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Alaskan marine transgressions record out-of-phase Arctic Ocean glaciation during the last interglacial

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ABSTRACT

Ongoing climate change focuses attention on the Arctic cryosphere's responses to past and future climate states. Although it is now recognized the Arctic Ocean Basin was covered by ice sheets and their associated floating ice shelves several times during the Late Pleistocene, the timing and extent of these polar ice sheets remain uncertain. Here we relate a relict barrier-island system on the Beaufort Sea coast of northern Alaska to the isostatic effects of a previously unrecognized ice shelf grounded on the adjacent continental shelf. A new suite of optically stimulated luminescence dates show that this barrier system formed during one or more marine transgressions occurring late in Marine Isotope Stage 5 (MIS 5) between 113 ka and 71 ka. Because these transgressions occurred after the warmest part of the last interglacial (ca. 123 ka) and did not coincide with the global eustatic sea-level maximum during MIS 5e, this indicates Arctic ice sheets developed out-of-phase with lower-latitude sectors of the Laurentide and Fennoscandian ice sheets. We speculate that Arctic ice sheets began development during full interglacial conditions when abundant moisture penetrated to high latitudes, and low summer insolation favored glacier growth. These ice sheets reached their full extents at interglacial-glacial transitions, then wasted away at the heights of mid-latitude glaciations because of moisture limitations.

INTRODUCTION

Changes in glacier extent and relative sea level (RSL) along the Beaufort Sea coast of Alaska during Marine Isotope Stage (MIS) 5 at ca. 130–71 ka (Lisiecki and Raymo, 2005; Shakun et al., 2015) provide insights into how the Arctic cryosphere responded to climate states different from those of the present. Peak global interglacial conditions occurred during MIS substage 5e (ca. 123 ka) when mean annual temperatures were 4–5 °C higher than present across much of the Arctic (Miller et al., 2010), and RSL was 6–9 m higher on many of the world's coastlines (Dutton et al., 2015). Two other periods of low global ice volume occurred during MIS substages 5a and 5c between ca. 99 and 81 ka (Shakun et al., 2015) and were accompanied by highstands of eustatic sea level reaching 20–30 m below modern (Rohling et al., 2008; Shakun et al., 2015). We hypothesize that raised marine deposits along the Arctic coast of Alaska provide insights into the timing and extent of Arctic Ocean Basin (AOB) glaciation during this period, when Milankovitch radiative forcing was intermediate between full-glacial and full-interglacial conditions and prompted unique responses in high-latitude glaciers (Svendsen, 2004).

Surficial deposits on the Arctic Coastal Plain of northern Alaska (Fig. 1) provide an archive of marine, alluvial, glacial, and aeolian deposits that span much of the Cenozoic (Dinter et al., 1990). One of the most striking geomorphic features on this coastal plain is a relict barrier-island system

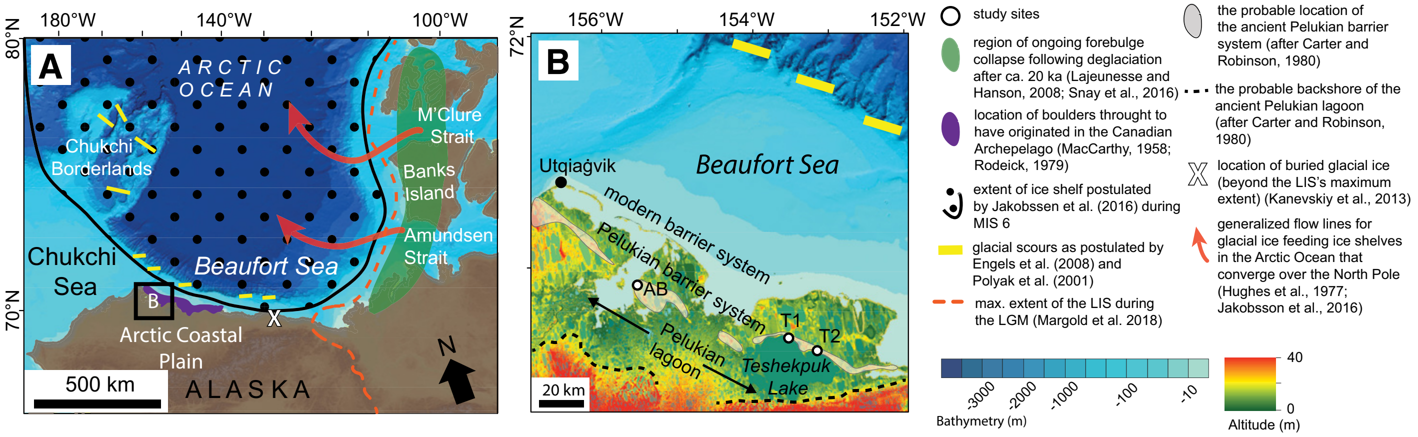

Figure 1. A: Regional evidence for pre-LGM (Last Glacial Maximum) glaciation of the Beaufort Sea Coast in the Arctic. B: Digital elevation model of the study area (black box in A). Teshekpuk Lake sites are T1 (Walrus Bluff, and additional sites described in the Data Repository [see footnote 1]: Lost Log and Drip) and T2 (Black Lagoon Bluff and an additional site described in the Data Repository: Fox Cub). AB—Admiralty Bay; MIS—Marine Isotope Stage; LIS—Laurentide Ice Sheet.

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now lying 6–10 m asl (above sea level) and stretching 180 km eastward from Utqiaġvik (Barrow) along the modern Beaufort Sea coast (Fig. 1). The RSL rise that formed this raised barrier system has been termed the Pelukian Transgression (PT) (Brigham-Grette and Hopkins, 1995) and, to date, only a relative chronology has been established for the event (see Section DR3.1 in the GSA Data Repository[1]).

Determining the age of the PT has taken on new significance with the renewal of interest in the ice-sheet glaciation of the AOB (Mercer, 1970; Hughes et al., 1977; Jakobsson et al., 2016; Gasson et al., 2018). Although the pan-Arctic ice sheets and ice shelves envisioned by Hughes et al. (1977) were initially dismissed for lack of field evidence, new data from sea-floor geomorphology supports the presence of grounded ice sheets in the Beaufort Sea (Engels et al., 2008; Jakobsson et al., 2008), the Chukchi Sea (Polyak et al., 2001; Niessen et al., 2013), and over the Lomonosov Ridge in the central AOB (Jakobsson et al., 2010, 2016) (Fig. 1; Fig. DR1). However, dating ancient ice-sheet glaciations can pose major challenges. The margins of floating ice shelves leave only subtle geological evidence on land (Davis et al., 2006), and these traces are easily effaced by more-recent glaciations and RSL changes. As a result, existing estimates for the timing of ice-sheet glaciation in the Arctic Basin rely primarily on limiting ages from biostratigraphic correlations in deep-sea cores (Jakobsson et al., 2010, 2016) and a limited selection of land-based chronologies (e.g., Svendsen, 2004; Astakhov, 2018). Biostratigraphic data suggest that at least once during MIS 6 (191–130 ka), and possibly on several later occasions, extensive ice shelves >1 km in thickness covered much of the AOB (Jakobsson et al., 2016). Here we use part of the archive of past RSL fluctuations preserved on the Arctic Coastal Plain of Alaska to describe and date the PT (for methods, see Section DR2) in order to test hypotheses that glacio-isostatic adjustment was a cause for that marine transgression and to explore the implications of the timing of the PT for the overall glacial history of the Arctic.

RESULTS

We studied six stratigraphic sections along an 80-km-long stretch of the Pelukian barrier system between Utqiaġvik and Teshekpuk Lake (Fig. 1; Fig. DR3, Table DR1). The stratigraphy of PT deposits are consistent with a landward-migrating system of barrier islands (Short, 1979; Reineck and Singh, 1980) (see the section descriptions in Section DR3). Sediment deposited in brackish lagoons and tidal flats lies at the base of five of the six sections (Figs. DR3 and DR4). These back-barrier facies are overlain by gravelly beach deposits, which in turn are capped by an ice-rich, yedoma-like loess unit. In the lower 4 m of the Black Lagoon section, lagoon and tidal flat facies alternate, possibly recording the longshore migration of a tidal inlet and/or a fluctuation in RSL.

Optically stimulated luminescence (OSL) ages from the PT deposits range from 113.0 ± 14.5 to 68.5 ± 9.2 ka (Fig. 2; Fig. DR3, Table DR2). The post–120 ka ages (n = 10) indicate that the peak of the transgression (-s), as evidenced by the barrier beach units, occurred after the warmest part of the last interglacial (MIS 5e, 129–116 ka). Furthermore, the distribution of the OSL ages suggests the possibility that the PT barrier system formed during two different events: 90–77 ka (Black Lagoon section) and 110 –95 ka (Walrus section) (Fig. 2). The occurrence of two transgressions is consistent with the occurrence of similar sedimentary facies at different elevations in some sections (Fig. DR3).

DISCUSSION

What could have caused marine transgressions reaching 10 m above present sea level thousands of years after the MIS 5e peak in eustatic sea level? Tectonism can be excluded, given the long-term stability of this trailing continental margin (Grantz et al., 1994; Shephard et al., 2013). We suggest two possibilities, both involving glacial isostatic adjustment: (1) collapse of a glacial forebulge generated by the Laurentide Ice Sheet (Fig. 3A), and (2) localized isostatic depression under the grounded margin of an ice shelf in the Beaufort Sea (Fig. 3B).

Hypothesis 1: Collapse of a Glacial Forebulge

Crustal deformation beneath ice sheets can displace the mantle laterally, which then creates a crustal forebulge under the surrounding unglaciated terrain (Peltier, 2015). By analogy with the situation along the eastern seaboard of the United States (DeJong et al., 2015), the PT may have been caused by a forebulge generated by the Laurentide Ice Sheet in northwestern Canada during MIS 6 and/or by the Innuitian Ice Sheet in the Canadian Arctic Archipelago. After the ice sheet retreated, the forebulge under the Beaufort Sea coastline would have collapsed and migrated eastward, causing the coastline to subside and intersect sea level during the eustatic sea level highstands occurring during MIS 5c (ca. 96 ka) and/or MIS 5a (ca. 82 ka) (Fig. 3A). Crucially, this scenario requires that a second forebulge was generated by the Laurentide Ice Sheet or Innuitian Ice Sheet during the Last Glacial Maximum (LGM, 18–23 ka) that raised Pelukian deposits high enough so they are still above sea level today.

Arguing against this double forebulge hypothesis is the absence of geomorphological evidence for subsidence along the Alaskan Beaufort Sea coastline today, indicating the absence of an LGM forebulge. In fact, the geodynamics model of Peltier et al. (2015) predicts the collapsing LGM forebulge now lies 1000 km to the east along the western margin of the

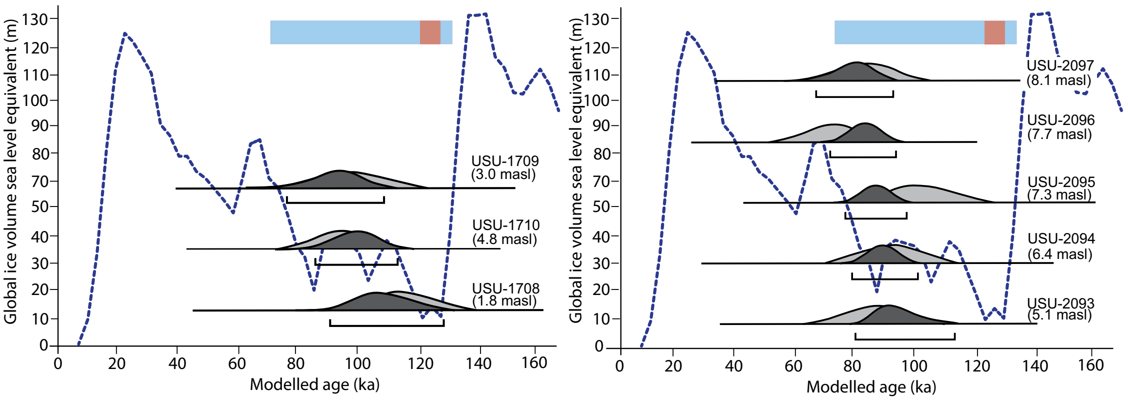

Figure 2. Bayesian model of optically stimulated luminescence (OSL) ages (Rhodes et al., 2003; Bronk Ramsey, 2009) from Walrus and Black Lagoon Bluffs, on the Alaskan Arctic Coastal Plain. Light-gray curves show initial ages with their standard errors. Dark-gray curves show modeled ages after stratigraphic position is accounted for. Blue shading on the bar at the top of the graph delineates Marine Isotope Stage 5 (MIS 5), the last interglacial. Red shading delineates the warmest period of the last interglacial, MIS 5e. Blue dotted line shows global ice volume sea-level equivalent (m), after Shakun et al. (2015). USU-xxxx—Utah State University sample number.

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[1] GSA Data Repository item 2018287, sample locations, methods, supporting material, and further results, is available online at http://www.geosociety.org/datarepository/2018/ or on request from editing@geosociety.org.

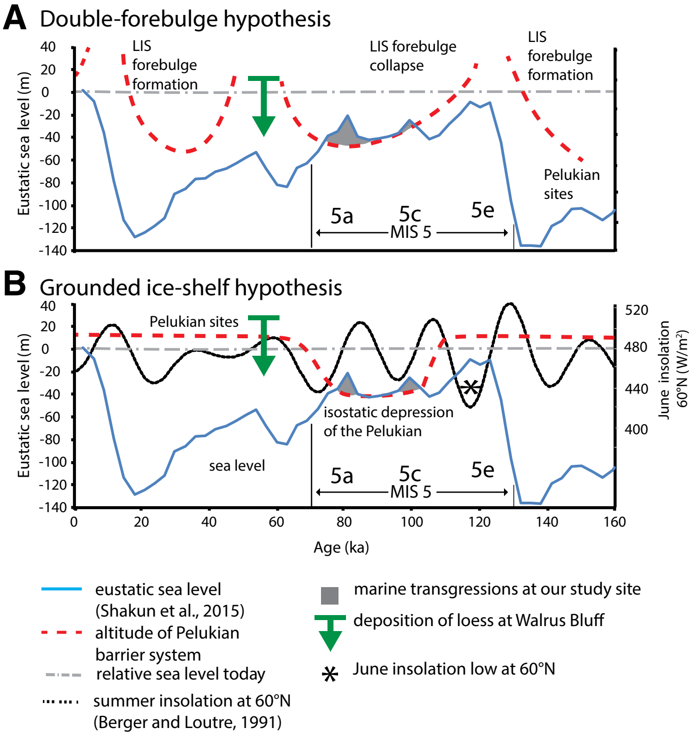

Figure 3. Schematic cross section showing alternate hypotheses for the mechanism and timing of the Pelukian transgression on the Beaufort Sea coast. LIS—Laurentide Ice Sheet; MIS—Marine Isotope Stage.

Canadian Arctic Archipelago (Fig. 1A) (Peltier et al., 2015; Snay et al., 2016), where, indeed, coastal subsidence is now in progress (Lajeunesse and Hanson, 2008).

Hypothesis 2: Isostatic Depression under an Arctic Ocean Ice Shelf

A second possibility is that the PT was caused by isostatic depression under the grounded margin of an ice shelf impinging on the Beaufort Sea coastline. Fluctuations in the thickness and extent of this grounded ice shelf, in conjunction with fluctuating eustatic sea level during the latter substages of MIS 5 would have caused multiple high stands in local RSL (Fig. 3B). Because these RSL highstands were relatively high and the Arctic Coastal Plain is low-lying, even minor amounts of isostatic depression were capable of causing marine transgressions. If true, this hypothesis must meet three requirements:

(1) Thick ice shelves fed by land-based ice sheets must have existed in the AOB, and, at times, their margins grounded along Alaska's Beaufort Sea coast.

(2) These Arctic ice sheets were extensive during MIS 5 when the Laurentide and Fennoscandian Ice Sheets were reduced in extent.

(3) The amount of isostatic depression required to submerge the Beaufort Sea coastline beneath RSL highstands during the later substages of MIS 5 is consistent with the thickness of a grounded ice-shelf margin.

Accumulating evidence indicates a thick ice shelf existed offshore in the Beaufort Sea on one or more occasions in pre-LGM time (Fig. 1A) (Jakobsson et al., 2016). Scour marks on bathymetric high points on the sea floor demonstrate that ice shelves up to 1000 m thick flowed out of the western AOB across the North Pole toward the Nordic Seas (Polyak et al., 2001; Niessen et al., 2013; Jakobsson et al., 2016). These ice sheets were fed by ice domes that were partially land-based; one of the largest, the Innuitian, was located over the Canadian Arctic Archipelago east of the Alaskan Beaufort Sea coast (Polyak et al., 2001; England et al., 2006; Stokes et al., 2006; Engels et al., 2008). This same region is the probable source area for the erratic stones occurring in the Flaxman and Pelukian deposits along the Alaskan coast (Rodeick, 1979) (Section DR4.2). Buried glacial ice of pre-LGM age that was possibly left by the grounded margin of an Arctic Ocean ice shelf occurs at several locations along the Beaufort Sea coast beyond the maximum extent of the Laurentide Ice Sheet and Innuitian Ice Sheet during the LGM (Kanevskiy et al., 2013). Also along the Beaufort Sea coast, large-scale lineations and scours, now 700 m below modern sea level, are consistent with the presence of a thick, westward-flowing ice shelf whose margin grounded along the Alaskan coastline (Fig. 1A) (Engels et al., 2008).

Consistent with the second requirement for Hypothesis 2, multiple lines of evidence indicate high-latitude glaciations were at times out-of-phase with peaks in global ice volumes, especially during glacial-interglacial transitions (Mangerud et al., 1998; Brigham-Grette et al., 2001; Hughes et al. 2013; Hughes and Gibbard, 2018) when solar insolation is high in wintertime within the zone of the Westerlies (30–60°N), but low in the Arctic during summer (Miller and De Vernal, 1992; Hughes et al., 2013) (for further discussion see Section DR3.2, Fig DR 2). The ages of high-latitude glaciations are generally poorly constrained, but some of them fall within MIS 5 (ca. 130–71 ka) (Brigham-Grette et al., 2001; Svendsen, 2004), at times when major changes in eustatic sea level occurred in response to large changes in global ice volume despite the absence of widespread growth in lower-latitude ice sheet sectors (Stokes et al., 2012; Shakun et al., 2015).

Based on generally accepted rates and magnitudes of glacio-isostasy (Sabadini et al., 2012), the grounded margin of a 1000-m-thick ice shelf would have been capable of causing submergence of the Pelukian barrier system during one or more of the latter substages of MIS 5. RSL during MIS 5a and MIS 5c reached 20–30 m below its present level for periods of 5–10 k.y. Submerging the Pelukian barrier (+10 m asl today) during these highstands would have required 30–40 m of isostatic depression, which in turn would have required 90–120 m of grounded ice to be present for 5–10 k.y. Given that the Arctic Ocean ice shelf was ~1000 m thick (Jakobsson et al., 2016), it is reasonable that 10% of its thickness was grounded over an appreciable area of the Beaufort Sea continental shelf.

CONCLUSIONS

The OSL-constrained sedimentological and geomorphological evidence presented here indicates that marine transgressions occurred along Alaska's Beaufort Sea coastline after the peak warmth and eustatic transgression of the last interglacial. The most likely cause of the PT was isostatic depression under the grounded margin of an ice shelf fed by the Innuitian Ice Sheet based in the Canadian Arctic Archipelago (Fig. 1B). The age of the PT indicates that maximum, Late Pleistocene glaciation in this sector of the AOB was out-of-phase with global ice volumes, which were largely controlled by the sizes of the LIS and Fennoscandian Ice Sheet. This suggests that Arctic glaciers respond uniquely to Milankovitch forcing, such that ice sheets develop in the Arctic when solar insolation at mid latitudes is high in wintertime, but low in the Arctic during summer, in response to the changes in moisture availability.

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