance, but lack definitive cyclicity in grain-size or thickness (Facies 1A). Outcrop of Facies 1A is frequently covered by drift and colluvium but it appears to be relatively deficient in macro-organic remains, although a single bivalve shell

was noted on the surface near the base of the facies. Rare clay laminae were visible in the middle of Facies 1A. The upper part of Facies 1 (Facies 1B) contains a larger amount of macro-organic remains within silts and fine- to medium-grained sands, including woody debris and allochtonous peat lenses, in addition to scattered dropstones and patchy occurrences of authigenic vivianite. Some exposures of Facies 1B exhibit evidence for turbidite deposition, in the form of packages of parallel-laminated and climbing-ripple-laminated sands, equivalent to Bouma Sequence units B-E, in addition to rarer slumped sediment (Figure 2).

Facies 1 is overlain by Facies 2 (10-50 m thick), which reaches its greatest thickness near the centre of the mesa. Facies 2 is dominated by 0.5-1.75 m-thick sets of inclined sand strata with unidirectional paleoflow towards the east and sporadic pebble lags (Facies 2A). Some of the inclined strata are organised into composite packages, where the foresets of overlying sets extend over the terminal foresets of underlying sets, and the inclined packages are frequently interbedded with flat-lying sands that occasionally contain current ripple lamination. These strata contain several accumulations of leaf material along their foresets, discussed later in this paper. In the southernmost part of the outcrop, Facies 2A grades laterally into Facies 2B, where peat horizons become more common and interbedded with thin (<20 cm) sand layers. The peats are dominantly fibric and range from sphagnum-dominated to shrub dominated. Numerous ice-wedge casts are preserved in Facies 2, including at least one that is clearly syn-sedimentary.

Paleoenvironmental Interpretation of the Fyles Leaf Beds site

Facies 1 is interpreted as a series of lacustrine deposits due to the infilling of a paleohollow, the horizontal bedding, evidence for turbidite deposition, evidence for slumping on the slopes of the paleohollow, and suggestion of shallowing upwards from the increased organic material in Facies 1B. Facies 2A is interpreted as fluvio-deltaic in origin as the largest (1.75 m-thick) sets would imply implausibly large in-channel barforms for a high altitude river system with

dimensions confined by the narrow paleohollow (Long 2021), and because some of the sets appear to be composite in form (Figure 2A-B). The inclined strata may thus be clinoforms of small deltas feeding into the lake system, with the thickness of the inclined sets approximating water depth at the lake margin. Support for this can be found in the lateral and upwards transition to more organic rich and horizontally laminated facies (Facies 2B), which are interpreted to record mires that developed around the lake margin in areas away from direct clastic sediment input.

The lacustrine interpretation is further supported by the present day topography of the region (Figure 3), allied with the recognition that sediment was transported from the west. The Fyles mesa has a maximum altitude of 360 m asl and is bounded on its western side by an unnamed 1.2 km-wide river valley, trending north-south. On the western side of this valley, a west-rising plateau of > 400 metres altitude exposes Paleozoic bedrock at surface, indicating an absence of Pliocene sediment accumulation at the same altitude as the Fyles Leaf Beds succession, and implying a localised region of accommodation at the latter (assuming there has been no post-depositional faulting). The Paleozoic plateau is presently incised by a canyon formed by an eastwards flowing stream that is misfit to the topography at the top of the plateau. It is thus plausible that the topography of the western plateau reflects the relict fluvial valley that was the conduit for the eastwards-transported sediment that accumulated within the lacustrine paleodepression, presently partially exposed on the Fyles mesa (Figure 3). Many of the hills to the east and south of the Fyles mesa also exhibit Paleozoic bedrock at the same altitude as the Pliocene lacustrine sediments, implying that the lake depocenter may have been relatively restricted in its extent (< 5 km width).

The Fyles Leaf Beds site is additionally notable as the location from where the first fossil evidence for Arctic camels has previously been reported (Rybczynski et al., 2013). The exact camel fossil location is situated near the top of Facies 2A as it grades into Facies 2B, thus recording interment of the fossil in a lake-margin location, potentially after transport of the remains in a feeder stream (L6 in Figure 2G).

Beaver Pond site

Strata at the Beaver Pond site are relatively poorly exposed, due to colluvium cover, and are restricted to a few small vertical cuts, typically less than 5 metres in vertical and lateral dimensions (Figure 4). The poor exposure means there is some uncertainty as to whether these cut exposures reflect a contiguous stratigraphy, or whether there has been post-depositional slumping in the sediment pile. In total, the succession constitutes 18 metres of sediment resting on the unconformity at the top of the Eocene Eureka Sound Group. The succession is most notable for a 1.2 metre-thick peat horizon (with some sand interbeds) from which beaver-cut wood and body fossils have been previously reported (Harington, 1978; Matthews and Fyles, 2000; Rybczynski, 2008; Mitchell et al., 2016; Plint et al., 2020). Extensive woody debris in this peat horizon is oriented differently in the lower and upper part of the peat, delineating a bipartite division of peat facies, discussed later. At least four other peat horizons also exist at scattered outcrops around the site and, while the poor exposure leads to some uncertainty, the peats appear to be laterally discontinuous and separated by sands. Within the sands, 2-5 cm pebbles are relatively common and, along with rare cobbles, are composed of several extraformational lithologies including gneiss, quartzite, granite and limestone. The lateral continuity of the peats is problematic to gauge given the limited outcrop, but within 100 metres laterally from the main fossil horizon, no peat is visible and the deposits comprise a succession of sands (Figure 4). This sand succession contains at least one 20 cm-thick package of aggradational wavy laminae, but in general the poor quality of outcrop means that few sedimentary structures are visible and no paleoflow data are available.

Paleoenvironmental Interpretation of the Beaver Pond site

Although the Beaver Pond site records coarse-grained lithologies similar to Facies 2A and 2B at Fyles Leaf Beds, the absence of horizontal lacustrine strata above the underlying unconformity, lack of observed clinoforms, and occasional cobble-sized exotic clasts suggests higher energy deposition for the clastic facies. Although poor exposure and a lack of paleocurrent data preclude a confident diagnosis, it is possible that these may be predominantly alluvial sands and adjacent overbank peats. Associated fossil flora imply that this would most likely have been deposited by a braided stream flowing through open forest with fire-burned undergrowth (see later sections) and thus prone to reorganisation and sediment reworking during flooding events, potentially explaining the discontinuity of sediment packages. The Beaver Pond succession is located at a slightly elevated altitude relative to the Fyles Leaf Beds succession (approximately 360-380 m asl), 9.2 km NNE of the latter, and the absence of definitive lacustrine strata provides further evidence for the geographic restriction of the Fyles Leaf Beds lake.

PLANT DEBRIS IN THE HIGH TERRACE DEPOSITS

Plant remains from the high terrace deposits have been studied from a variety of paleoecological perspectives (Fyles, 1989; Matthews and Fyles, 2000; Ballantyne et al., 2006; Csank et al., 2011; Fletcher et al., 2017, 2019; Plint et al., 2020; Porter et al., 2022), but have not previously been considered as sedimentary particles within the succession. Such a perspective has offered insights into plant debris accumulations in correlative strata of the Beaufort Formation *sensu stricto* (Davies et al., 2014), and we here identify a series of facies motifs of plant debris that inform on life-sediment interactions at the time of deposition.

Phytoclast-lined cross-strata

Facies 2A at Fyles Leaf Beds is notable as many of the clinoforms in the succession have their inclined foresets lined with well-preserved allochtonous leaf litter (Figure 5). Phytoclast-lining

can be witnessed on multiple scales, from the 1 m-scale foresets of the largest clinoforms, to individual ripple-scale packages of cross-lamination (e.g., Figure 5B). The plant linings are remarkable as they can constitute laminae that are only as thick as a layer of individual leaves.

The inclined phytoclast-linings have analogy in modern lacustrine delta environments where depositional energy is elevated (Spicer and Wolfe, 1987). In such settings, phytoclast debris is sorted as bedload in the same fluid as inorganic sands. Mixed plant and sediment debris are swept over the rollover point on the delta but settle at different rates and thus create foreset slopes with alternate compositions of leaf debris and sand (Spicer and Wolfe, 1987). The dominance of leaves and moss at the expense of remains such as cones and twigs (common elsewhere in the high terrace deposits) suggest that the plant debris had previously been sorted by hydraulic processes in the feeder streams, because waterlogged larger debris is more likely to have hydraulic equivalence to inorganic sediment (Spicer and Wolfe, 1987). The implication of this is that the leaf material that constitutes the phytoclast-lined foresets at Fyles Leaf Beds is most likely allochtonous material derived from upstream. The fact that much of the leaf debris is well-preserved, with only occasional sign of physical abrasion (see examples in Figures 5-7), suggests that the high energy conditions necessary for the formation of phytoclast-lined foresets was intermittent and likely seasonal. A scenario where autumnal leaf litter entered a gently flowing stream and sporadically mobilized downstream, before being interred as lake-margin deltaic foresets during seasonal discharge peaks, would explain the preservation of complete leaves on the inclined strata.

Laminated diverse debris

Distinct sedimentary packages of thin (< 5 cm) laminae of alternating clastic silt to sand grade sediment and organic remains are present throughout Facies 2B at Fyles Leaf Beds (Figure 6). The organic detritus in these packages is a poorly sorted mixture of leaves, twigs, moss, cones,

charcoal, and animal fecal pellets. The absence of hydraulic sorting in these remains suggests that they are predominantly autochtonous, but that organic deposition was frequently interrupted with clastic sediment, preventing the development of peat facies. The inorganic sediment that separates the layers is often well rounded and sorted, possibly indicating abrasion by wind action. The location of this facies, immediately adjacent to fluvio-deltaic facies, suggests that it records a lake-adjacent mire, colonized by a variety of plant and animal life but subject to intermittent blanketing by unconsolidated windblown sediment. A supply of such sediment would have been abundant from exposed fluvial bar tops during low flow stages of the rivers that fed the lake system. The laminated debris presents further evidence for seasonality in the form of cryogenic brittle cracking of sediment at the time of deposition (Rybczynski et al., 2013; Figure 6A).

Fire-scarred wood and charcoal

Fire-scarred wood and charcoal has been observed at both the Fyles Leaf Beds and Beaver Pond sites and has been used to document the northernmost evidence of fire during the Pliocene (Fletcher et al., 2019, Fletcher et al., 2021b). An increase of macro-charcoal evidence for fire upsection at the Beaver Pond site is consistent with an upsection increase in the abundance of *Pinus* and *Picea* which foster high fire severities (Fletcher et al., 2019). At the Fyles Leaf Beds site, coarse sand sized charcoal is apparent throughout all of Facies 2 (e.g., Fig. 6B). The relatively high abundance of dwarf and arboreal *Betula* which are less tolerant of shade, suggests that crown fires were less probable, and both species have high mortality rates in regions with high fire severity, consistent with the high abundance of *Larix* (which are typically associated with low fire severity and moderate fire frequency) (Fletcher et al. 2021b). We also observed a high frequency (~10%) of large (> 20 cm diameter) logs which exhibited evidence of at least one episode of fire scarring in their tree-rings at the Fyles Leaf Beds site, which may be consistent with frequent low-moderate intensity fires.

Utilized plant debris

Some of the plant debris in the high terrace deposits has characteristics indicative of its exploitation by other organisms. The most striking such debris are the beaver-cut sticks at the Beaver Pond site that attest to harvesting of woody plants by beavers (see next section), but other debris can be seen to have interacted with different organisms. A large volume of woody debris at both Beaver Pond (Figure 7A) and Fyles Leaf Beds (Figure 7B) show signs of horizontal borings that resemble galleries constructed by longhorned beetle (Cerambycidae) larvae reported from equivalent-aged strata in Greenland (Böcher, 1995). Individual leaves at Fyles Leaf Beds are seen to contain small-sized circular perforations, less than 1 mm in maximum diameter, that likely represent generalized insect feeding damage (Figure 7C) (Labandeira et al., 2007). Rarely, woody debris can be seen to have been colonized by lichens (ascertained where woody debris is excavated from the sediment pile and seen to host fossilized lichen) (Figure 7D).

One large log from Facies 1B at Fyles Leaf Beds contains evidence for vertical borings, up to 0.8 cm in diameter, which have rugose inner walls. Borings with a similar dimension have been described from woody debris in the Plio-Pleistocene Kap København Formation of northern Greenland, where they have been ascribed to the activity of potter wasps (Eumeninae) (Böcher, 1995). However, as the visible rugosity to the boring walls (Figure 7E-F) is dissimilar to the form seen in wasp cavities (which are frequently exploitations of pre-existing holes) (Cooper, 1979), the Beaufort Formation borings appear more similar to the ichnogenus *Teredolites*. The context of this log within lacustrine sediments suggests that it drifted onto the lake and later settled to the bottom prior to its utilization by teredinid bivalves. Freshwater examples of *Teredolites* are rare but have analogy from other Cenozoic successions (Plint and Pickerill, 1985; Shipway et al., 2019).

Evidence for organism-organism interactions preserved in the plant debris of the high terrace deposits is sporadically distributed and so provides evidence for only individual case studies (Figure 7). However, the multitude of individual examples are evidence that the debris supplied by the Pliocene polar forests was integral to the life strategies of multiple other organisms in the ecosystem, at least including mammals, insects, bivalves and lichens.

WOODY DEBRIS ACCUMULATIONS IN THE HIGH TERRACE DEPOSITS

Horizons with concentrations of woody debris are present at both Fyles Leaf Beds and the Beaver Pond site (Figure 8). Prominent amongst these is the wood accumulation within the main fossil-bearing peat at Beaver Pond, where a fraction of the woody debris exhibits evidence for woodcutting by beavers (Figure 4C; Harington, 1978; Matthews and Fyles, 2000; Rybczynski, 2008; Mitchell et al., 2016; Plint et al., 2020). Early studies of this section (e.g., Fyles, 1989) recognised the beaver-cut sticks and referred to the horizon as the 'beaver peat' without any inference of how the woody debris accumulated. Subsequently, Tedford and Harington (2003) inferred that the mass of beaver cut sticks, associated with peat and cobble-bearing sand, could record the possible core of a beaver dam structure. More recent work (Mitchell et al., 2016) has cast doubt on the evidence for a single dam, based on the recognition of multiple recurring peat horizons at the site, and the inference that the peat at the main fossil site would have required thousands of years to accumulate.

Ascertaining whether the Beaver Pond accumulation records a deliberate beaver construction is significant because the extinct beaver genus preserved as body fossils in the high terrace deposits, *Dipoides*, diverged from a common lineage with the extant beaver, *Castor*, around 23 Ma (Rybczynski, 2007). While *Castor* are widely regarded as important ecosystem engineers at present, with major influences on landscapes, biodiversity, ecosystems and nutrient pathways (e.g., Brazier et al., 2021), the extent to which the smaller *Dipoides* (approximately

2/3 the size of *Castor*) performed similar functions is unknown. From a phylogenetic perspective, woodcutting did not evolve in the castorid lineage until about 20 Ma (Rybczynski, 2007, 2008; Plint et al., 2020), in an hypothesized even smaller bodied ancestor to both *Dipoides* and *Castor*¸ of a kilogram or less size (the modern beaver is over 10 times larger or more, being on average 12-25 kg, and as large as 40 kg). The small body size of the common ancestor suggests that the ecology was very different from that seen in modern beavers. Although a small rodent could use wood in the construction of a nest or a lodge, its diminutive form might preclude the animal from building a durable dam. Assuming smaller animals had less physical strength, they would be less suited to meeting the demands of initiating a dam in flowing water and would have been limited to utilizing smaller wood fragments for construction. Diminutive dams constructed of small wood particles would be vulnerable to being washed out by relatively small fluctuations in stream discharge (Butler, 1989), and so would be far less durable structures than modern beaver dams. Thus, if the small-bodied ancestor of *Dipoides* and *Castor* is assumed to have been unlikely to have cut wood for dam-building purposes, any evidence that *Dipoides* did exhibit dam construction would signal convergent evolution of dam-building behaviour in the two clades.

Plint et al. (2020) have recently used carbon and nitrogen isotopes of coeval subfossil plants and beaver collagen from the Beaver Pond site to show that *Dipoides* was certainly consuming wood as a food source. Although *Castor* presently gnaws wood for both nutrition and construction, Plint et al. (2020) suggested two lines of evidence to favour the conclusion that *Dipoides* cut wood for nutrition, but not for dam construction: 1) the relatively small size of the common ancestor of *Castor* and *Dipoides* (see above); and 2) the absence of conclusive evidence for a beaver dam. In such a scenario, the observed accumulation of beaver cut sticks could be simply due to hydraulic sorting of cut and uncut woody debris (i.e., a woody debris 'jam'), without any intent of dam-construction to the deposit.

Beaver Pond: jam or dam?

Analysis of the sedimentary fabric of the Beaver Pond woody debris accumulation has the potential to offer insights into the likelihood of the horizon representing a fossil beaver dam or lodge. However, this is challenging because definitive facies characteristics of beaver dams and ponds have not previously been identified from the stratigraphic record (Robinson et al., 2007; Mitchell et al., 2016; Davies et al. 2020; Plint et al. 2020). The recognition of such facies is itself hindered by the limited understanding, and known variability, of the internal structure of modern beaver dams (Hajic and Walz, 2000). Anecdotal evidence suggests a variety of means of modern dam construction: large logs that can be both longitudinal or transverse to flow, the presence or absence of vertical pointed stakes, and association with or without mud and cobbles (Jung and Staniforth, 2010; Gould and Gould, 2012). Even if the most diagnostic characteristics of modern beaver dams were fully understood, their presence in the stratigraphic record could be underdetermined due to factors that opaquely rendered those signatures: namely changes in the beaver dam fabric due to compaction, collapse, and decay. Additionally, the fact that modern beaver dams can range up to 100 metres in length and 5 metres in height (Gurnell, 1998) means that any individual construction could have dimensions more than stratal exposure, and thus be only partially revealed at outcrop.

Comparison with Skipsea Withow beaver dam facies

To attempt to remedy this comparative knowledge gap, we here compare the Beaver Pond deposits to a facies signature from Holocene strata exposed at Skipsea Withow, East Yorkshire, England (Figure 9). The Skipsea Withow deposits have been long recognised as lacustrine muds and peats that yield a variety of deer, reindeer, elk and pike remains, alongside abundant woody debris of oak, hazel and alder (Phillips, 1829; Gilbertson, 1984; Cadman et al., 2018; Connell, 2018). Carbon-14 dates for the succession indicate that the lake in which the sediments were deposited likely persisted from 9880±80 to 4500±50 years BP (Connell, 2018) and the succession contains animal bones radiocarbon-dated to approximately 9400 years BP (Cadman et al., 2018). Significantly, several unpublished archaeological reports have documented the abundance of both beaver-cut wood (Hillam, 1994) and preserved beaver hair (McCarroll, 2017) within the deposit, which suggest that the deposit may be an appropriate case study for the expected facies signature of an ancient beaver dam deposit.

Our fieldwork at the Skipsea Withow site has identified several characteristics that support the suggestion that the outcrop in part preserves a fossil beaver dam (Figure 9), and which can be compared with the facies signature at Beaver Pond.

Dimensions and sediment types

The Skipsea Withow deposits presently occupy a 59 metre-wide, 1.2 metre-thick bowl-shaped depression within a mud-rich glacial diamict that was deposited during the Dimlington Stadial (late Devensian, 31-16 ka; Evans et al., 1995). The outcrop occurs within a rapidly retreating coastal cliff, and the width of the deposit was previously recorded as being approximately 400 metres (Phillips, 1829; Connell, 2018). The depression is lined at its base with a pebble lag (Figure 9C) and consists of two distinct layers – a lower unit comprising mud and silt, with abundant woody debris and an upper unit with more peaty sediment and an even greater abundance of woody debris. The upper part of the unit has been obscured and truncated by more recent soil development.

The Beaver Pond deposits differ from the Skipsea Withow deposits in two main aspects. Firstly, the extent of the exposure at Beaver Pond is diminutive in comparison to the coastal cliff exposure at Skipsea Withow, which reduces the capacity to recognise the architecture of the organic-rich sediment. Secondly, the Beaver Pond deposits do not sit directly on a paleo-scour unconformity, rendering the base of the deposits less distinct. Despite these differences,

there are similarities in 1) the composition of the sediment types at both localities, and 2) a bipartite division of strata based on woody debris orientation at Beaver Pond (Figure 8A) and orientation and abundance at Skipsea Withow.

The pebble lags in the Skipsea Withow deposits imply that the depression into the underlying till was initiated by flowing water. The subsequent infill by finer grained sediment and increasing organic debris is a signature of silting up of this depression and a transition from lotic to lentic conditions, with analogy to other Holocene beaver pond sites in the region (Wells et al., 2000). The recognition of this facies signature is reliant on both the full architecture of the depression being visible, and clear evidence for incision at the base of the unit. The cessation of sedimentation after the deposition of the Skipsea Withow deposit permits the recognition of a bowl-shaped architecture, conducive to interpretation as a beaver pond. The absence of such an architectural expression at Beaver Pond is inconclusive, as the relative lateral discontinuity of the Beaver Pond site (Figure 4E) suggests that the entirety of the original deposit is not visible (either due to relatively recent slumping or Pliocene erosional truncation during fluvial reorganisation). Lithological similarities suggest that the outcrop expression could be a truncated fraction of, and/or a condensed version of, a sedimentary package like Skipsea Withow. Sediment aggradation forced by modern beaver damming is typically less upon alluvium substrates, compared to areas where pre-existing scours exist (Persico and Meyer, 2009), and so the succession at Beaver Pond may be expected to be naturally thinner than that at Skipsea Withow. Both sites are relatively diminutive compared to the scale of some modern beaver ponds (Hood and Larson, 2015), but comparable in thickness to stratigraphic layers formed by recent beaver ponds that were interrupted by intermittent sediment from free-flowing conditions (Snieszko et al., 2021).

Beaver-cut wood

Both deposits contain an abundance of beaver-cut wood, but with variable cutting styles visible (Figure 10) that likely reflect the different clades responsible (Rybczynski, 2008). The Skipsea Withow *Castor*-cut wood exhibits a greater diversity of cutting styles, including larger logs that have been bevelled to approximately half diameter and exhibit mechanical fracture on the opposite side (Figure 10F), suggestive of tree-felling. Additionally, numerous instances of wood that appears to have been stripped longitudinally on opposite sides are present (Figure 10G-H) and may reflect beaver modification. Both Skipsea Withow and Beaver Pond share evidence of sharpened stick ends and rarer pieces of wood that have been chipped in the middle of their length (Figures 10A-E).

A significant difference between the two sites are the dimensions of teeth-marks and area of damage to the woody debris. The wood cut by *Castor* at Skipsea Withow exhibits larger incisor marks and occurs over larger areas on larger pieces of woody debris, compared to the *Dipoides* cut wood at Beaver Pond. This characteristic appears to be reflective of the smaller size and rounded cutting edge of the lower incisors of *Dipoides*, which is known to have produced smaller teeth marks and have exhibited a diminished range of wood-cutting strategies, relative to *Castor*, which has lower incisors that are wider and straighter (Rybczynski, 2008).

Much of the woody debris at Skipsea Withow is waterlogged and partially-decayed – taphonomic conditions that are detrimental to the preservation of tooth marks (Manning et al., 2014) and render it problematic to gauge the percentage of woody debris in the unit that exhibits beaver-cutting. However, at Beaver Pond, stick counts have shown that approximately 30% of the woody debris exhibits evidence of beaver modification (Mitchell et al., 2016). Such a percentage is directly analogous to the proportion of beaver-cut sticks that constitute extant beaver dams (Blersch and Kangas, 2014).

Woody debris fabric

Both deposits exhibit a bipartite division into upper and lower facies, and the long axes orientations of woody debris in these layers have been measured and compared (Figure 11). Each example exhibits a shift in preferred woody debris orientation from its lower to upper part. In Skipsea Withow, the dominant orientation of woody debris in the lower part is offset by 20° from the upper part, and in Beaver Pond the degree of offset is 50°. Such variation would be expected in a vertical transect through a beaver construction through analogy with the behaviour of modern beavers. The construction of beaver dams by the extant species *Castor canadiensis* involves two phases: 1) intentional construction via selection, modification and placement of wood and sediment, which creates an obstacle that facilitates 2) the passive capture and accretion of wood and sediment from flowing water (Blerch and Kangas, 2014). The second phase of construction is thus reliant on the recruitment of woody debris that floats and snags on the beaver construction and should be expected to be oriented relative to local hydraulic conditions, while the earlier and stratigraphically lower debris would have been deliberately placed at a different orientation. An alternative explanation may be found in passive log jams that form in rivers, and which create an obstacle with one orientation of woody debris that subsequently induces a secondary offset orientation (Braudrick et al., 1997; Gastaldo and Degges, 2007; Gibling et al., 2010). However, the sedimentary context of the accumulations at Skipsea Withow and Beaver Pond suggest that such an explanation is unlikely because neither exhibit the gravel clasts and other debris, sharp upwards transitions to mud, perpendicular relationships with mounded sand bodies, and multiple metre-thicknesses that also typify log jam deposits (Gastaldo and Degges, 2007; Gibling et al., 2010).

Woody debris dimensions

The dimensions of woody debris at the two sites are distinct. At Skipsea Withow, woody debris varies from twigs of > 5 cm length and > 1 cm diameter, to logs up to 3 metres in length and 30 cm in diameter. In contrast, the wood at Beaver Pond is rarely longer than 30 cm in length (although previous collections at the locality may have diminished the content, and at least one larch log, ~150 cm long and 20 cm wide, has previously been reported; Csank et al., 2011). The reason for variable woody debris dimensions between the sites could be purely environmental, as the size of woody debris in modern beaver constructions is primarily governed by the availability and type of local riparian vegetation (Fustec and Cormier, 2007), with preferred sizes on the same magnitude as both sites, between 1 and 5 cm in diameter and up to 3 m in length (Blerch and Kangas, 2014). The variability in woody debris size could reflect both the size of wood that the smaller *Dipoides* was able to cut as well as different ecotopes in different climatic settings: as the majority of trees near the Beaver Pond site were less than 3 metres tall (Fyles, 1989), the diminutive stature would have been a primary constraint on the size of the largest debris available.

The waterlogged nature of the sediments at Skipsea Withow means that it is problematic to remove individual pieces of wood to analyse their size, without breaking the particles. However, this was possible at the Beaver Pond site, and a comparison was made of the dimensions of beaver-cut versus uncut woody debris (Figure 12). The number of retrieved sticks was limited by previous collections at the site, but a clear trend was visible that the dimensions of beaver-cut wood were greater than uncut wood. This pattern has direct analogy to modern beaver constructions, where deliberately modified and placed wood is larger than the woody debris that passively accumulates in the dam structure, minimizing energy expenditure on dam construction (Blerch and Kangas, 2014).

A possible beaver dam at Beaver Pond

The sedimentological characteristics of the woody debris deposits at Beaver Pond are directly comparable with the likely beaver dam deposit at Skipsea Withow, with all dissimilarities explainable by the different dimensions of outcrop exposure, the nature of the underlying strata,

the dimensions and strategies of the beaver clades involved, and the local riparian vegetation. The characteristics are all circumstantially supportive of the woody debris at Beaver Pond having accumulated as a deliberate construction, which subsequently expanded through passive recruitment of woody debris.

Three possible contentions against the presence of a beaver dam origin can be argued against as follows:

1) *Beaver-cut wood records only nutritional consumption*. Plint et al. (2020) found that woody plants at the site were a source of nutrition for *Dipoides*. It is thus possible that the cut sticks could be the remains of a foodpile if, like extant beavers, *Dipoides* used underwater foodpiles of cut sticks as an overwintering food strategy. However, sticks showing cut marks consistent with consumption of the nutritious cambium of the woody debris such as bark stripping (e.g., Rybczynski, 2008, Fig 3B, D) are rare. The majority of sticks do not show cut marks from feeding, and instead the style of cutting is directly analogous to those within the dam construction at Skipsea Withow (Figure 10).

2) Dipoides *was too small to build effective dams.* It is certainly true that *Dipoides* was smaller than *Castor* and would have been a less adept dam builder due to several body-size related reasons, including more limited physical strength and a smaller brain with potentially less engineering capacity. *Dipoides* also had a reduced cutting efficiency due to its rounded incisors, resulting in a relatively smaller bite size (Rybczynski, 2008). However, modern analogue may indicate it was still capable of effective damming, because today beavers operate with an unused potential capacity to build dams in settings with higher stream powers than their actual preferred dam locations. Modern beaver ponds can be constructed in settings with a range of stream powers, ranging from the minimum stream power necessary to maintain perennial flow up to bankfull powers of 2000 $J \cdot s^{-1} \cdot m^{-1}$: yet, despite this potential, *Castor* is observed to

preferentially build dams in settings where bankfull stream powers are almost ten times less than the maximum (Pollock et al., 2004). In other words, it is feasible that *Dipoides,* even with less cutting efficiency (Rybczynski, 2008) was sufficiently large and proficient that the maximum potential stream powers it could endure for dam-building overlapped with the sub-maximum potential stream powers preferred for dam-building by *Castor.*

3) *The Beaver Pond peat took too long to accumulate to record a beaver dam*. Mitchell et al. (2016) used modern peat accumulation rates to calculate that the total 2.4 metres of peat seen at the Beaver Pond site would have taken approximately 49,000 years to form, and thus would far exceed the longevity of an individual beaver dam. However, this accumulation time is potentially an extreme overestimate for the actual mass of peat that can be witnessed at outcrop. The scale of the visible outcrop (less than 5 m^2) is a miniscule spatial fraction of the original peat-forming environment. The comparative sedimentation rates that Mitchell et al. (2016) estimated from modern environments were calculated as an average time to accumulate the mass of an entire fen. Such a calculation cannot account for the multitude of 'outcrop scale' pockets of rapid or negligible accrual that patchwork together to create that average rate. It is inaccurate to directly translate calculated historic accrual rates at whole environment scale to infer the accumulation of a specific two-dimensional stratigraphic sediment pile, because outcrop scale will naturally discretize stratigraphic time to counterintuitively short intervals (Paola et al., 2018; Davies et al., 2020; Davies and Shillito, 2021). Modern beaver ponds are illustrative of this, in that within a wider environment they are patches where both accommodation space and sediment supply (clastic and organic) may be substantially higher than the broader spatial average. Within ponds, rapid accumulation of detritus can occur at sedimentation rates of decimetres per year (e.g., Butler and Malanson, 1995; Pollock et al., 2007; Persico and Meyer, 2009; Thompson et al., 2016; Puttock et al., 2018) sustained for up to 20 years of beaver activity and continuing for ~70 years after dam abandonment (Wright et

al., 2003; Hastings et al., 2007). It is thus feasible that any specific outcrop-scale pile of organic debris could have accumulated over the order of tens, not thousands, of years, and be directly associated with a single dam structure. This is particularly likely for the peats at Beaver Pond, which are composed of recognisable and intact items of organic detritus (Figure 4D), rather than the amalgamated mush that would be expected to develop over 49,000 years.

The sedimentological context of the Beaver Pond woody debris accumulation is supportive of the hypothesis that the accumulation could record a fossil beaver construction (Tedford and Harrington, 2003), especially when differences with other woody debris deposits in the Beaufort Formation *sensu lato* are considered (see next section). Environmental factors would have provided strong selection pressures in favour of the evolution of wood-cutting (Rybczynski, 2007), and the construction of dams or lodges would have been advantageous to *Dipoides* in several ways: mitigating strong seasonality in climate (Ballantyne et al., 2010) by protecting against drought and instances of elevated fluvial discharge (e.g., evidence from the phytoclast-lined clinforms at Fyles Leaf Beds), providing a food cache in winters (Rybczynski, 2007), and offering defence against predators (Plint et al., 2020). It is significant that the fabric of the accumulation demonstrates that it is directly dam-like in form, whether or not it represents a purpose-built construction. It could be that the original wood-pile construction was either unintentional (accumulated wood cut primarily for nutrition (Plint et al., 2020) or an initially ineffective and rudimentary dam. Once erected, such an obstacle would encourage hydrodynamic self-organization into a larger dam-like form through the accrual of transported and jammed woody debris, with an influence on local geomorphology comparable to a purpose-built dam. Passive accumulation of cut wood would have led to further feedbacks in the stability of depositional features, as an abundance of small beaver cuttings can increase riparian vegetation recruitment due to the provision of propagules, which can then establish on sand bars (Levine and Meyer, 2019).

The presence of beaver dams in the succession may provide explanation for other paleoecological characteristics of the High Terrace Deposits on Ellesmere Island, and could suggest that the apparent convergent evolution of dam-building within *Dipoides* had a significant ecological impact. The high biodiversity of fossil remains could reflect increased habitat heterogeneity/niche availability and animal behaviour around dams increasing the presence and density of other large mammals in the area (Hood and Larsen, 2014; Stringer and Gaywood, 2016; Gauvin et al., 2020). Similarly, the presence of beaver dams is known to promote the availability of deadwood and encourage invertebrate populations (Mourant et al., 2020) and could explain the abundance of woody debris recording beetle galleries (Figure 7).

***Other woody debris deposits in the Beaufort Formation* sensu lato**

A final key characteristic that supports the notion that the Beaver Pond site records a beaver construction is the dissimilarity of the woody debris fabric to that seen elsewhere in the high terrace deposits and related strata. Woody debris is common at other locations, including within fluvio-deltaic facies (Facies 2A) at Fyles Leaf Beds, close to the camel fossil site (Figure 8B). At this location, the orientation of woody debris exhibits a wider spread of orientations, on average parallel to the eastwards flow direction of the fluvio-deltaic system (Figure 11D). Such orientations differ from woody debris jam deposits, which tend to organise perpendicular to flow, and the lake margin setting may imply these record a form of a driftcretion (Kramer and Wohl, 2015). Driftcretions form on the margins of standing water bodies, where thin accumulations of drifted woody debris are aligned with the shoreline (Kramer and Wohl, 2015). Other isolated woody debris occurs within the lacustrine facies (Facies 1B) at Fyles Leaf Beds, where its incorporation within turbidite layers indicates the transport of waterlogged woody debris to the lake bottom (Figure 8D). Lacustrine woody debris that is not directly associated with tractional turbidite deposition (Figure 8C) likely records driftwood that has become

waterlogged and sunk (as was also likely the case for the large *Teredolites*-bored log; Figure 7E-F).

Woody debris accumulations from the Beaufort Formation on Meighen Island, coeval to the high terrace deposits, have previously been shown to contain an abundance of unique cross-bedded accumulations of wood particles (Davies et al., 2014) (Figure 13). These deposits have previously been interpreted as woody bedforms, the development of which required an abundance of waterlogged but undecayed wood that would have been available from the seasonal polar forests of the Pliocene. No such accumulations have been identified in the high terrace deposits, and the orientation fabric of wood in such piles is different from the other deposits described here (Figure 11). It is possible that the preferential accumulation of such bedforms, in the distal coastal plain reaches of the Beaufort Formation, reflects the accumulation of woody debris from an extended upreach catchment that was not afforded to the high terrace deposits. However, while woody dune-scale bedforms were not observed, ripple-scale bedforms, composed of small woody debris, are rarely present in the turbidite deposits of Fyles Leaf Beds Facies 1B (Figure 13A). The formation of such tractional bedforms, composed only of woody material that is naturally less dense than water, attests to the fact that similar conditions of waterlogging, limited decay, and abundant plant debris were common features of the Pliocene polar forests, even in hinterland sedimentary environments.

CONCLUSIONS

Pliocene strata of the Canadian High Arctic record the sedimentological and paleontological signatures of an anactualistic polar boreal forest, with potential analogy to the near-future Earth. Observations of plant debris from the succession reveal clues to organism-sediment and organism-organism interactions in this setting, including herbivory on wood-forming plants by ancient beavers. The nature of sediment outcrop means that only a few snapshots of such

interactions are visible, largely on a small scale, but these suggest a network of complex interactions in this vanished 'alternative Earth' (Figure 14). Phytoclast-lined strata suggest seasonality in fluvial systems feeding small lacustrine deltas, laminated organics show the persistence of overbank mires, and features such as lichen-encrusted wood and the borings of beetles and bivalves demonstrate how the debris from the polar forests helped to sustain a diverse ecosystem. Particularly notable are woody debris accumulations that present circumstantial evidence for having been constructed by the extinct beaver clade, *Dipoides*, as an early example of ecosystem engineering and convergent evolution of dam-building. Elsewhere, accumulations of wood as driftcretions, rafted driftwood, and unique woody bedforms attest to the pervasiveness of woody debris in the polar forests, and its redistribution by a variety of means. The preserved evidence for life-sediment interactions demonstrates how such phenomena can be unique to particular time intervals. In some cases, the types of interactions appear similar, even when different clades have been involved (e.g., contrasting construction by *Dipoides* versus *Castor*). In other ways, unique aspects of the ancient environment have combined to create phenomena that are unreported at the present day (e.g., the presence of woody sedimentary bedforms). The life-sediment interactions of the Pliocene polar forests demonstrate that the ecological interactions that may be expected in a near-future Earth will be diverse, and triggered when the northwards advance of the latitudinal treeline increases the availability and abundance of plant debris in Arctic regions.

ACKNOWLEDGMENTS

The fieldwork for this study was primarily undertaken during the 2019 PoLAR-FIT Expedition to Ellesmere Island. NSD's participation in this was supported by a United Kingdom & Canada Arctic Partnership Bursary for 2019, awarded through the NERC Arctic Office and Department of Business, Energy and Industrial Strategy (UK Science and Innovation Network). JCG acknowledges the significant financial and critical logistical support over the past decades from

Polar Continental Shelf Program (PCSP), and NSERC Discovery Grant 06785-19 and NSERC Northern Research Supplement 362148-19. AR's participation was supported by Geogenetics, Globe Institute, and the Research Council of Norway (KLIMAFORSK, 294929). JM was supported by the Explore21 initiative of the American Museum of Natural History. AR was supported by NSERC Discovery and Northern Research Supplement grants.

REFERENCES

BALLANTYNE, A., RYBCZYNSKI, N., BAKER, P., HARINGTON, C.R., AND WHITE, D. 2006. Pliocene Arctic temperature constraints from the growth rings and isotopic composition of fossil larch. Palaeogeography, Palaeoclimatology, Palaeoecology, 242, pp. 188-200

BALLANTYNE, A.P., GREENWOOD, D.R., SINNINGHE DAMSTÉ, J.S., CSANK, A.Z., EBERLE, J.J., AND RYBCZYNSKI, N. 2010. Significantly warmer Arctic surface temperatures during the Pliocene indicated by multiple independent proxies. Geology, 38: 603–606.

BARENDREGT, R.W., MATTHEWS, J.V., JR., BEHAN-PELLETIER, V., BRIGHAM-GRETTE, J., FYLES, J.G., OVENDEN, L.E., MCNEIL, D.H, BROUWERS, E., MARINCOVICH, L., RYBCZYNSKI, N., AND FLETCHER, T.L., 2021, Biostratigraphy, Age, and Paleoenvironment of the Pliocene Beaufort Formation on Meighen Island, Canadian Arctic Archipelago: Geological Society of America Special Paper 551, p. 1–39,

BLERSCH, D.M. AND KANGAS, P.C., 2014. Signatures of self-assembly in size distributions of wood members in dam structures of *Castor canadensis*. Global ecology and conservation, 2, pp.204-213.

BÖCHER, J., 1995. Paleoentomology of the Kap København Formation, a Plio-Pleistocene secquence in Peary Land, North Greenland. Meddelser om Grønland, 33, pp. 1-82.

Braschi, L., 2015. Chronostratigraphy of the Beaufort Formation, western Canadian Arctic Archipelago. Unpublished Masters Thesis, Dalhousie University.

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, 22(7), pp.669-683.

Brazier, R.E., Puttock, A., Graham, H.A., Auster, R.E., Davies, K.H. and Brown, C.M., 2021. Beaver: Nature's ecosystem engineers. Wiley Interdisciplinary Reviews: Water, 8(1), p.e1494

Burke, K.D., Williams, J.W., Chandler, M.A., Haywood, A.M., Lunt, D.J. and Otto-Bliesner, B.L., 2018. Pliocene and Eocene provide best analogs for near-future climates. Proceedings of the National Academy of Sciences, 115(52), pp. 13288-13293.

Butler, D.R., 1989. The failure of beaver dams and resulting outburst flooding: a geomorphic hazard of the southeastern Piedmont. The Geographical Bulletin, 31(1), pp.29-38.

Butler, D.R. and Malanson, G.P., 1995. Sedimentation rates and patterns in beaver ponds in a mountain environment. Geomorphology, 13(1-4), pp.255-269.

Cadman, S., Knight, B., Elliott, B., Schadla-Hall, T., Robson, H.K. and Milner, N., 2018. The Discovery of Mesolithic Red Deer at Skipsea Withow. Yorkshire Archaeological Journal, 90(1), pp.1-12.

Connell, E.R., 2018. Itinerary 16: North Holderness: Barmston south to Mappleton. In: Rawson, P.F. Wright, J.K. (eds.) Geology of the Yorkshire Coast (Geologists' Association Guide No. 34). The Geologists' Association, London. pp.151-155.

Cooper, K.W., 1979. Plasticity in nesting behavior of a renting wasp, and its evolutionary implications. Studies on Eumenine wasps, VIII (Hymenoptera, Aculeata). Journal of the Washington Academy of Sciences, pp.151-158.

Csank, A.Z., Tripati, A.K., Patterson, W.P., Eagle, R.A., Rybczynski, N., Ballantyne, A.P., and Eiler, J.M. 2011. Estimates of Arctic land surface temperatures during the early Pliocene from two novel proxies. Earth and Planetary Science Letters, 304: 291–299.

Davies, N.S., Gosse, J.C. and Rybczynski, N., 2014. Cross-bedded woody debris from a Pliocene forested river system in the High Arctic: Beaufort Formation, Meighen Island, Canada. Journal of Sedimentary Research, 84(1), pp.19-25.

Davies, N.S., Shillito, A.P., Slater, B.J., Liu, A.G. and McMahon, W.J., 2020. Evolutionary synchrony of Earth's biosphere and sedimentary-stratigraphic record. Earth-Science Reviews, 201, p.102979.

Davies, N.S. and Shillito, A.P., 2021. True substrates: The exceptional resolution and unexceptional preservation of deep time snapshots on bedding surfaces. Sedimentology, 68, 3307-3356.

Dawson, M.R. and Harington, C.R., 2007. *Boreameryx*, an unusual new artiodactyl (Mammalia) from the Pliocene of Arctic Canada and endemism in Arctic fossil mammals. Canadian Journal of Earth Sciences, 44(5), pp.585-592.

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, 44: 206–216.

Elias, S.A., and Matthews, J. V. 2002. Arctic North American seasonal temperatures from the latest Miocene to the early Pleistocene, based on mutual climatic range analysis of fossil beetle assemblages. Canadian Journal of Earth Sciences, 39: 911–920.

Evans, D.J., Owen, L.A. and Roberts, D., 1995. Stratigraphy and sedimentology of Devensian (Dimlington Stadial) glacial deposits, east Yorkshire, England. Journal of Quaternary Science, 10(3), pp.241-265.

Fletcher, T., Feng, R., Telka, A.M., Matthews Jr, J.V. and Ballantyne, A., 2017. Floral dissimilarity and the influence of climate in the Pliocene High Arctic: Biotic and abiotic influences on five sites on the Canadian Arctic Archipelago. Frontiers in Ecology and Evolution, 5, p.19.

Fletcher, T.L., Warden, L., Damsté, J.S.S., Brown, K.J., Rybczynski, N., Gosse, J.C., and Ballantyne, A.P. 2019. Evidence for fire in the Pliocene arctic in response to amplified temperature. Climate of the Past, 15: 1063–1081.

Fletcher, T.L., Telka, A., Rybczynski, N. and Matthews Jr, J.V., 2021a. Neogene and early Pleistocene flora from Alaska, USA and Arctic/Subarctic Canada: New data, intercontinental comparisons and correlations. Paleontologica Electronica, 24(1): a08. https://doi.org/10.26879/1121paleo-electronica.org/content/2021/3274-arctic-macroflora

Fletcher, T., Eble, C., Damsté, J.S., Brown, K.J., Rybczynski, N., Gosse, J., Liu, Z. and Ballantyne, A., 2021b. Widespread wildfire across the Pliocene Canadian Arctic Archipelago. Palaeogeography, Palaeoclimatology, Palaeoecology, 584, p.110653.

Fustec, J. and Cormier, J.P., 2007. Utilisation of woody plants for lodge construction by European beaver (*Castor fiber*) in the Loire valley, France. Mammalia, 71(1-2), pp.11-15.

Fyles, J.G. 1989. High Terrace Sediments, Probably of Neogene Age, West-Central Ellesmere Island, Northwest Territories. Current Research, Part D, Geological Survey of Canada, Paper 89-1: 101–104. doi:10.4095/126676.

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

Fyles, J.G., Marincovich Jr, L., Matthews Jr., J. V., and Barendregt, R. 1991. Unique mollusc find in the Beaufort Formation (Pliocene) on Meighen Island, Arctic Canada. Current Research, Part B, Geological Survey of Canada, 91–1B: 105–112.

Fyles, J.G., Hills, L.V., Matthews, J.V., 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, 22–23: 141–171.

Gastaldo, R.A. and Degges, C.W., 2007. Sedimentology and paleontology of a Carboniferous log jam. International Journal of Coal Geology, 69(1-2), pp.103-118.

Gauvin, L.Y., Gallant, D., Tremblay, E., Berteaux, D. and Lecomte, N., 2020. Spatiotemporal changes in biodiversity by ecosystem engineers: how beavers structure the richness of large mammals. bioRxiv. doi: https://doi.org/10.1101/2020.12.02.406785

Gibling, M.R., Bashforth, A.R., Falcon-Lang, H.J., Allen, J.P. and Fielding, C.R., 2010. Log jams and flood sediment buildup caused channel abandonment and avulsion in the Pennsylvanian of Atlantic Canada. Journal of Sedimentary Research, 80(3), pp.268-287.

Gilbertson, D.D., 1984. Late Quaternary Environments and Man in Holderness. British Archaeological Review Series 134.

Gosse, J.C., Ballantyne, A.P., Barker, J.D., Csank, A.Z., Fletcher, T.L., Grant, G.W., Greenwood, D.R., MacPhee, R.D. and Rybczynski, N., 2017. PoLAR-FIT: Pliocene

Landscapes and Arctic Remains—Frozen in Time. Geoscience Canada: Journal of the Geological Association of Canada/Geoscience Canada: journal de l'Association Géologique du Canada, 44(1), pp.47-54.

Gosse, J.C., Stashin, S. and Davies, N., 2021. Advances in the chronostratigraphy of the Beaufort Formation, Arctic Canada. Atlantic Geology, 57, pp.115-116.

Gould, J.L. and Gould, C.G., 2012. Animal architects: building and the evolution of intelligence. Basic Books.

Gurnell, A.M., 1998. The hydrogeomorphological effects of beaver dam-building activity. Progress in Physical Geography, 22(2), pp.167-189.

Hajic, E.R. and Walz, G.R., 2000. Evidence of prehistoric beaver activity in the Des Plaines River valley, Illinois. Wetlands Research. Inc., Technical Paper 8.

Harington, C.R., 1978. Quaternary vertebrate fauna of Canada and Alaska and their suggested chronological sequence. Syllogeus, 15, 105 pp.

Hastings, A., Byers, J.E., Crooks, J.A., Cuddington, K., Jones, C.G., Lambrinos, J.G., Talley, T.S. and Wilson, W.G., 2007. Ecosystem engineering in space and time. Ecology letters, 10(2), pp.153-164.

Heer, O. 1868. Enhaltdend die in Nordgronland, auf der Melville insel, im Banksland, in Island und in Spitzbergen entdeckten fossilien Pflanzen. Flora Fossilis Arctica, 1.

Hillam, J., 1994, The dendrochronological potential of timbers from Withow Gap, Skipsea, Humberside. Ancient Monuments Library Report 31/94. 7 pp.

Hood, G.A. and Larson, D.G., 2014. Beaver-created habitat heterogeneity influences aquatic invertebrate assemblages in boreal Canada. Wetlands, 34(1), pp.19-29.

Hood, G.A. and Larson, D.G., 2015. Ecological engineering and aquatic connectivity: a new perspective from beaver‐ modified wetlands. Freshwater Biology, 60(1), pp.198-208.

Hutchison, J.H. and Harington, C.R., 2002. A peculiar new fossil shrew (Lipotyphla, Soricidae) from the High Arctic of Canada. Canadian Journal of Earth Sciences, 39(4), pp.439-443.

Jung, T.S. and Staniforth, J.A., 2010. Unusual Beaver, *Castor canadensis*, dams in central Yukon. The Canadian Field-Naturalist, 124(3), pp.274-275.

Kramer, N. and Wohl, E., 2015. Driftcretions: The legacy impacts of driftwood on shoreline morphology. Geophysical Research Letters, 42(14), pp.5855-5864.

Labandeira, C.C., Wilf, P., Johnson, K.R. and Marsh, F., 2007. Guide to insect (and other) damage types on compressed plant fossils. Smithsonian Institution, National Museum of Natural History, Department of Paleobiology, Washington, DC. 25 p.

Levine, R. and Meyer, G.A., 2019. Beaver-generated disturbance extends beyond active dam sites to enhance stream morphodynamics and riparian plant recruitment. Scientific reports, 9(1), pp.1-12.

Long, D.G.F., 2021. Trickling down the paleoslope: an empirical approach to paleohydrology. Earth-Science Reviews, p.103740.

Manning, A.D., Coles, B.J., Lunn, A.G., Halley, D.J., Ashmole, P. and Fallon, S.J., 2014. New evidence of late survival of beaver in Britain. The Holocene, 24(12), pp.1849-1855.

Matthews, J. V., and Ovenden, L.E. 1990. Late Tertiary plant macrofossils from localities in Arctic/sub- Arctic North America: a review of the data. Arctic, 43: 364–392.

Matthews, J. V. Jr., and Fyles, J. G. 2000. Late Tertiary plant and arthropod fossils from the high-terrace sediments on Fosheim Peninsula, Ellesmere Island, Nunavut. in Environmental

Response to Climate Change in the Canadian High Arctic, Vol. 259, eds M. Garneau and B. T. Alt (Geological Survey of Canada), 295–317.

McCarroll, J., 2017, Discovery of possible *Castor fiber* (beaver) hair at Skipsea Withow Gap, Holderness, East Yorkshire, UK, October 2017 – Preliminary Report. Unpublished report, University of Hull.

Mecham, G.F. 1855. Further Papers relative to the Recent Arctic Expedition. In Search of Sir John Franklin and the crews of H.M.S" Erebus" and "Terror." London: H.M. Stationery Office. pp. 499–540

Mitchell, W.T., Rybczynski, N., Schröder-Adams, C., Hamilton, P.B., Smith, R., and Douglas, M. 2016. Stratigraphic and paleoenvironmental reconstruction of a mid-Pliocene fossil site in the high arctic (Ellesmere Island, Nunavut): Evidence of an ancient peatland with beaver activity. Arctic, 69: 185–204.

Mourant, A., Lecomte, N. and Moreau, G., 2021. Size matters: When resource accessibility by ecosystem engineering elicits wood‐ boring beetle demographic responses. Ecology and Evolution, 11(2), pp.784-795.

Murray, A.M., Cumbaa, S.L., Harington, C.R., Smith, G.R. and Rybczynski, N., 2009. Early Pliocene fish remains from Arctic Canada support a pre-Pleistocene dispersal of percids (Teleostei: Perciformes). Canadian Journal of Earth Sciences, 46(7), pp.557-570.

Pagani, M., Liu, Z., Lariviere, J., and Ravelo, A.C. 2010. High Earth-system climate sensitivity determined from Pliocene carbon dioxide concentrations. Nature Geoscience, 3: 27–30.

Paola, C., Ganti, V., Mohrig, D., Runkel, A.C. and Straub, K.M., 2018. Time not our time: Physical controls on the preservation and measurement of geologic time. Annual Review of Earth and Planetary Sciences, 46, pp.409-438.

Persico, L. and Meyer, G., 2009. Holocene beaver damming, fluvial geomorphology, and climate in Yellowstone National Park, Wyoming. Quaternary Research, 71(3), pp.340-353.

Phillips, J., 1829. llustrations of the geology of Yorkshire: or, a description of the strata and organic remains of the Yorkshire coast. John Murray, London, 192 pp.

Plint, A.G. and Pickerill, R.K., 1985. Non‐ marine Teredolites from the Middle Eocene of southern England. Lethaia, 18(4), pp.341-347.

Plint, T., Longstaffe, F.J., Ballantyne, A., Telka, A. and Rybczynski, N., 2020. Evolution of woodcutting behaviour in Early Pliocene beaver driven by consumption of woody plants. Scientific Reports, 10(1), pp.1-16.

Pollock, M.M., Pess, G.R., Beechie, T.J. and Montgomery, D.R., 2004. The importance of beaver ponds to coho salmon production in the Stillaguamish River basin, Washington, USA. North American Journal of Fisheries Management, 24(3), pp.749-760.

Pollock, M.M., Beechie, T.J. and Jordan, C.E., 2007. Geomorphic changes upstream of beaver dams in Bridge Creek, an incised stream channel in the interior Columbia River basin, eastern Oregon. Earth Surface Processes and Landforms, 32(8), pp.1174-1185.

Porter, T.J., Anhäuser, T., Halfar, J., Keppler, F., Csank, A.Z. and Williams, C.J., 2022. Canadian Arctic Neogene temperatures reconstructed from hydrogen isotopes of lignin‐ methoxy groups from sub‐ fossil wood. Paleoceanography and Paleoclimatology, p.e2021PA004345.

Puttock, A., Graham, H.A., Carless, D. and Brazier, R.E., 2018. Sediment and nutrient storage in a beaver engineered wetland. Earth Surface Processes and Landforms, 43(11), pp.2358-2370.

Robinson, S., Beaudoin, A.B., Froese, D.G., Doubt, J. and Clague, J.J., 2007. Plant macrofossils associated with an early Holocene beaver dam in interior Alaska. Arctic, pp.430-438.

Rybczynski, N., 2007. Castorid phylogenetics: implications for the evolution of swimming and tree-exploitation in beavers. Journal of Mammalian Evolution, 14(1), pp.1-35.

Rybczynski, N., 2008. Woodcutting behavior in beavers (Castoridae, Rodentia): estimating ecological performance in a modern and a fossil taxon. Paleobiology, 34(3), pp.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, 4: 1550–1559.

Shipway, J.R., Rosenberg, G., Concepcion, G.P., Haygood, M.G., Savrda, C. and Distel, D.L., 2019. Shipworm bioerosion of lithic substrates in a freshwater setting, Abatan River, Philippines: Ichnologic, paleoenvironmental and biogeomorphical implications. PloS one, 14(10), p.e0224551.

Śnieszko, Z., Rurek, M. and Hojan, M., 2021. Medieval Relict Beaver Ponds in the Polish Plain: Studies from the Tuchola Forest. Water, 13(6), p.777.

Spicer, R.A. and Wolfe, J.A., 1987. Plant taphonomy of late holocene deposits in trinity (Clair Engle) lake, Northern California. Paleobiology, 13(2), pp.227-245.

Stashin, S., 2021. Late Cenozoic Basin Evolution of the Western Canadian Arctic Archipelago: the Beaufort Formation and Iperk Sequence. Unpublished Masters Thesis, Dalhousie University.

Stringer, A.P. and Gaywood, M.J., 2016. The impacts of beavers *Castor* spp. on biodiversity and the ecological basis for their reintroduction to Scotland, UK. Mammal review, 46(4), pp.270-283.

Tedford, R.H., and Harington, C.R. 2003. An arctic mammal fauna from the Early Pliocene of North America. Nature, 425: 388–390.

Thompson, S., Vehkaoja, M. and Nummi, P., 2016. Beaver-created deadwood dynamics in the boreal forest. Forest Ecology and Management, 360, pp.1-8.

Torsvik, T.H. and Cocks, L.R.M., 2016. Earth history and paleogeography. Cambridge University Press.

Tozer, E.T. 1956. Geological reconnaissance Prince Patrick, Eglington and western Melville Islands, Arctic Archipelago, Northwest Territories. Geological Survey of Canada, 55: 32.

Wells, C.E., Hodgkinson, D. and Huckerby, E., 2000. Evidence for the possible role of beaver (Castor fiber) in the prehistoric ontogenesis of a mire in northwest England, UK. The Holocene, 10(4), pp.503-508.

Wright, J.P., Gurney, W.S. and Jones, C.G., 2004. Patch dynamics in a landscape modified by ecosystem engineers. Oikos, 105(2), pp.336-348.

FIGURE CAPTIONS

Figure 1 – Location of the study sites within the Canadian High Arctic, showing places mentioned in the text. Inset shows location of Beaver Pond (BP) and Fyles Leaf Beds (FLB) sites in the region of Strathcona Fiord, Ellesmere Island.

Figure 2 – Sedimentological character of the high terrace deposits at the Fyles Leaf Beds locality. A) Basal strata of Facies 1, immediately above the paleotopographic unconformity (out of photograph), showing a detached southward moving slump on the steep lake slope. Scale bar is 20 cm. B) Facies 1B consisting of horizontally bedded silts and fine sands, recording lacustrine turbidites with ripple lamination indicating transport towards the south (left of photograph). Visible scale bar is 1 metre. C) Facies 1B containing dropstone (red circle) and rafted peat debris (white circle). Pen is 14 cm. D) Facies 2A consisting of composite packages of inclined medium-grained sand strata, recording fluvio-deltaic deposition towards the east (out of photograph). Note rollover of clinoforms in area circled. Scale bar is 2 m. E) Facies 1B looking perpendicular to flow. Scale bar is 2 m. F) Ripple marks (white arrow) and organic debris and leaf layers in horizontally bedded sands in Facies 2B. Visible ruler is 60 cm. G) Measured stratigraphic logs (L1, etc) through locality showing relative location and facies present. L4-5 are the location of the Fyles Leaf Beds and L6 is the location of the camel fossil site. LX-Z are primarily through the underlying Eureka Sound Group. H) Interpreted facies distribution in the cliff section drawn to scale, with images of the succession taken from helicopter.

Figure 3 – Geomorphology of area west of Fyles Leaf Beds, suggesting paleovalley of rivers feeding the lake sediments. A) View west from top of Fyles mesa showing misfit valley incised into Paleozoic bedrock. B) High Resolution Digital Elevation Model Mosaic Hillshade digital relief model showing Fyles Leaf Bed (FLB) relative to paleoflow (PF) recorded in fluvio-deltaic sediments and misfit valley to west. Altitude of surrounding bedrock implies that the lake at FLB was of limited width. Image in B from HRDEM Mosaic - CanElevation Series (https://open.canada.ca/data/en/dataset/0fe65119-e96e-4a57-8bfe-9d9245fba06b). Contains information licensed under the Open Government Licence – Canada.

Figure 4 – Sedimentological character of the high terrace deposits at the Beaver Pond locality. A) Position of the Beaver Pond fossil site relative to the unconformity between the Eocene Eureka Sound Group and Pliocene high terrace deposits. Note limited extent of outcrop, largely masked by colluvium and slumped drift. Scale bar is 10 metres. B) Detail of the Beaver Pond fossil site comprising peat horizon with woody debris (circled) within succession of sands and gravels. Scale bar is 1 metre. C) Excavated fossil site showing in situ woody debris with beaver teeth marks (arrowed). Scale bar is 6 cm. D) Detail of peat from fossil site, containing cones and other plant debris. Scale bar is 5 cm. E) Within 100 metres laterally from the fossil horizon, no peat is visible and the high terrace deposits comprise a contiguous succession of sands with aggradational wave ripple lamination. Scale bar is 1 metre.

Figure 5 – Leaf-rich cross-strata at Fyles Leaf Beds. A) Eastwards directed inclined sandy strata interpreted as recording small clinoforms (Facies 2A in Fig. 2). Box shows area enlarged in B. Scale bar is 1 metre. B) Detail of previous image showing sporadic laminae rich in leaf and other plant debris (arrows). Scale bar is 10 cm. C) Plan view of leaf lamina, with partial *Betula* leaf, suggesting low energy settling of debris. Scale bar is 1 cm. D) Plan view of leaf lamina rich in comminuted plant debris, including leaves, seeds and bark. Scale bar is 1 cm.

Figure 6 – Flat-laminated organic-rich deposits in Facies 2B at Fyles Leaf Beds. A) Succession of non-cyclic organic debris and sand laminae. Note that succession is penetrated by a small crack (white arrow) with its upper termination draped by successive layers (black arrow), suggesting periodic freezing of ground during time of deposition. Scale bar is 10 cm. B) Laminae consisting of transported charcoal debris (arrowed) in lower part of section. Visible part of ruler is 15 cm. C) Inclined laminae of well-sorted and rounded wind-blown sand in central part of section. Scale bar is 10 cm. D) Leaf litter laminae at top of section. Scale bar is 2 cm. E) Detail from leaf litter laminae showing intact leaves. Scale bar is 1 cm. F) Detail from leaf litter laminae showing flattened rodent(?) fecal pellets. Scale bar is 1 cm.

Figure 7 – Examples of plant debris utilized by other organisms in the high terrace deposits. A-B) Cortex of woody debris fragments showing signs of consumption by wood-boring insects from the Beaver Pond fossil site (A) and Fyles Leaf Beds Facies 1B (B). Scale bar is 1 cm. C) *Betula* leaf showing likely generalized insect damage, Fyles Leaf Beds Facies 2A. Scale bar is 1 cm. D) Lichen encrusted woody debris, Fyles Leaf Beds Facies 1B. Scale bar is 1 cm. E-F) Large drifted log from Fyles Leaf Beds Facies 1B. Box in E is enlarged in F and shows vertical boring into wood, with rugose edges to internal part of boring diagnostic of the ichnogenus *Teredolites* and indicative of wood-boring/-feeding bivalves. Debris from Fyles Leaf Beds Facies 1B, implying freshwater boring bivalves. Scale bar is 10 cm in E and 1 cm in F.

Figure 8 – Styles of woody debris accumulations in the high terrace deposits on Ellesmere Island. A) Beaver Pond fossil site: woody debris in peat, exhibiting two preferred orientations above and below dashed line (see text). Scale bar is 1 metre. B) Fyles Leaf Beds Facies 2A: two lenses of woody debris (arrowed) within fluvio-deltaic sands, adjacent to camel fossil site. Scale bar is 1 metre. C-D) Fyles Leaf Beds Facies 1B: isolated woody debris particles within dark anoxic sediment (C) and overlying lacustrine turbidite (D). Scale bar is 10 cm in C, visible part of ruler is 21 cm in D.

Figure 9 – Comparative analogue for stratigraphic expression of beaver dam facies: Holocene (c. 9 ka) peat deposits at Skipsea Withow, East Yorkshire, England (53°'58' 2".9"N 00°'11' 4".5"W). A) Paleotopographic depression in underlying Devensian glacial till (DT) has been filled with peat and organic-rich mud (overlain by modern soil). Lens of organic rich Holocene sediment is 59 metres across and 1.2 metres thick in its centre. B) Location of Skipsea Withow in Great Britain. C) Detail of lens margin showing wood-rich peaty sediment onlapping onto underlying till deposits. Large woody debris (white) and basal pebble lag (black) arrowed. Scale bar is 20 cm. D) Detail of the centre of the lens, showing bipartite partition into lower facies where mud content exceeds woody debris, and upper facies where small woody debris

is the dominant material. Geologist for scale is 1.85 m. E) Detail of peat material from upper facies, containing preserved beaver hair (arrowed). Scale bar is 1 cm.

Figure 10 – Comparison of beaver-cut wood at Beaver Pond fossil site and Skipsea Withow. A) Cartoon illustrating types of beaver cuts present in wood debris at the two sites (Beaver Pond has only lateral-chipped and sharpened examples; all are present at Skipsea Withow). B-C) Beaver Pond examples, showing sharpened stick end (B) and laterally-chipped wood fragment (C). D-H) Skipsea Withow examples, including (D) sharpened stick ends (white arrows) in addition to bevelled-broken (yellow arrow) and stripped (blue arrow) fragments, within upper wood-rich facies in centre of depression; (E) laterally chipped wood; (F) bevelled-broken wood; (G-H) two opposite sides of a wood fragment that has been longitudinally stripped. Scale bar is 1 cm in B and 5 cm in C, G and H. Measuring stick is 20 cm long in D, E and F.

Figure 11 – Rose diagrams comparing orientation of woody debris at Beaver Pond site to other locations. A) Beaver Pond stick orientations show different preferred orientations in the upper (n = 15) and lower (n = 30) part of the section (see Figure 8A) that are offset by c. 50°. B) Skipsea Withow orientations are offset by 20° in upper (n = 45) and lower (n = 34) part of section (See Figure 9D). C) Stick orientations in woody lenses at Fyles Leaf Beds (see Figure 8B) show weakly preferred orientation (n = 33), with high scatter of directions. D) Stick orientations in cross-bedded wood accumulations of the Beaufort Formation on Meighen Island (see text and Figure 13C) are strongly aligned in one direction (n = 100).

Figure 12 – Comparison of dimensions of beaver cut and uncut wood at the Beaver Pond site. Histograms show frequency of different size classes for length and diameter of wood particles (n=40).

Figure 13 – Examples of woody debris incorporated into bedforms at various sites. A) Small woody debris organised into cross-laminated foresets of ripples in lacustrine turbidites. Debris may occur with (black arrow) or without (white arrow) alternating foresets of sand. Facies 1B at Fyles Leaf Beds. B-C) Dune bedforms comprised entirely of cross-bedded woody debris, Beaufort Formation, Meighen Island. Woody foresets picked out by drifted sand in (B), appearance as fresh face shown in (C). Scale bar in B is 20 cm, measuring stick in C is 1 metre.

Figure 14 – Summary of the impacts of a High Arctic latitudinal treeline on landscape diversity, resources and biodiversity, as evidenced by sedimentary and paleontological signatures in the high terrace deposits and Beaufort Formation.

Figure 1

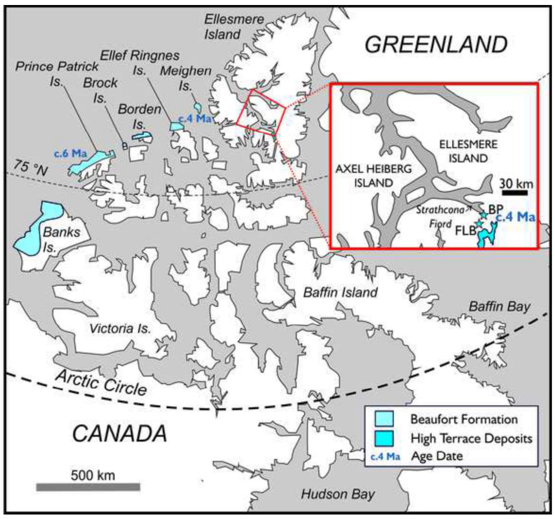


Figure 2 Click here to access/download;Figure;HT Fig 2.jpg

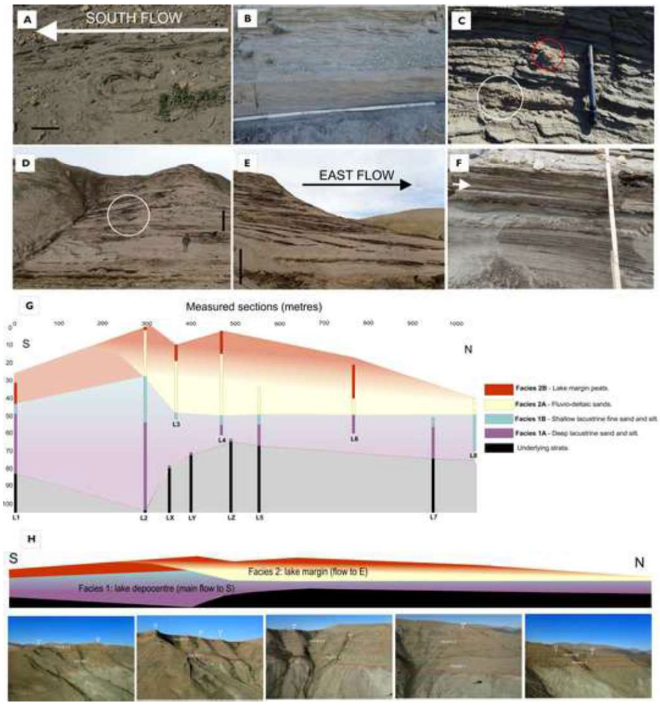


Figure 3 Click here to access/download;Figure;HT Fig 3.jpg

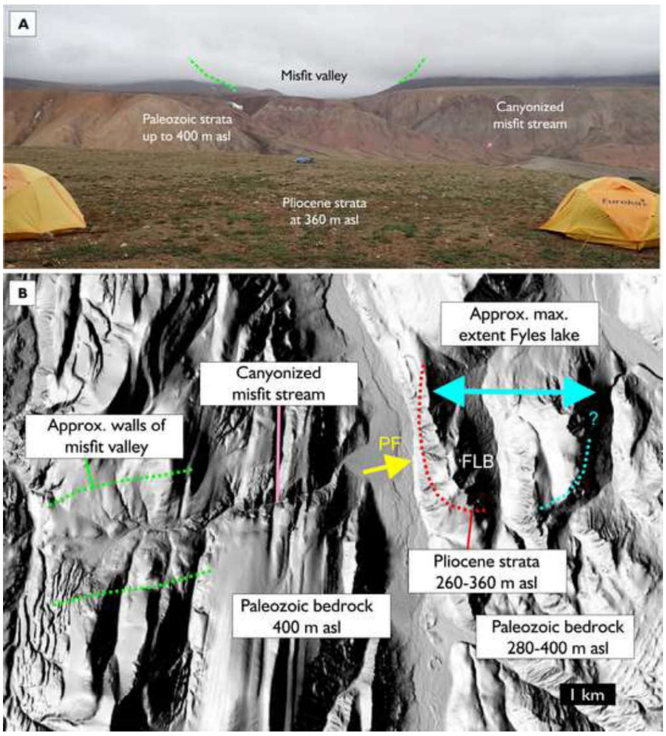


Figure 4 Click here to access/download;Figure;HT Fig 4.jpg

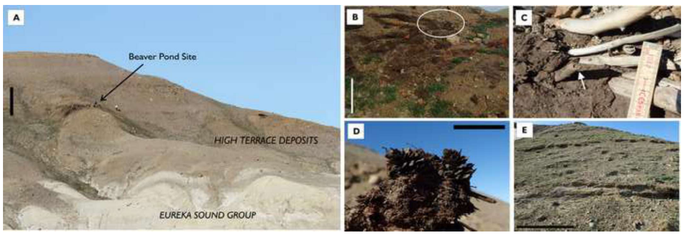


Figure 5 Click here to access/download;Figure;HT Fig 5.jpg

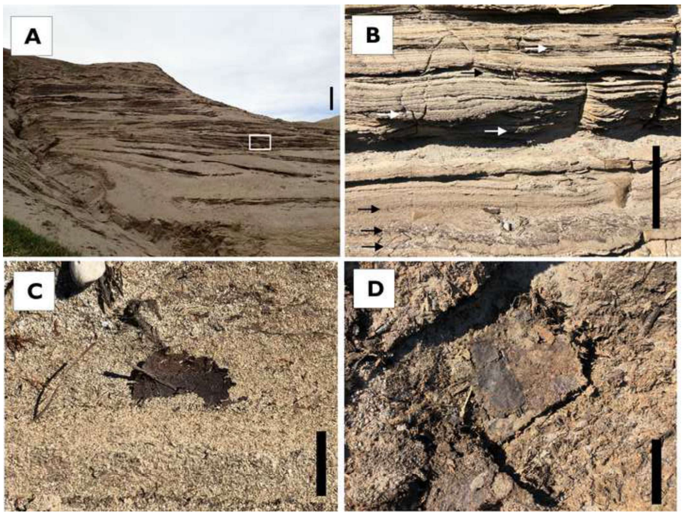


Figure 6 Click here to access/download;Figure;HT Fig 6.jpg

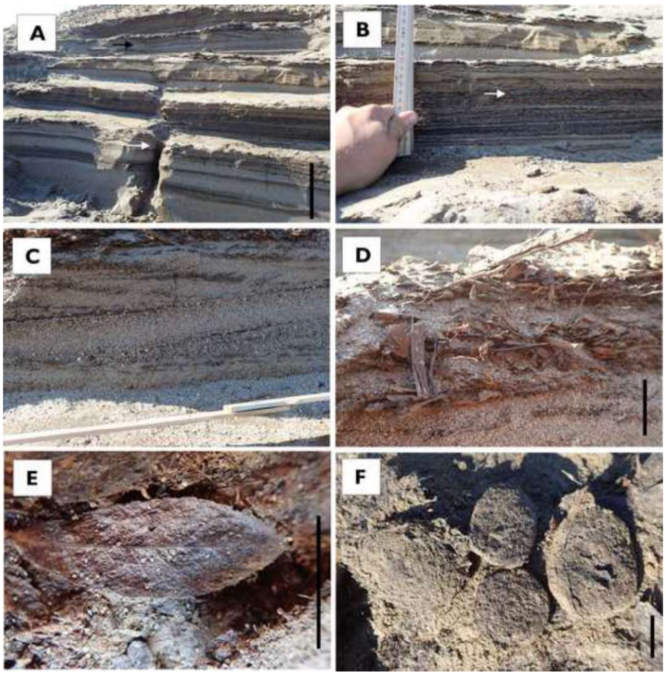


Figure 7 Click here to access/download;Figure;HT Fig 7.jpg

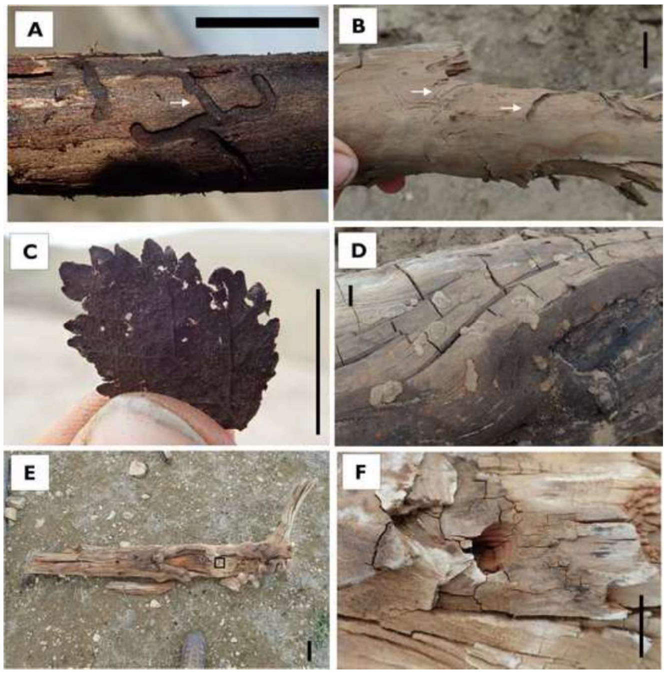


Figure 8 Click here to access/download;Figure;HT Fig 8.jpg

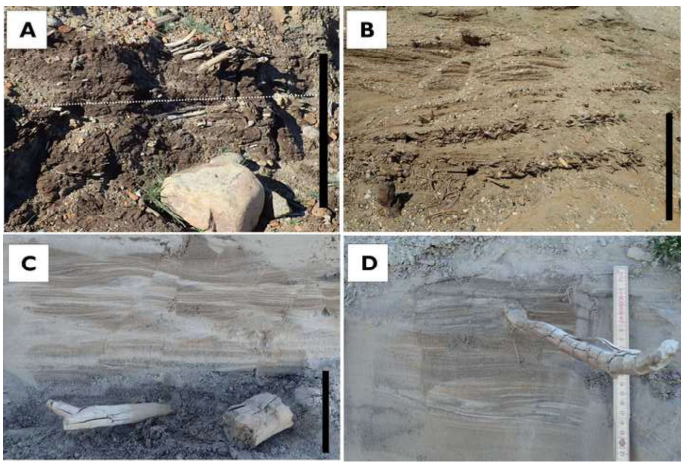


Figure 9 Click here to access/download;Figure;HT Fig 9.jpg

Figure 10

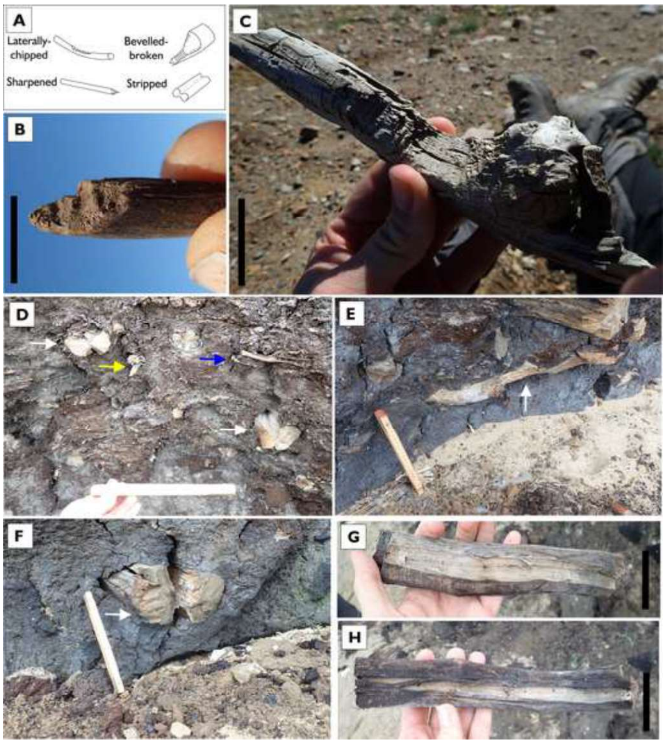


Figure 11

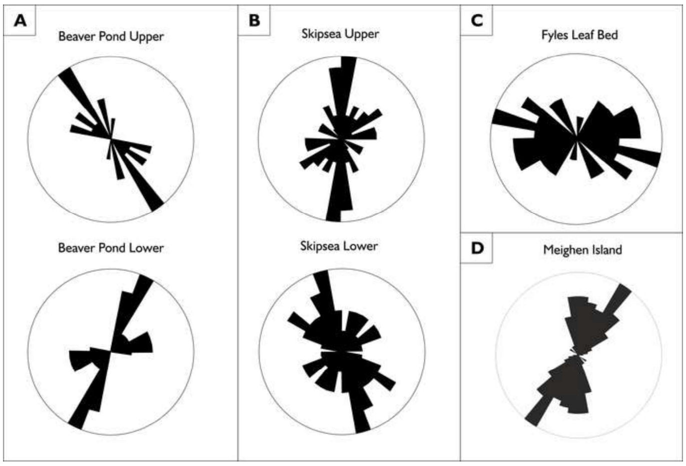


Figure 12

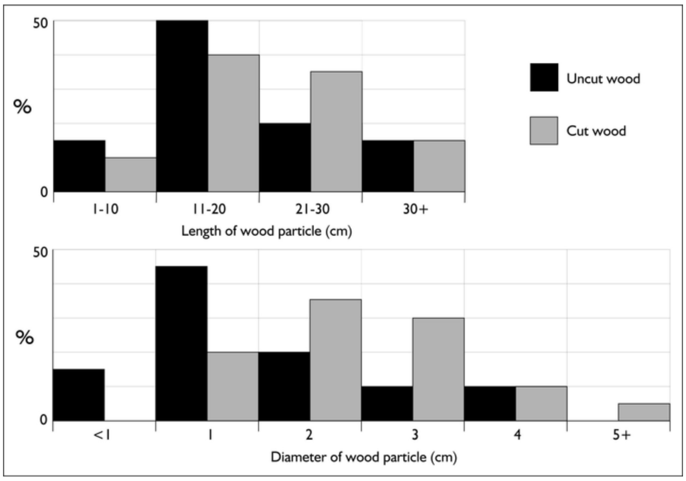
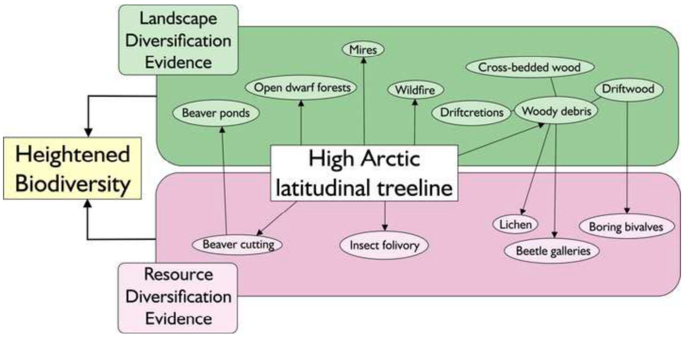


Figure 13

Figure 14



Landscape Diversification Evidence
Mires
Cross-bedded wood
Open dwarf forests
Wildfire
Driftwood
Beaver ponds
Driftcretions
Woody debris
Heightened Biodiversity
High Arctic latitudinal treeline
Lichen
Boring bivalves
Beaver cutting
Insect folivory
Beetle galleries
Resource Diversification Evidence