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Wood, whales, and the water's edge: Three proxies for interpreting past sea-ice conditions on Arctic beaches

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Sea ice is an important variable affecting Arctic coastlines, influencing beach morphology and the stranding of whales and driftwood. For ancient beaches, these proxies can provide an archive of Holocene sea-ice dynamics.

The water's edge: Beaches

Sea ice is an essential player in the construction, protection, and erosion of Arctic beaches because it regulates wave climate and heat delivery to the coast, influences nearshore currents, and transports sediment on- and offshore. For example, in summers, when the landfast ice does not melt away, beach formation does not occur (e.g. Funder et al. 2011). A long open-water season, on the other hand, allows waves and currents to modify the shoreline: building beaches or eroding coastal bluffs.

The history of Holocene coastal landscape development has been preserved in many places across the circumpolar Arctic due to glacioisostatic adjustment following deglaciation, causing a fall in relative sea-level (RSL) – the process responsible for the spectacular flights of raised beaches up to hundreds of meters above modern sea level (MSL; Fig. 1). Determining the ages of such raised beaches is most often accomplished via radiocarbon dating organic matter incorporated in or on their surfaces, or, less frequently, using optically stimulated luminescence dating of buried beach sediments (Simkins et al. 2015). Holocene wave climate histories, and, accordingly, summer sea-ice conditions, can be reconstructed by combining well-dated RSL curves with observations of the presence or absence of raised beach ridges, beach-ridge morphology, degree of beach-cobble roundness, and sea-ice-pushed boulders (e.g. Forbes and Taylor 1994; Funder et al. 2011; St-Hilaire-Gravel et al. 2010).

Wood and whales

Sea ice also controls access to the coast for drifting organic matter like wood and whale carcasses, and records of past sea-ice severity in coastal zones may be developed from such data (e.g. Dyke et al. 1997; Dyke et al. 1996; Hole and Macias-Fauria 2017). Interpretation of these proxies, however, is not a straightforward case of less sea ice enabling more driftage. Arctic driftwood, which originates in the vast boreal forests of North America and Eurasia, must spend one to 15 years traversing the Arctic Ocean, drifting with one or both of the two major surface currents (the Beaufort Gyre and the Transpolar Drift) before it has any chance of becoming stranded on a barren Arctic beach or being exported to the North Atlantic (Tremblay et al. 1997). If the driftwood isn't quickly frozen into sea ice at its entry point to the Arctic Ocean and advected off the continental shelves by local currents, it becomes waterlogged and sinks within six to 17 months (the range depends on the species and the part of the tree that is adrift; Häggblom 1982) or gets blown back onshore by storms. After traveling around

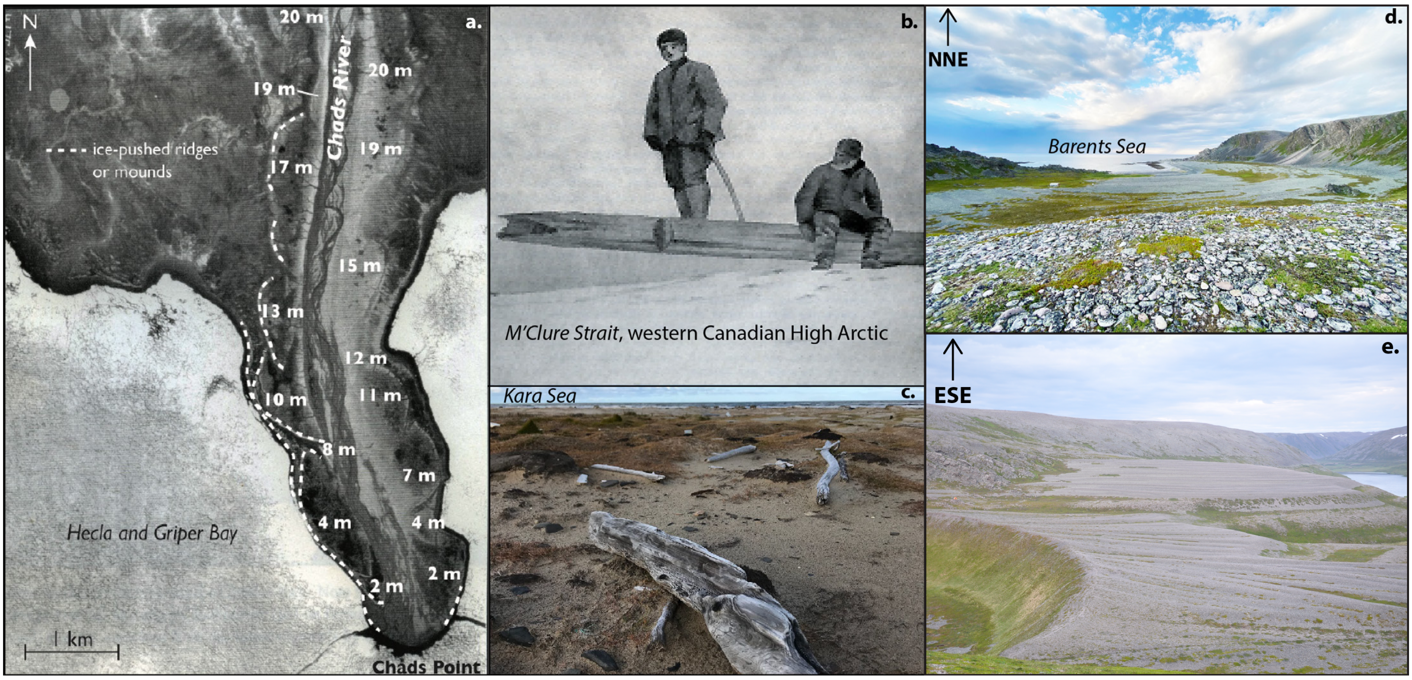

Figure 1: (A) Rare "finger delta" (Forbes and Taylor 1994) with prominent, ice-pushed ridges on western side and narrow summer shore lead. Shore lead appears as a black, coast-parallel strip separating white sea ice and grey beaches (Photo credit: National Air Photo Library, Chad's Point, Melville Island, Northwest Territories, Canada; 1950). Numbers indicate elevations of paleoshorelines in meters above MSL. **(B)** Lithograph showing "log found in M'Clure Strait drifting eastward with ice". From Bernier's 1910 Report on the dominion of Canada government expedition to the Arctic Islands and Hudson Strait on board the *D.G.S. Arctic* (published by Government Printing Bureau, Ottawa). **(C)** Driftwood logs stranded on a modern beach on the Kara Sea, Russia (Photo credit: Vadim Simonsen, 2018). **(D)** Glacioisostatically uplifted raised gravel beach ridges, Varanger Peninsula, Barents Sea, Norway (Photo credit: Chantel Nixon, 2020). **(E)** Same location as (D) with transgressive erosional scarp shown on the left (Photo credit: Chantel Nixon, 2020).

Figure 2: (A) Beached sperm whale (*Physeter macrocephalus*) on northwestern Varanger Peninsula, northern Norway, some 500–700 km south of the winter floe edge (Photo credit: Chantel Nixon, 2020). **(B)** Close-up of sperm whale head resting on cobbles and other driftage: a plastic boot (yellow arrow), and driftwood (red arrows; Photo credit: Chantel Nixon, 2020).

the Arctic Ocean on multiyear sea ice for several years and once again in proximity to land, access is required for stranding; if the coastal zone is locked up below thick sea ice, driftwood cannot make landfall. The spectacular but vanishing landfast, multiyear sea-ice ice shelves of northern Ellesmere Island, Canada, attest to this phenomenon: 69 radiocarbon-dated samples of driftwood collected from behind the ice shelves (stranded prior to ice-shelf establishment and the onset of coastal blockage) record a clear hiatus in driftwood deposition from around 5500 cal yr BP until breakup of the ice shelves and re-opening of these high Arctic fjord coasts, a process which started in the 1950s (England et al. 2008).

If sea ice in the shore zone is highly mobile, winds and currents can transport it onshore, resulting in the formation of sea-ice push ridges (Forbes and Taylor 1994). Sea-ice push can excavate older sediments, including any driftwood they contain, from below MSL and redeposit them alongside modern wood on the same shoreline, especially if RSL is rising. On Eglinton Island in the western Canadian Arctic, for example (where RSL fell to an offshore lowstand in the late Holocene, but is now rising), cut and prepared timber was observed alongside 3000-year-old driftwood (Nixon et al. 2016). As long as it can be demonstrated that the older driftwood has not moved downslope from higher elevations, such assemblages provide not only a minimum age for the onset of RSL rise, but also clear evidence for the consistent development of mobile, multiyear sea ice and summer shore leads over the same period.

Unlike driftwood, whale bones found on Arctic beaches, most commonly those of the bowhead whale (*Balaena mysticetus*), require open water for stranding, because when the whales die, their bloated carcasses float for some time before either sinking or being driven ashore by waves and currents (Fig. 2). Once stranded, they decompose, leaving behind only skeletal material, which can be radiocarbon dated. The annual migrations of bowhead whales reflect their preference for floe-edge habitat (Dyke and Morris 1990), although they are wary of becoming trapped beneath multiyear ice. Earlier studies have shown that reduced summer sea-ice conditions in the central Canadian Arctic Archipelago enabled bowhead whales to migrate well beyond their current range several times during the Holocene, with peak abundances between 9500 and 12,800 cal yr BP (Dyke and Morris 1990). Numerous subfossil whale bones have also been documented from Norway, Greenland, Russia, and Antarctica, although many of these reflect historic whaling-era activity (ca. 17th–early 20th centuries) and have not generally been applied in reconstructions of past sea-ice conditions as they have in the Canadian Arctic.

New directions in driftwood research

Determining the precise origin of Arctic driftwood provides insight into changes in driftwood trajectories across the Arctic Ocean, which are influenced by changes in the positions of the Beaufort Gyre and Transpolar Drift (Tremblay et al. 1997). Driftwood provenancing has so far been accomplished with dendrochronology (for recent driftwood; e.g. Linderholm et al. 2021) or by identification of the wood to its genus or species level with the broad and unverified assumption that, of the two most common genera of Arctic driftwood, *Larix* and *Picea*, *Larix* originates from Siberia and *Picea* from North America (Dyke et al. 1997). New techniques exploring isotopic ratios in driftwood (strontium, for example) are currently being investigated to improve provenancing (Hole et al. 2022).

To reconstruct more robust paleo-sea-ice histories using coastal proxies, the whale-bone, driftwood, and raised-beach data should be examined together where possible (e.g. Dyke and Morris 1990). Nonetheless, the spatially and temporally low-resolution nature of such records means that they are better suited to providing a broad framework for Holocene sea-ice severity into which higher-resolution paleo-sea-ice studies, such as those derived from marine sediment cores, may fit. Future research directions should also focus on filling in geographic gaps along the Russian Arctic coast (Hole and Macias-Fauria 2017) and Antarctica, as well as exploring new potential proxies for past sea-ice conditions in the coastal zone with materials such as pumice from Icelandic volcanic eruptions (Farnsworth et al. 2020).

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