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

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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.

Palaeoclimatic 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 packs. This paper presents original field data that refines the sedimentological context of plant debris accumulations from the anachronistic 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 paleontographic 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 motifs 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 biodistinctive deposits and landforms including mires, dicrophic mires, 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 CO2 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, 2010), with a similar continental geography to modern-day Earth (Torsvik and Cocks, 2010), with a similar continental geography to modern-day Earth (Torsvik and Cocks, 2010). Mean annual temperature was likely elevated global temperatures were exacerbated in Arctic regions due to an asymmetrical high-latitude forest component (Ballantyne et al., 2007; Dawson and Harington, 2007; Murray et al., 2009; Rybczynski et al., 2013) and a particularly diverse and striking mammal fauna that includes bear, horse, deerlet, badger, rabbit, shrew, and camel fossils (Hutchison and Harington, 2002; Tedford and Harington, 2003; 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 tuliptail fish, scap-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, 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 anachronistic (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 cataloging characteristics of plate 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 foraminiferal 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 (Plant et al., 2020), but we compare sedimentary facies evidence with new data from a case study of definitive Holocene beaver dam facies (Skopea 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 synthesized the reported observations to demonstrate how the suite of snapshots of life-sediment interaction can be combined to refine the palaeoenvironmental context of key Pliocene fossil sites in the region.

### THE HIGH TERRACE DEPOSITS OF ELLESMORE ISLAND

The strata described here belong to the ‘high terrace deposits’ of Ellesmere Island, an informal stratigraphic term for scattered Pliocene sedimentary outliers 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; Herz 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 form and fauna have resulted in the high terrace deposits frequently being considered as ‘Beaufort Formation *sensu lato*’ or ‘Beaufort Formation equivalent’ — crestal strata that are differentiated only by recording slightly different palaeoenvironmental facies (Rybczynski et al., 2013; Fletcher et al., 2019; Stashin, 2021).

Recent geoarchaeological 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; Brauchi, 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 (78°25’N 042°34’W), named for the discovery of abundant leaf litter and plant remains at the site by Fyles (1989); and “Site A” (there), and the Beaver Pond site (78°35’N 042°22’W) named for an abundance of beaver cut-sticks discovered in peat layers (Harrington, 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 km² 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 (Essence Europa Sound Group and Cretaceous Iachem 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 laminite 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 allochthonous peat lenses, in addition to scattered dropstones and patchy occurrences of authigenic vivianite. Some exposures of Facies 1B exhibit evidence for turbidity 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). 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 (78°25’N 042°34’W), named for the discovery of abundant leaf litter and plant remains at the site by Fyles (1989); and “Site A” (there), and the Beaver Pond site (78°35’N 042°22’W) named for an abundance of beaver cut-sticks discovered in peat layers (Harrington, 1978; Matthews and Fyles, 2000).

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 southermmost 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.
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 allochthonous 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 slumping in the sediment pile. In total, the succession constitutes 18 metres of sediment resting on the unconformity at the top of the Eskdale Upper terrace 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 (Harrington, 1979; 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 a.s.l), 9.2 km NNW 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 (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 alluvial/allogenic leaf litter (Figure 5). Phytoclast-lining
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 woodworking 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 12-25 kg, and as large as 40 kg) did exhibit dam-construction should signal 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 Walie, 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 opaque rendered these 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 Skipsøea 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 Skipsøea Withow, East Yorkshire, England (Figure 9). The Skipsøea Withow deposits have been long recognised as lacustrine muds and peats that yield a variety of deer, reedland, 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
Woody debris fabric

beaver dams (Hillam, 1994) and preserved beaver hair
(McCarron, 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, 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.

Both deposits contain an abundance of beaver-cut wood, but with variable cutting styles visible (Figure 10) that likely reflect the different clades responsible (Rybaczynski, 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 sharp-ended 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 has exhibited a diminished range of wood-cutting strategies, relative to Castor, which has lower incisors that are wider and straighter (Rybaczynski, 2008).

Much of the woody debris at Skipsea Withow is waterlogged and partially-decayed; a taphonomic feature 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 (Blench and Kangas, 2014).

Wooden debris fabric

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
the dimensions and strategies of the beaver clades involved, and the local riparian vegetation.

3. 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.

These possible contentsions 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
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 m⁻² m⁻¹, yet, despite this potential, *Castor* is observed to

32 532 preferentially build dams in settings where bankfull stream powers are almost ten times less
33 than the maximum (Pollock et al., 2004). In other words, it is feasible that *Dipoides*, even with
34 less cutting efficiency (Rybczynski, 2008) was sufficiently large and proficient that the
35 maximum potential stream powers it could endure for dam-building overlapped with the sub-
36 maximum potential stream powers preferred for dam-building by *Castor*.

37 3) The Beaver Pond post took too long to accumulate to record a beaver dam. Mitchell et al.
38 (2016) used modern peat accumulation rates to calculate that the total 2.4 metres of peat seen
39 at the Beaver Pond site would have taken approximately 49,000 years to form, and thus would
40 far exceed the longevity of an individual beaver dam. However, this accumulation time is
41 potentially an extreme overestimate for the actual mass of peat that can be witnessed at outcrop.
42 The scale of the visible outcrop (less than 5 m

30
43 length) is a miniscule spatial fraction of the original
44 peat-forming environment. The comparative sedimentation rates that Mitchell et al. (2016)
45 estimated from modern environments were calculated as an average time to accumulate the
46 mass of an entire fen. Such a calculation cannot account for the multitude of outcrop scale
47 pockets of rapid or negligible accrual that patchwork together to create that average rate. It is
48 inaccurate to directly translate calculated historic accrual rates at whole environment scale to
49 infer the accumulation of a specific two-dimensional stratigraphic sediment pile, because
50 outcrop scale will naturally discretize stratigraphic time to contemporaneously short intervals
51 (Paola et al., 2018, Davies et al., 2020, Davies and Skilling, 2021). Modern beaver ponds are
52 illustrative of this, in that within a wide environment they are patches where both
53 accommodation space and sediment supply (clastic and organic) may be substantially higher
54 than the broader spatial average. Within ponds, rapid accumulation of detritus can occur at
55 sedimentation rates of decimetres per year (e.g., Butler and Malanson, 1995; Pollock et al.,
56 2007; Pensico and Meyer, 2009; Thompson et al., 2016; Patteck et al., 2018) sustained for up
57 to 20 years of beaver activity and continuing for ~70 years after dam abandonment (Wright et
58 al., 2003; Hastings et al., 2007). It is thus feasible that any specific outcrop-scale pile of organic
59 debris could have accumulated over the order of tens, not thousands, of years, and be directly
60 associated with a single dam structure. This is particularly likely for the peats at Beaver Pond,
61 which are composed of recognisable and extract items of organic detritus (figure 4D), rather
62 than the amalgamated muck that was expected to develop over 49,000 years.

63 The sedimentological context of the Beaver Pond woody debris accumulation is supportive of
64 the hypothesis that the accumulation could record a fossil beaver construction (Tedford and
65 Harrington, 2003), especially when differences with other woody debris deposits in the
66 Beaufort Formation s. l. are considered (see next section). Environmental factors would
67 have provided strong selection pressures in favour of the evolution of wood-cutting
68 (Rybczynski, 2007), and the construction of dams or lodges would have been advantageous to
69 *Dipoides* in several ways: mitigating strong seasonality in climate (Ballantyne et al., 2010) by
70 protecting against drought and instances of elevated fluvial discharge (e.g., evidence from the
71 phytosclerotin clutches at Fyles Leaf Beds), providing a food cache in winters (Rybczynski,
72 2007), and offering defence against predators (Plint et al., 2020). It is significant that the fabric
73 of the accumulation demonstrates that it is directly dam-like in form, whether or not it
74 represents a purpose-built construction. It could be that the original wood-pile construction
75 was either unintentional (accumulated wood cut primarily for nutrition (Plint et al., 2020) or
76 an initially ineffective and rudimentary dam. Once erected, such an obstacle would encourage
77 hydrodynamic self-organization into a larger dam-like form through the accrual of transported
78 and jammed woody debris, with an influence on local geomorphology comparable to a
79 purpose-built dam. Passive accumulation of cut wood would have led to further feedbacks in
80 the stability of depositional features, as an abundance of small beaver cuttings can increase
81 riparian vegetation recruitment due to the provision of propagules, which can then establish on
82 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 Dipoidae 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; Gavin et al., 2020). Similarly, the presence of beaver dams is known to promote the availability of deadwood and encourage invertebrate populations (Moavail 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 Braver 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 driftrefection (Kramer and Wohl, 2015). Driftcreations form on the margins of standing water bodies, where thin accumulations of drifted woody debris are aligned with the creflow (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 sink (as was also likely the case for the large Travolettes-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-beded 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 of 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 palaeontological signatures of an anachronistic 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). Phytoelast-laid strata suggest seasonality in fluvial systems feeding small lacustrine deltas, laminated organics show the persistence of overbank mines, 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, Dipoidea, as an early example of ecosystem engineering and convergent evolution of dam-building.

Elsewhere, accumulations of wood as driftreflections, rafled driftwood, and unique woody bedforms attest to the perseveriveness 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 Dipoidae 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.

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Figure 3. Castorid phylogenetics: implications for the evolution of swimming and tree-exploitation in beavers. Journal of Mammalian Evolution, 14(1), pp.1-55.


Sedimentological character of the high terrace deposits at the Beaver Pond locality. A) Basal strata of Facies 1, immediately above the paleosolographic unconformity (out of photograph), showing a detached southward moving slump on the steep 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 mud-cemented sand strata, recording fluvo-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. L1-4 are the location of the Fyles Leaf Beds and L6 is the location of the camel fossil site. L5-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 2. 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. 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. a) Leaf-ech cross-stratas 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 laminar-rich in leaf and other plant debris (arrows). Scale bar is 10 cm. C) Plan view of leaf lamina, with partial Bentia leaf, suggesting low energy settling of debris. Scale bar is 1 cm. D) Plan view of leaf laminae rich in comminuted plant debris, including leaves, seeds and bark. Scale bar is 1 cm.

Figure 6. a) 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 of 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 4. Sedimentological character of the high terrace deposits at the Beaver Pond locality. a) Basal strata of Facies 1, immediately above the paleosolographic unconformity (out of photograph), showing a detached southward moving slump on the steep 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 mud-cemented sand strata, recording fluvo-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. L1-4 are the location of the Fyles Leaf Beds and L6 is the location of the camel fossil site. L5-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. a) View west from top of Fyles mesa showing mudic valley incised into Paleozoic bedrock. b) High Resolution Digital Elevation Model Mosaic Hillsdale digital relief model showing Fyles Leaf Bed (FLB) relative to paleoflow (PF) recorded in fluvo-deltaic sediments and mudic 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/50f6511c-f96e-4a75-8b10-0a0245b0a6b0). Contains information licensed under the Open Government Licence - Canada.
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) Lichens 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 mucous 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 fluviodeltaic sands, adjacent to eroded 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″N 00°11′5″W). A) Palaeotopographic 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 laterally-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-E) 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 part of the section (see Figure 13A) that are offset by c. 50°. B) Skipsea Withow orientations are offset by 20° in upper (n = 45) and lower (n = 30) part of the section (see 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 arrows) alternating foresets of sand. Facies 1B at Fyles Leaf Beds. B-C) Dune bedforms comprised entirely of cross-beded 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 palaeontological signatures in the high terrace deposits and Beaufort Formation.