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A millennial-scale record of Arctic Ocean sea ice variability and the demise of the Ellesmere Island ice shelves

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[1] Sea-ice ice shelves, at the apex of North America (>80° N), constitute the oldest sea ice in the Northern Hemisphere. We document the establishment and subsequent stability of the Ward Hunt Ice Shelf, and multiyear landfast sea ice in adjacent fiords, using 69 radiocarbon dates obtained on Holocene driftwood deposited prior to coastal blockage. These dates (47 of which are new) record a hiatus in driftwood deposition beginning $\sim$5500 cal yr BP, marking the inception of widespread multiyear landfast sea ice across northern Ellesmere Island. This chronology, together with historical observations of ice shelf breakup ($\sim$1950 to present), provides the only millennial-scale record of Arctic Ocean sea ice variability to which the past three decades of satellite surveillance can be compared. Removal of the remaining ice shelves would be unprecedented in the last 5500 years. This highlights the impact of ongoing 20th and 21st century climate warming that continues to break up the remaining ice shelves and soon may cause historically ice-filled fiords nearby to open seasonally. **Citation:** England, J. H., T. R. Lakeman, D. S. Lemmen, J. M. Bednarski, T. G. Stewart, and D. J. A. Evans (2008), A millennial-scale record of Arctic Ocean sea ice variability and the demise of the Ellesmere Island ice shelves, *Geophys. Res. Lett.*, *35*, L19502, doi:10.1029/2008GL034470.

1. Introduction

[2] Three decades of satellite surveillance shows that Arctic Ocean sea ice reached a record level of reduction in 2007, surpassing the previous absolute minimum (2005) by more than 1.4 million km^2 [*Kerr*, 2007]. Notwithstanding the importance of these observations, a proper understanding of recent sea ice reduction [*Nghiem et al.*, 2007; *Serreze et al.*, 2007; *Comiso et al.*, 2008] requires a long-term perspective exceeding the past three decades. Here, we document the chronology of the oldest sea ice in the Northern Hemisphere, the sea-ice ice shelves of northern Ellesmere Island (Figure 1). Prior to this study, the age of the ice shelves was poorly constrained, rendering unknown the broader significance of their ongoing reduction. Here we clarify the age of the Arctic ice shelves using a total of 69 radiocarbon ages obtained on samples of Holocene (10,000 yr BP-present) driftwood transported across the Arctic Ocean and deposited on northern Ellesmere Island. A hiatus in driftwood deposition from the mid-Holocene to present documents the formation of widespread multiyear landfast sea ice. These findings make the ice shelves several thousands of years older than originally proposed.

[3] The recent reduction of Arctic Ocean pack ice along the coast of northern Alaska and the Yukon has contributed to the earlier removal of landfast sea ice there [*Mahoney et al.*, 2007]. Assuming that this relationship holds true for northern Ellesmere Island, then the Holocene history of ice shelf formation and break-up should also serve as a proxy for adjacent Arctic Ocean sea ice variability. The antiquity and ongoing removal of these ice shelves serves to amplify the significance of modern sea ice reduction documented by satellite surveillance of the Arctic Ocean.

2. Study Area

[4] The ice shelves of northern Ellesmere Island (Figure 1) are unique in the Northern Hemisphere and at the submission of this paper (April 2008) they covered about 950 km^2. These included the Markham, Ward Hunt and Petersen ice shelves that are composed of multiyear landfast sea ice sustained by the basal accretion of brackish seawater and intermittent years of net snow accumulation [*Hattersley-Smith et al.*, 1969; *Lyons et al.*, 1971; *Jeffries*, 1987; *Jeffries et al.*, 1991]. Therefore, they are distinct from glacier ice shelves [*Lemmen et al.*, 1988]. However, the Milne and Serson ice shelves have a significant component of glacier ice and therefore are classified as composite ice shelves [*Lemmen et al.*, 1988; *Narod et al.*, 1988].

[5] These modern ice shelves are recognized to be remnants of a much more extensive "Ellesmere Ice Shelf" first described by late 19th century sledging parties [*Nares*, 1878; *Peary*, 1907] (Figure 1). Their accounts refer to a 600 km-long platform of sea ice attached to the coast, described as having "long prairie-like swells at its surface" [*Peary*, 1907, p. 181]. This description is consistent with the surface topography of modern ice shelves that display distinctive, parallel ridges and troughs (Figure S1 in the auxiliary material[1]). These sledging trips across northern Ellesmere Island coincided with the end of the Little Ice Age (LIA; 1600–1900 A.D.), an interval of climate deterioration favouring widespread expansion of snow and ice across the Canadian High Arctic [*Evans and England*, 1992; *Levesque and Svoboda*, 1999; *Wolken et al.*, 2005].

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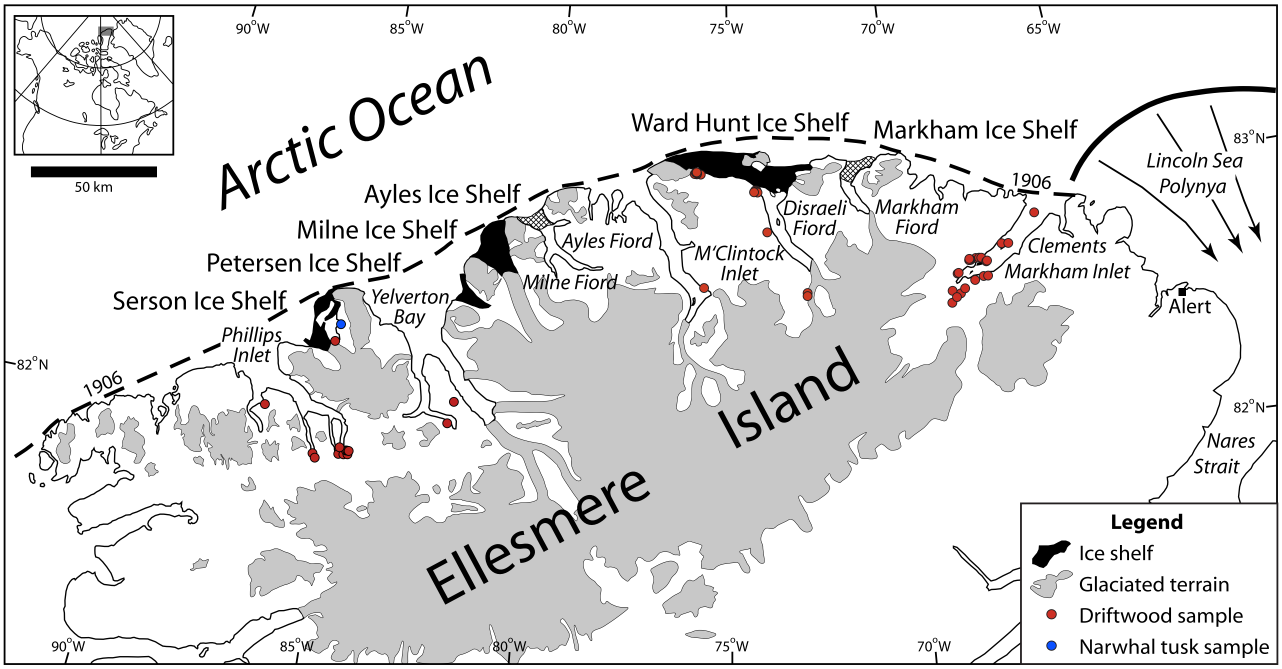

Figure 1. The ice shelves of northern Ellesmere Island, Nunavut, Canada. The dashed black line marks the probable extent of the "Ellesmere Ice Shelf" in 1906 [*Vincent et al.*, 2001]. The Ayles and Markham ice shelves (cross-hatched) were removed from the coast in August 2005 [*Copland et al.*, 2007], and August, 2008, respectively (D. R. Mueller, Summer 2008 loss of Arctic ice shelves, available from http://www.people.trentu.ca/∼dmueller/iceshelfloss2008/, 2008 (accessed 4 September 2008)).

[6] Systematic investigations of the ice shelves followed after aircraft surveillance in 1946 discovered gigantic "ice islands" up to 700 km^2 in the Arctic Ocean that were initially of unknown provenance [*Koenig et al.*, 1952]. These were subsequently traced to northern Ellesmere Island where the surface topography of several ice shelves matched that of the ice islands. Mapping of the ice shelves based on aerial photographs obtained in 1959/60 indicated that the ice shelves then covered approximately 2100 km^2 and extended up to 16 km into the Arctic Ocean. At this time, the total area of identified 'ice islands' in the Arctic Ocean, including the channels of the Canadian Arctic Archipelago (CAA), was about 2500 km^2 [*Crary*, 1958]. Hence, by 1960, the combined area of ice shelves and ice islands was approximately 4600 km^2, roughly half the estimated area of the "Ellesmere Ice Shelf" at the end of the LIA [*Vincent et al.*, 2001] (Figure 1). Since then, the largest ice shelf reduction involved the calving of 600 km^2 from the Ward Hunt Ice Shelf during 1961/62 [*Hattersley-Smith*, 1963; *Holdsworth*, 1970]. Additional fracturing of the Ward Hunt Ice Shelf between 2000 and 2002 was reported based on RADARSAT imagery and subsequent fieldwork [*Mueller et al.*, 2003], emphasizing its increasing vulnerability to full removal, like the Ayles Ice Shelf in 2005 [*Copland et al.*, 2007] (Figure 1). During the summer of 2008, the Markham Ice Shelf was also removed, whereas the Serson and Ward Hunt ice shelves underwent reductions of 122 and 22 km^2, respectively (L. Copeland, personal communication, 2008).

3. Methods

[7] Forty-seven new radiocarbon dates, utilising accelerator mass spectrometry (AMS), were obtained on postglacial driftwood collected inland of Ward Hunt Ice Shelf and from five adjacent fiords occupied today by multiyear landfast sea ice (Clements Markham Inlet, M'Clintock Inlet, Yelverton Inlet, Phillips Inlet, and Disraeli Fiord; Figure 1). These new dates add significantly to a total of 22 previously reported driftwood ages from the north coast of Ellesmere Island. The chronology of driftwood deposition records intervals when both Arctic Ocean surface currents and seasonally ice-free fiords allowed driftwood to enter. Preservation of this driftwood record was favoured by its entrapment on marine shorelines that were subsequently elevated from the sea by postglacial emergence. Periods lacking driftwood deposition imply the non-availability of driftwood-bearing sea ice by ocean currents and/or blockage of the northern Ellesmere Island coast by multiyear landfast sea ice. The youngest driftwood samples provide maximum-limiting ages for the inception of the sea shelves and multiyear landfast sea ice now separating that driftwood from the Arctic Ocean.

[8] The delivery and deposition of driftwood on northern Ellesmere Island is affected by four variables. These are: 1) the influx of driftwood into the Arctic Ocean from northward flowing rivers in the circum-Arctic region [*Dyke et al.*, 1997]; 2) the availability of sea ice to raft wood across the Arctic Ocean during its three-year voyage, without which it would become water-logged and sink [*Häggblom*, 1982]; 3) the presence of favourable ocean currents directing driftwood to northern Ellesmere Island from source areas mainly in Russia [*Dyke et al.*, 1997]; and 4) the lack of ice shelves and multiyear landfast sea ice along the northern Ellesmere Island coast permitting driftwood deposition [*Crary*, 1960]. We assume that throughout the Holocene the rate of driftwood incursion into the Arctic Ocean has remained

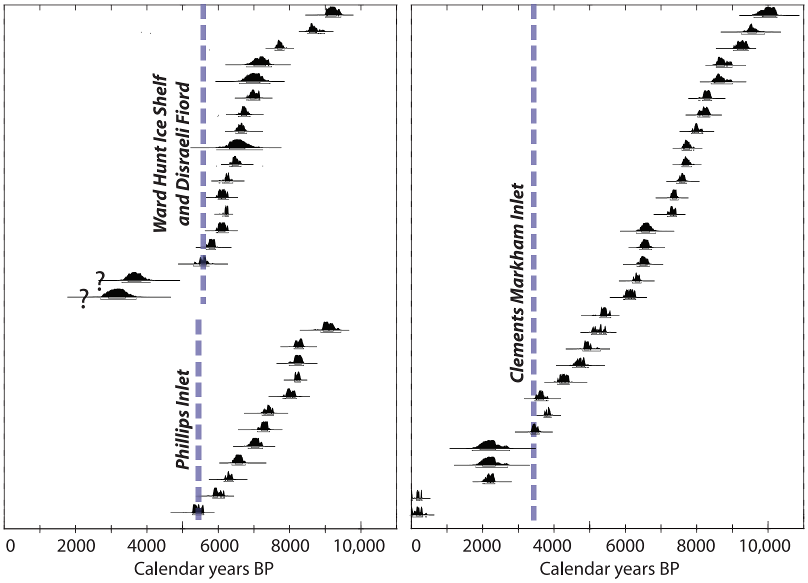

Figure 2. Radiocarbon-dated driftwood samples from northern Ellesmere Island. Each date is plotted showing its calibrated probability distribution (OxCal v3.7 [*Reimer et al.*, 2004]). Termination of driftwood deposition in Phillips Inlet and behind the Ward Hunt Ice Shelf occurred abruptly at 5500 cal yr BP. Younger radiocarbon ages reported by *Crary* [1960] are designated with a question mark (see text). In Clements Markham Inlet a temporary cessation occurs approximately 3500 cal yr BP, after which driftwood re-enters intermittently to present.

similar (because the circumpolar boreal forest has occupied the Arctic Ocean drainage throughout this interval) and that there has been sufficient sea ice to transport driftwood to northern Ellesmere Island.

[9] Most driftwood is transported across the Arctic Ocean by sea ice entrained in the Transpolar Drift that originates on the continental shelves of northern Russia [*Dyke et al.*, 1997]. During the Holocene, the Transpolar Drift has had three different configurations, ultimately controlled by atmospheric circulation [*Dyke et al.*, 1997; *Tremblay et al.*, 1997]: 1) an eastward routing through Fram Strait when driftwood is delivered to the European Arctic, 2) a westward routing when driftwood is delivered to the CAA, including northern Ellesmere Island, and 3) a split routing when driftwood is delivered less abundantly to both 1 and 2, above. Since deglaciation, approximately 9500 cal yr BP, driftwood has been deposited on northern Ellesmere Island but more abundantly since 4500 cal yr BP when a westward shift in the Transpolar Drift is proposed [*Dyke et al.*, 1997]. Thus, from 4500 cal yr BP to present, northern Ellesmere Island was geographically disposed to driftwood delivery, rendering its history of deposition a useful proxy for the presence or absence of ice shelves. Below, we summarize the new driftwood ages and discuss their implications for ice shelf history and stability. All ages are reported in calendar years Before Present (cal yr BP) at the 95% confidence level (Table S1). All reported radiocarbon ages in this study were calibrated using the program OxCal v3.7, which uses the IntCal04 calibration curve [*Reimer et al.*, 2004].

4. Results

[10] Our new age determinations significantly expand the previously reported driftwood chronology from northern Ellesmere Island [*Stewart and England*, 1983; *Dyke et al.*, 1997]. Most of the radiocarbon dated samples reported here were collected from sites landward of the Ward Hunt Ice Shelf as well as from Clements Markham and Phillips inlets, two fiords occupied by multiyear landfast sea ice (Figure 1). Of the 69 driftwood dates, nineteen were collected inland of the Ward Hunt Ice Shelf, including Disraeli Fiord (Figures 1 and S1). These samples range in age from 9200 to 5500 cal yr BP, after which the entry of driftwood terminated (Figure 2 and Table S1). Furthermore, 12 samples fall between 7000 and 5500 cal yr BP, recording an interval of widespread driftwood deposition. West of the Ward Hunt Ice Shelf, 14 samples from Phillips Inlet show a similar age distribution, with the last entry of driftwood about 5400 cal yr BP, while seven of the ages are younger than 7000 cal yr BP (Figure 2). Nineteen new radiocarbon ages obtained on driftwood collected within Clements Markham Inlet bring its current total to 31, and show nearly continuous driftwood deposition from 9900 to 3500 cal yr BP (Figure 2). After 3500 cal yr BP driftwood is rare in Clements Markham Inlet. However, intervals of sea ice removal are recorded by three ages ranging from 2800 to 1700 cal yr BP, and by two modern samples (Figure 2 and Table S1).

[11] Prior to ice shelf formation, driftwood reached northern Ellesmere Island sporadically from the onset of deglaciation until about 7000 cal yr BP, when its abundance increased, consistent with a westward shift of the Transpolar Drift [*Dyke et al.*, 1997]. From 5500 cal yr BP to present, driftwood entry terminated landward of the Ward Hunt Ice Shelf and within Phillips Inlet. This cessation contrasts with driftwood deposition in Clements Markham Inlet until 3500 cal yr BP and continuous deposition to present along northeast Ellesmere Island [*England*, 1983; *Stewart and England*, 1983]. This indicates that the absence of driftwood younger than 5500 cal yr BP behind Ward Hunt Ice Shelf and within Phillips Inlet is due to its preclusion by the

establishment of multi-year landfast sea ice and sea-ice ice shelves rather than a change in availability controlled by atmospherically-driven ocean currents.

5. Discussion

[12] Previous efforts to date the Ward Hunt Ice Shelf involved radiocarbon dating of enclosed "dirt layers" and marine organisms, as well as driftwood collected on its landward margin [*Crary*, 1960]. The dirt layers are allochthonous (wind-transported from Ellesmere Island) thereby rendering uncertain the relationship between their organic content and the absolute age of the ice shelf. Furthermore, in one case, a dirt layer was reported contaminated by soot from diesel fuel used to melt the ice (38 meltings produced 1 g of carbon) [*Crary*, 1960]. Other dates obtained on marine shells and sponges, entrained by basal accretion and collected from the bottom of the ice shelf, range from 3400 to 13,200 14C yr BP [*Lowdon and Blake*, 1970; *Lyons and Mielke*, 1973]. Two driftwood samples collected landward of the ice shelf dated 3400 and 3000 14C yr BP [*Crary*, 1960]. These driftwood dates are commonly cited to record the onset of ice shelf growth, and have calibrated ages of 4100-3300, and 3700–2700 cal yr BP, respectively (Figure 2 and Table S1). If correct, they record a brief removal of the Ward Hunt Ice Shelf after 5500 cal yr BP. However, these ages are not given precedence here because they were not duplicated in our expanded database and they are products of earlier radiocarbon dating by conventional beta-counting that warrant confirmation.

[13] Continued delivery of driftwood to Clements Markham Inlet from 5500 to 3500 cal yr BP reflects more frequent sea-ice clearance of this large fiord following establishment of the ice shelves to the west (Figure 2). Today, a prominent, recurrent (annual) polynya expands northwestward from the north end of Nares Strait, progressing across the Lincoln Sea towards the mouth of Clements Markham Inlet [*Kwok*, 2006] (Figure 1). In the process of its northward expansion, Arctic Ocean sea ice is evacuated from the Lincoln Sea polynya southward into Nares Strait. This evacuation removes sea ice as far west as the mouth of Clements Markham Inlet, therefore increasing the likelihood of its seasonal clearance. Our dates indicate that after 5500 cal yr BP, Clements Markham Inlet did not develop multiyear landfast sea ice until 3500 cal yr BP. This lag of 2000 years in the establishment of multiyear landfast sea ice may record the influence of the Lincoln Sea polynya until 3500 cal yr BP, after which driftwood entry is infrequent (Figure 2). The variability of driftwood deposition across northern Ellesmere Island underscores the potential significance of local conditions affecting sea ice regime. After 3500 cal yr BP, severe sea ice and ice shelves persisted across northern Ellesmere Island until the 20th century.

[14] If the northern Ellesmere Island ice shelves co-vary with the extent of Arctic Ocean pack ice, as proposed for northern Alaska [*Mahoney et al.*, 2007], then their significant reduction between 1906 and ∼1950 should also reflect a previously undocumented interval of Arctic Ocean sea ice reduction. This would have foreshadowed the modern decline documented by satellite surveillance. Therefore, the future stability of the remaining Ellesmere Island sea-ice ice shelves also provides an important measure of the ongoing integrity of Arctic Ocean sea ice. We note that the detachment of the Ayles Ice Shelf (2005) was accompanied by an unusually large area of open water (15 km wide) vs. buttressing pack ice [*Copland et al.*, 2007]. The ongoing demise of the Ellesmere ice shelves during the summer of 2008 signals the unabated removal of the oldest sea ice in the Northern Hemisphere.

[15] Based on the new suite of driftwood ages, we conclude that the Ellesmere Ice Shelf and its historical remnants began to form shortly after 5500 cal yr BP. Paleotemperature records in cores retrieved from the Agassiz Ice Cap, northern Ellesmere Island also show a progressive decline in mean annual temperature since the mid Holocene [*Fisher et al.*, 1995], with the worst sea ice conditions in the CAA coinciding with late 19th century exploration [*Koerner*, 1977]. Our model of ice shelf initiation and stability could be readily tested by expanding existing driftwood surveys to other parts of northern Ellesmere Island that remain uninvestigated, (e.g., Ayles and Markham fiords). This should also include the former eastern sector of the Ward Hunt Ice Shelf and fiords where the chronology of glacial input to composite ice shelves remains undocumented.

[16] We emphasize that stranded driftwood in the circumpolar region records a natural buoy system transported by sea-ice [*Häggblom*, 1982] whose trajectory is controlled by atmospherically-driven surface currents [*Dyke et al.*, 1997; *Tremblay et al.*, 1997]. This driftwood record spans the last ten thousand years, warranting integration with other glaciological and biological environmental proxies, as well as coupled ocean-atmosphere modelling [*Tremblay et al.*, 1997]. However, we regard the lack of driftwood deposition landward of existing ice shelves during the past 5500 years to record blockage by sea ice rather than unfavourable atmospheric circulation because younger wood is present elsewhere on northern Ellesmere Island [*Stewart and England*, 1983].

6. Conclusion

[17] Radiocarbon dated driftwood deposited landward of the modern Ward Hunt Ice Shelf and inside multiyear landfast sea ice in Phillips Inlet, records its exclusion for more than five millennia. This contrasts markedly with the historical and ongoing breakup of the northern Ellesmere Island ice shelves since the beginning of the 20th century. The removal of the remaining ice shelves and the opening of historically ice-filled fiords nearby, should it occur, would be without precedent in the last 5500 years. This underscores and clarifies the magnitude of ongoing Arctic Ocean sea ice reduction in response to 20th/21st century warming.

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