

2008

Arctic Perennial Ice Cover Over the Last 14 Million Years

Dennis A. Darby
Old Dominion University

Follow this and additional works at: https://digitalcommons.odu.edu/oeas_fac_pubs

 Part of the [Geochemistry Commons](#), [Oceanography Commons](#), and the [Paleontology Commons](#)

Repository Citation

Darby, Dennis A., "Arctic Perennial Ice Cover Over the Last 14 Million Years" (2008). *OEAS Faculty Publications*. 278.
https://digitalcommons.odu.edu/oeas_fac_pubs/278

Original Publication Citation

Darby, D. A. (2008). Arctic perennial ice cover over the last 14 million years. *Paleoceanography*, 23(1), PA1S07. doi:10.1029/2007pa001479

This Article is brought to you for free and open access by the Ocean, Earth & Atmospheric Sciences at ODU Digital Commons. It has been accepted for inclusion in OEAS Faculty Publications by an authorized administrator of ODU Digital Commons. For more information, please contact digitalcommons@odu.edu.

Arctic perennial ice cover over the last 14 million years

Dennis A. Darby¹

Received 29 April 2007; revised 1 August 2007; accepted 27 September 2007; published 5 February 2008.

[1] Knowledge of the long-term history of the perennial ice is an important issue that has eluded study because the Cenozoic core material needed has been unavailable until the recent Arctic Coring Expedition (ACEX). Detrital Fe oxide mineral grains analyzed by microprobe from the last 14 Ma (164 m) of the ACEX composite core on the Lomonosov Ridge were matched to circum-Arctic sources with the same mineral and 12-element composition. These precise source determinations and estimates of drift rates were used to determine that these sand grains could not be rafted to the ACEX core site in less than a year. Thus the perennial ice cover has existed since 14 Ma except for the unlikely rapid return to seasonal ice between the average sampling interval of about 0.17 Ma. Both North America and Russia contributed significant Fe grains to the ACEX core during the last 14 Ma.

Citation: Darby, D. A. (2008), Arctic perennial ice cover over the last 14 million years, *Paleoceanography*, 23, PA1S07, doi:10.1029/2007PA001479.

1. Introduction

[2] Recent model predictions of the disappearance of the Arctic perennial ice cover in as little as 50 years are cause for concern [Holland *et al.*, 2006; Comiso, 2006]. While alarming, we still do not understand the long-term history of the perennial ice cover in the Arctic Ocean to fully appreciate the causes of its formation and whether it came and went several times in the past. The ACEX composite core provides a window into the long history of the Arctic pack ice [Backman *et al.*, 2006, 2008]. This paper uses the precise source determination of detrital Fe oxide grains to determine whether they require more than a year to drift to the ACEX core site. Both straight line drift and curvilinear drift patterns analogous to that of today are considered along with a range of drift velocities to estimate the drift time based on the sources of these Fe grains. This is the only provenance source technique that allows for precise matching of individual ice-rafted grains in core samples to circum-Arctic shelves. Simply stated, if all of the grains require less than a year to reach the ACEX site, then it can be assumed that only seasonal ice existed. If significant numbers of these ice-rafted grains come from sources of more than 1 year of typical ice drift time, then a perennial ice cover is required.

[3] The discovery of sand and coarser detritus in the ACEX core back to the mid-Eocene (~45 Ma) suggests some ice rafting back to this time [Moran *et al.*, 2006]. Ice rafting is the only reasonable explanation for sand-sized grains to reach the Lomonosov Ridge, at least for the last 14 million years covered by this study when this ridge was certainly a topographic marine high in the Arctic Ocean, separated from the Barents Shelf by deep ocean. Both sea

ice and glacial ice transport sand-sized sediment but sea ice is usually restricted to material less than about 200–250 μm [Reimnitz *et al.*, 1993b, 1998; Nürnberg *et al.*, 1994; Eicken *et al.*, 2005]. However, because sea ice can incorporate even pebbles and cobbles under some circumstances, a sea ice mode can only be determined by precise knowledge of the source, where this source is unglaciated. Textural aspects of the ice-rafted sediment can also be helpful in distinguishing the type of ice involved [Reimnitz *et al.*, 1987, 1993a; Nürnberg *et al.*, 1994; Darby, 2003].

[4] The mineralogy and chemistry of individual Fe oxide mineral grains has been used to match grains to unique composition types in source areas around the Arctic, even after drift distances of thousands of kilometers [Darby *et al.*, 2002]. These Fe oxide minerals provide unique compositions, much like a fingerprint, because they incorporate large amounts of accessory elements into their crystal whether they form during igneous or metamorphic processes. For example, magnetite can accommodate up to 40% substitution for Fe in its composition and still remain magnetite [Darby, 1998].

2. Methods

2.1. Sampling and Fe Grain Analysis

[5] The upper 164 m of the composite ACEX core was sampled at somewhat irregular intervals averaging 1.06 m (± 1.18 m, standard deviation). On the basis of the age model for this core [Backman *et al.*, 2008], this sampling interval equates to an average of about 0.17 Ma (± 0.35). On average then, the 1 cm thick sample slices would equate to about 1 ka. These 1 cm thick slices consisting of an average 6.8 g dry weight (freeze-dried) were dispersed in deionized water and wet sieved through 250 μm , 63 μm , and 45 μm sieves [Darby and Bischof, 1996]. The dried fractions >45 μm were examined under a microscope for aggregates and resieved where necessary. The magnetic Fe oxide grains consisting of magnetite, titanomagnetite, ilmenite, hematite, and chromite plus various exsolved combinations of these

¹Department of Ocean, Earth, and Atmospheric Sciences, Old Dominion University, Norfolk, Virginia, USA.

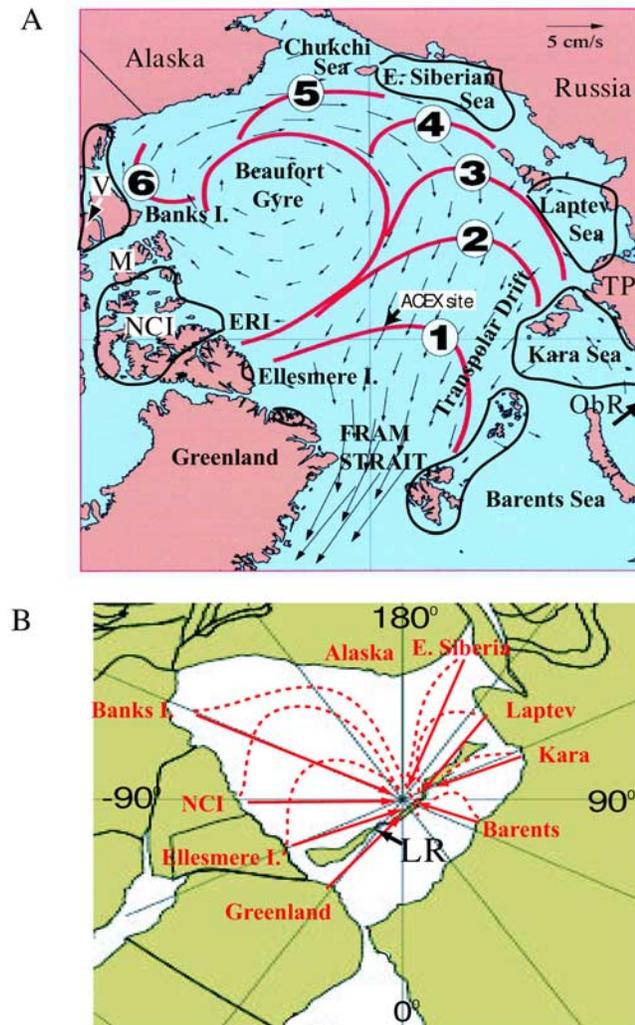


Figure 1. (a) Modern drift ice trajectories showing the average years (circled) to Fram Strait [from *Colony and Thorndike*, 1984; *Rigor*, 1992]. Note that by subtracting 1 year from these, you have the average time for ice drift today to the ACEX core site. The Fe grain source areas are encircled except for the northern Alaska and Chukchi source areas [see *Darby*, 2003]. Abbreviations are V, Victoria Island (location shown by arrow); M, Melville Island; ERI, Ellef Ringnes Island; NCI, northern Canadian Islands; and TP, Taymyr Peninsula. (b) Tectonic reconstruction of the Arctic Ocean with the circum-Arctic landmasses rotated back in time via their plate boundaries to their 15 Ma location relative to ACEX. Two possible end-member drift patterns are the projected straight-line (solid) and analogous Modern (dashed) drift patterns from potential source areas to the ACEX core site on the Lomonosov Ridge (LR). Reconstruction does not depict accurate shorelines.

minerals were separated from the 45–63 μm and 63–250 μm fractions with a hand magnet and the Frantz magnetic separator [Darby and Bischof, 1996]. The Fe grains from both size fractions were mounted together in epoxy plugs, ground to expose the grains, polished, photo-

graphed, and identified under reflected light at 1000 X using oil immersion. The plugs were then cleaned and about 100 grains from each sample analyzed (avg. = 92 ± 22) by an electron probe microanalyzer for 12 element oxides [Darby and Bischof, 1996].

[6] Matching the Fe grains to sources utilizes the large circum-Arctic database of more than 400 samples and 20,000 grain analyses from all of the shelves and coastal areas around the Arctic Ocean for these same 12 elements [Darby, 2003]. Unique source compositions result from combinations of the 12 elements in each mineral type. The matching employs discriminant function analyses with very stringent probabilities so that the grains are only matched to source compositions of the same mineral type at >0.95 probability of group membership and >0.5 probability that the matched grain is closer for all 12 elements to the group centroid than all grains composing that group from the source area. Tests of the robustness of this approach indicate that less than 5–8% of the matches are in error, thus the cutoff for a definitive match to a source area is set at 8% of the total grains matched in a sample or about 5 grains [Darby, 2003]. This approach avoids forced matches and an average of 56% of the analyzed grains (50 grains ± 15 per sample) are successfully matched to a source. Because so few grains matched to a particular source area can definitively identify a source, far less grains are required for this sourcing method than most other source determinations [Darby, 2003]. In order to avoid errors due to low grain numbers and less than statistically significant numbers of matched Fe grains, a weighted percent is used [Darby, 2003]. This is computed by multiplying the percent of matched Fe grains by the actual number of these grains and dividing by 10 so that fewer than 10 grains results in a decreased weighted percent compared to the normal percent. These weighted percents do not sum to 100% and all weighted percents greater than or equal to 10% are significant based on tests showing fewer than 8% erroneous matches [Darby, 2003].

2.2. Estimated Ice Drift

[7] In order to determine the distances from the different source areas important in the ACEX core, the present positions of these source areas were rotated back to their 15 Ma position relative to the tectonic plate on which each occurs (see www.ods.n.de for rotation procedures). This resulted in a 15 Ma tectonic reconstruction of the landmasses around the Arctic Ocean but not a true map of the Arctic coastline because these landmasses have also eroded and changed over this time. This reconstruction only provides an estimate of the distances from these landmasses to the ACEX core site at 15 Ma. Owing to the reduced size of the Arctic Ocean at 15 Ma, projected drift paths were slightly shorter for some sources than today. Because the actual drift paths are not known, drift distances from detected sources to the ACEX core site are calculated using a straight line and not a curvilinear path analogous to the Modern Beaufort Gyre and Transpolar Drift (Figures 1a and 1b). The straight-line distances approximated in Figure 1b are then used to calculate the time it might take ice to drift these distances, which are based on the actual rotated

Table 1. Drift Distances and Times Based on a Reconstruction of the Arctic Ocean at 15 Ma and Today^a

	Latitude	Longitude	Kilometers	Drift Years for Different Rates		
				5 cm/s	3 cm/s	1.8 cm/s
<i>Modern Locations</i>						
ACEX core site	87.54	-138.30				
Northern Greenland	83.3	30.00	1014	0.6	1.0	1.8
Northern Ellesmere Island	83	75	1017	0.6	1.0	1.8
Ellef Ringnes Island	79.25	103.00	1347	0.8	1.4	2.4
Banks Island	75	122.00	1733	1.1	1.8	3.1
East Siberian Sea	72	-162.00	1753	1.1	1.9	3.1
Chukchi Sea	70	165.00	2084	1.3	2.2	3.7
Laptev Sea	74	-130.00	1508	1.0	1.6	2.7
Kara Sea	76	-90.00	1389	0.9	1.5	2.4
N Kara Sea	82	-85.00	758	0.5	0.8	1.3
Mackenzie Delta	70	130.00	2247	1.4	2.4	4.0
Barents Sea	81.3	-31.00	1080	0.7	1.1	1.9
<i>15 Ma Reconstructed Locations</i>						
Northern Greenland	82.0	17.5	993	0.6	1.0	1.7
Northern Ellesmere Island	83.0	58.1	999	0.6	1.1	1.8
Ellef Ringnes Island	80.4	92.6	1320	0.9	1.4	2.3
Banks Island	76.5	116.2	1734	1.1	1.8	3.1
East Siberian Sea	73.3	-159.2	1785	1.1	1.9	3.1
Chukchi Sea	71.9	164.5	2106	1.3	2.2	3.7
Laptev Sea	74.4	-124.9	1541	1.0	1.6	2.7
Kara Sea	76.2	-84.9	1295	0.8	1.4	2.3
Northern Kara Sea	82.1	-77.6	640	0.4	0.7	1.1
Mackenzie Delta	71.7	126.1	2253	1.4	2.4	4.0
Barents Sea	81.0	-25.5	927	0.6	1.0	1.6

^aThe location for the northern Canadian Islands is represented by the island closest to the ACEX core site, Ellesmere Island. Ellef Ringnes Island could also be used for this source area. All distances are straight line, direct to ACEX core site at 15 Ma and today.

coordinates (Table 1). The curvilinear paths of modern ice drift would take longer to reach the ACEX core site, so the straight-line drift paths provide the defining test of whether the drift path requires more than a year and thus perennial ice cover.

[8] On the basis of the experience provided by several decades of data from the International Arctic Buoy Drift project, ice rarely drifts in a straight-line direction for more than a month. However, an average overall drift time for Modern ice from various locations around the Arctic can be calculated [Colony and Thorndike, 1984; Rigor and Wallace, 2004]. For example, ice formed near Ellef Ringnes Island would drift with the Beaufort Gyre until it reached the 180° longitude where it either remains in the Beaufort Gyre or it blends with the Transpolar Drift (TPD) and moves across the central Arctic toward the ACEX core site [Rigor and Wallace, 2004]. Total transit time would be about 5–6 years if the ice escapes the Beaufort Gyre the first time around (Figure 1a). Using these times and the distances covered, the estimated drift speed is between 1.0 and 5 cm/sec. Today the overall average ice drift is only 1.8 cm/s in the Amerasian half of the Arctic, west of the Lomonosov Ridge (I. Rigor, personal communication, 2007). Using this speed, nearly all of the source areas are more than a 1-year drift from the ACEX site today and only ice from the northern Kara Sea and perhaps northern Greenland could drift to this core site assuming a straight-line path in less than a year (Table 1).

[9] If the Arctic is reduced in size back to the 15 Ma reconstruction, there is little change in the drift times (Figure 1b and Table 1). The Fram Strait had already

attained sufficient width to support opposing exit and entry surface currents at 14 Ma [Jakobsson *et al.*, 2007] but the Bering Strait was not present until about 5 Ma [Marincovich and Andrey, 1999; Gladenkov *et al.*, 2002]. The absence of this important inflow might have slowed ice drifts in the Arctic [Aagaard and Carmack, 1989; deBoer and Nof, 2004]. Thus the estimates of drift years to the ACEX core site shown in Table 1 for 15 Ma are probably too low. If average modern drift rates are 1.8 cm/s then the 15 Ma rate would be slower, but in order to provide a conservative determination of perennial ice conditions, a rate of 3 cm/s will be used. Assuming a straight-line drift instead of the more likely curvilinear drift paths and using a 3 cm/s drift speed, only those sources more than 1 year of drift distant are used as an indicator of perennial ice conditions. Using this straight-line drift speed, both today and at 15 Ma, the sources from the Laptev Sea east to the Canadian Islands (Ellesmere Island) would be more than a 1-year drift distance from the Lomonosov Ridge ACEX core site (Figure 1b and Table 1). Because the Modern drift path is curvilinear [Rigor and Wallace, 2004] and the drift paths 15 Ma were probably curvilinear too, all of these sources would actually be much more than 1-year drift from the ACEX site throughout the last 15 Ma.

3. Results and Discussion

3.1. Fe Grain Matches

[10] The sum of Fe grains matched to sources more than a years drift from the ACEX core site (Table 1) show significant numbers throughout the last 14 million years

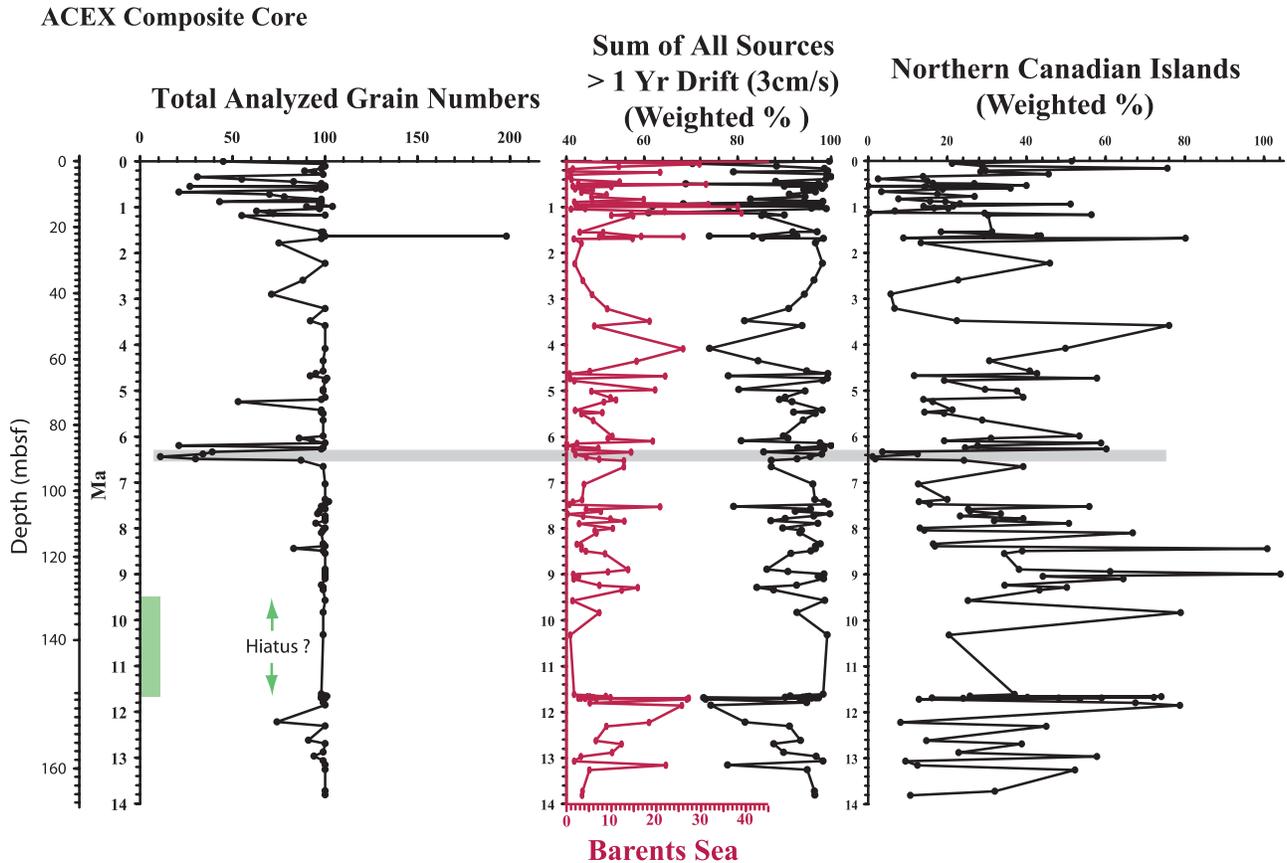


Figure 2a. Total number of Fe grains analyzed and Fe grain matches to all sources more than 1-year drift distance from the ACEX core site assuming an average 3 cm/s drift at 15 Ma, which includes sources from Ellesmere Island west to the southern half of the Kara Sea. The weighted percent of Fe grains from the Barents Sea is shown separately and is the only significant source within 1-year drift (Table 1). This source clearly accounts for most of the remaining Fe grains not included in the sources plotted as >1-year drift distance. The northern Canadian Islands (all of the Queen Elizabeth Islands north of 75°N) account for an important percentage of the Fe grains from sources of more than 1-year drift distance. At nearly all depths, save a few in the last 1.1 Ma and those during an interval of low total grain numbers highlighted in gray between 6.3 and 6.5 Ma, the sources of more than 1-year drift distance contain large enough numbers of grains matched to these combined sources to be highly significant ($P > 0.99$).

except for a few isolated samples between 6.3 and 6.5 Ma and within the last 1.1 Ma where the total number of Fe grains recovered for analysis are low (Figure 2a). The average number of Fe grains per sample matched to these distant sources is $35 (\pm 11)$. Even without Ellesmere Island, the average number of grains matched to distant sources is $30 (\pm 10)$. Unless the sampling missed rapid switches to seasonal ice, this data indicates that a perennial ice cover has persisted for the last 14 million years. While there is a chance that the amount of time between most samples is sufficient for a temporary switch to seasonal ice, the probability that this condition is missed in all 133 samples from the ACEX core is low.

[11] Because the Fe grains come from all of the sources between the Canadian Islands and the southern Kara Sea (Figure 2b), the ice cover must have extended across the entire central Arctic during the summers. Otherwise, the ice

transporting grains from these sources would have melted before reaching the Lomonsov Ridge at ACEX. The margins could still have been ice free as they are today in summer.

3.2. Sea Ice Rafting or Glacial Bergs?

[12] In previous studies of ice rafting using the Fe grain fingerprinting proxy, the sediment was younger than 100 ka [Bischof and Darby, 1997; Darby et al., 1997; Darby and Bischof, 2004; Darby et al., 2002; Polyak et al., 2003]. Any sources that were not glaciated within this interval were considered to be sea ice entrainment areas and glacial icebergs could be eliminated as a transport agent. Only the Canadian Islands such as Ellesmere or Ellef Ringnes Island source areas, the Barents Sea, Greenland, and the outlet areas for the Laurentide Ice sheet such as Banks Island were problematic because they could be the source of

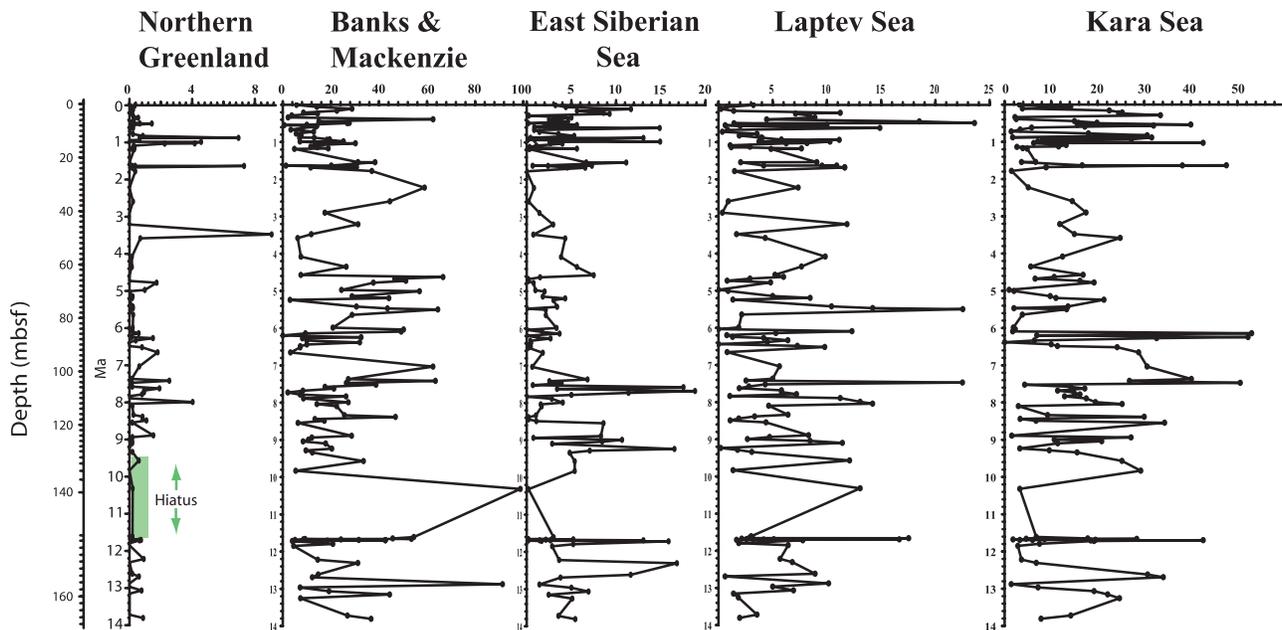


Figure 2b. Individually important sources showing a fluctuating pattern so that no one source dominates throughout the core. Clearly, both North American and Russian (combined East Siberian, Laptev, and Kara seas) sources contribute nearly the same throughout the ACEX core. Plots are weighted percent, and values greater than 10% are considered significant.

both icebergs and sea ice. All of these glaciated areas except northern Greenland were important sources for the ACEX core over the last 14 Ma. This and the fact that there is a much larger uncertainty as to which circum-Arctic areas might have undergone some form of glaciation prior to 400 ka, dictates that relying on areas known to be glaciated during the middle to late Pleistocene is not a reliable criteria for distinguishing sea ice rafting from iceberg rafting over the last 14 Ma.

[13] A comparison of the 10 largest Fe grains in each sample of 13 sea ice samples (HOTRAX [Darby *et al.*, 2005]), 10 till samples from Banks and Victoria Islands [Darby and Bischof, 1996], and 69 random ACEX samples shows that there is a clear separation between the glacial samples and the other two groups with bulk sand fraction abundances $>250 \mu\text{m}$ (Figure 3). The one sea ice sample with Fe grains larger than $200 \mu\text{m}$ probably originated as anchor ice forming in the nearshore environment where it could entrain coarser sediment by freezing to the bottom. It is clearly different from the other sea ice samples. The overlap between some of the ACEX samples with the sea ice samples would be improved if all of the aggregated grains in the ACEX samples were removed from the $>250 \mu\text{m}$ fraction as was the case with the sea ice and till samples. The ACEX samples could not be sonified to break up these aggregates because this would also destroy some of the microfauna needed for other studies.

[14] This size data indicates that most, if not all, of the ACEX samples involve sea ice rafting and not glacial icebergs. Because some icebergs can transport finer sediment than the Laurentide till samples shown here, we cannot preclude that all of the ACEX sediment was trans-

ported by sea ice, but the lack of any Fe grains larger than $180 \mu\text{m}$ in the ACEX samples suggests that glacial bergs were a minor transport mode for these samples. Closer spaced sampling might have included more glacial ice-rafted sediments, especially in the last 1.5 Ma.

3.3. Sea Ice Entrainment Processes

[15] The Fe grains represent the coarser end of the sediment normally entrained by what is thought to be the most common process of sea ice entrainment, suspension freezing [Reimnitz *et al.*, 1993b]. This occurs in water depths generally less than 30 m during open water conditions when winds and cold air produce turbulent mixing of super cooled water to the bottom and fine sediment is temporarily suspended. Ice crystals form near the bottom and float the suspended sediment to the surface [Reimnitz *et al.*, 1993b; Nürnberg *et al.*, 1994]. Other means of entrainment include anchor ice where the ice freezes to the bottom [Reimnitz *et al.*, 1987]. Evidence for this type of ice-rafted sediment generally includes sediment larger than $250 \mu\text{m}$ possibly with rounded pebbles and/or megafauna. When anchor ice entrains fine-grained sediment, the resulting deposit is very similar to that from suspension freezing. The importance of windblown sediment onto the pack ice or overwash of flooding rivers is not certain but thought to be of minor importance [Reimnitz *et al.*, 1993b; Nürnberg *et al.*, 1994]. Given the length of time represented by the ACEX core samples (1 cm \sim 0.5–1.5 ka), the frequency of these entrainment events is not an issue and that at least the most common processes would occur several times over this sample interval in all the shelf areas around the Arctic

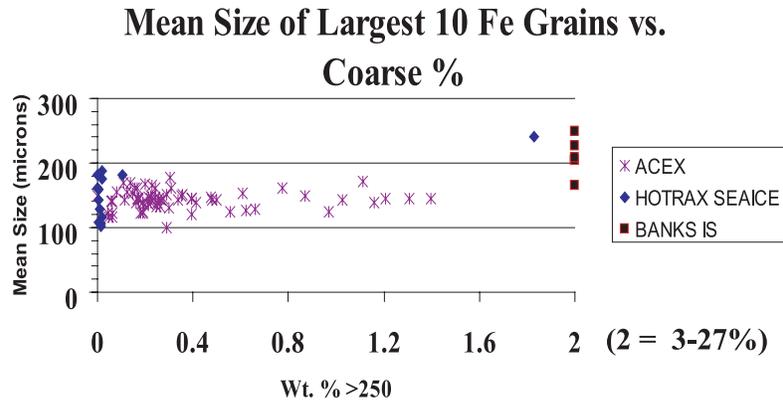


Figure 3. Mean of the largest 10 Fe grains (long diameter) plotted against the total $>250 \mu\text{m}$ for Modern sea ice samples (Healy Oden Trans_Arctic Expedition (HOTRAX)), Laurentide glacial tills on Banks and Victoria islands, and the last 14 Ma record in the ACEX core. There is overlap of the Fe grain sizes from Modern sea ice samples and ACEX samples with $<0.2\%$ sand $>250 \mu\text{m}$. The glacial till deposits contain 3–27% $>250 \mu\text{m}$ and for convenience are plotted at 2%. The Fe grains in these samples are clearly coarser than sea ice except for the one probable anchor ice sample with Fe grains $>200 \mu\text{m}$.

Ocean. Thus the Fe grains would still be representative of the dominant sources and thus net ice drift paths.

[16] Not all entrainment events will involve sediment as coarse as $45\text{--}250 \mu\text{m}$. However, again, given the large amount of time represented by the sample slices from the ACEX cores, the assumption is that events involving this coarser fraction would be occurring often enough to leave a record in each sample.

[17] The abundance of Fe grains in the ACEX core samples averages 16 grains/g (± 7). This is slightly larger than the average of 11.8 grains/g (± 3.8) in Holocene sediment in core 94BC28 from nearby on the Lomonosov Ridge, probably because of compaction of the older ACEX sediment. Thus entrainment of Fe grains occurred often enough to be present, if not abundant in all samples during the last 14 Ma.

3.4. Relative Importance of Source Areas

[18] The dominant source on average in the ACEX composite core for the last 14 Ma is the northern Canadian Islands including Ellesmere Island (Figure 2a and Table 2). This is somewhat surprising because this area does not contain extensive shelf areas where sea ice entrainment might occur. However, the Fe grains reflect the sources where entrainment is most common, and these might not always be the areas where the largest volume of ice forms. For example, today a large amount of ice forms on the extremely wide East Siberian Sea, but little sediment is entrained, at least sand-sized sediment, by this ice based on the low numbers of grains matched to this large shallow, source area (Table 2) [Darby *et al.*, 2002]. Thus the width of the shelf is not related to the amount of sediment, especially coarser sediment entrained by sea ice.

[19] The consensus of Modern sea ice sediment studies is that the Laptev Sea is the dominant source for the part of the Arctic within the main track of the TPD, including the

ACEX site [Nürnberg *et al.*, 1994; Nørgaard-Pedersen *et al.*, 2003]. This is based largely on clay mineral abundances, in particular, slightly elevated levels of the clay smectite, which occurs in the Tamyr Peninsula and thus the nearby Laptev Sea and parts of the Kara Sea. Drift tracks of sea ice also suggest the eastern Laptev Sea as an important sea ice factory [Eicken *et al.*, 1997, 2000, 2002].

[20] The dirty sea ice samples collected during the Healy Oden Trans-Arctic Expedition (HOTRAX) on the Lomonosov Ridge and at the Pole are only between 230 and 450 km closer to North America than the ACEX site and they show a significant contribution from the northern Canadian Islands (Figure 4). Also important in these sea ice samples from 2005 are the Laptev and Kara seas, suggesting that the ice in the TPD reaches these sample locations.

[21] The presence of multiple sources in the same sea ice sample is due to mixing over several melt seasons as the sediment collects in melt ponds on the ice surface and ice floes break up and rejoin throughout their long transit across the Arctic [Darby, 2003]. Ice floes in the Beaufort Gyre near Alaska were found to contain mixed sources 40% of the time [Darby, 2003] while these ice floes near the Pole that are at least 3 years from the major sources of entrainment on the marginal shelves [Rigor and Wallace, 2004], contain mixed sources in more than half the samples. The numbers of these dirty sea ice samples is still very small, even including those collected by all expeditions over the last 30 years [Darby, 2003].

[22] Box core 94BC28 on the Lomonosov Ridge, only 280 km north of ACEX has better resolution than the ACEX core during the last 50 ka. It along with box core PS1230 in Fram Strait can be used to compare changes in sources from the more recent sediment record of Fe grain sources to that found in the ACEX core. Box core 94BC28 is 43 cm in length and contains sediment dated to an extrapolated

Table 2. Comparison of Primary Sources Averaged Over 14 Ma in ACEX Core With the Last 50 ka Average in a Nearby Core 94BC28 and Last 34 ka in PS1230 From Fram Strait^a

Source Area	Average Value Plus/Minus Standard Deviation		
	94BC28 at 88.87°N, 140.18°E	PS1230 at 78.9°N, 4.8°W	ACEX at 87.52°N, 136.11°E
Northern Greenland	1.5 ± 2.6	4.0 ± 4.1	0.8 ± 2.2
Northern Canadian Islands	21.3 ± 12.0	19.1 ± 7.0	33.5 ± 17.9
Ellef Ringnes Island	13.0 ± 19.1	7.6 ± 5.2	1.2 ± 1.5
Northern Ellesmere Island	3.4 ± 5.1	1.5 ± 2.5	12.5 ± 7.7
Banks Island	10.4 ± 12.3	19.1 ± 8.6	17.4 ± 15.9
Mackenzie River	4.0 ± 5.2	2.3 ± 3.7	5.9 ± 6.1
Chukchi Sea	2.7 ± 3.7	4.1 ± 3.7	0.7 ± 1.0
East Siberian Sea	8.3 ± 8.6	4.9 ± 4.5	4.5 ± 4.9
Laptev Sea	7.2 ± 7.8	11.5 ± 6.5	6.5 ± 3.4
Kara Sea	9.3 ± 9.3	7.9 ± 7.7	16.9 ± 12.1
Northern Kara Sea	1.0 ± 2.5	0.4 ± 1.2	0.2 ± 0.4
Barents Sea	2.7 ± 3.7	10.2 ± 6.2	10.2 ± 9.8

^aValues for core 94BC28 are from *Darby et al.* [1997]; values for PS1230 are from *Darby* [2003]. While the northern Canadian Islands are the largest source or one of the largest in all three cores, there is a significant shift from northern Ellesmere Island to Ellef Ringnes Island from the older ACEX record to the more recent record. Significant differences between the ACEX and younger core records are in bold type. Note that Ellef Ringnes Island and northern Ellesmere Island are included in the northern Canadian Islands, and the Kara Sea also includes the northern Kara Sea.

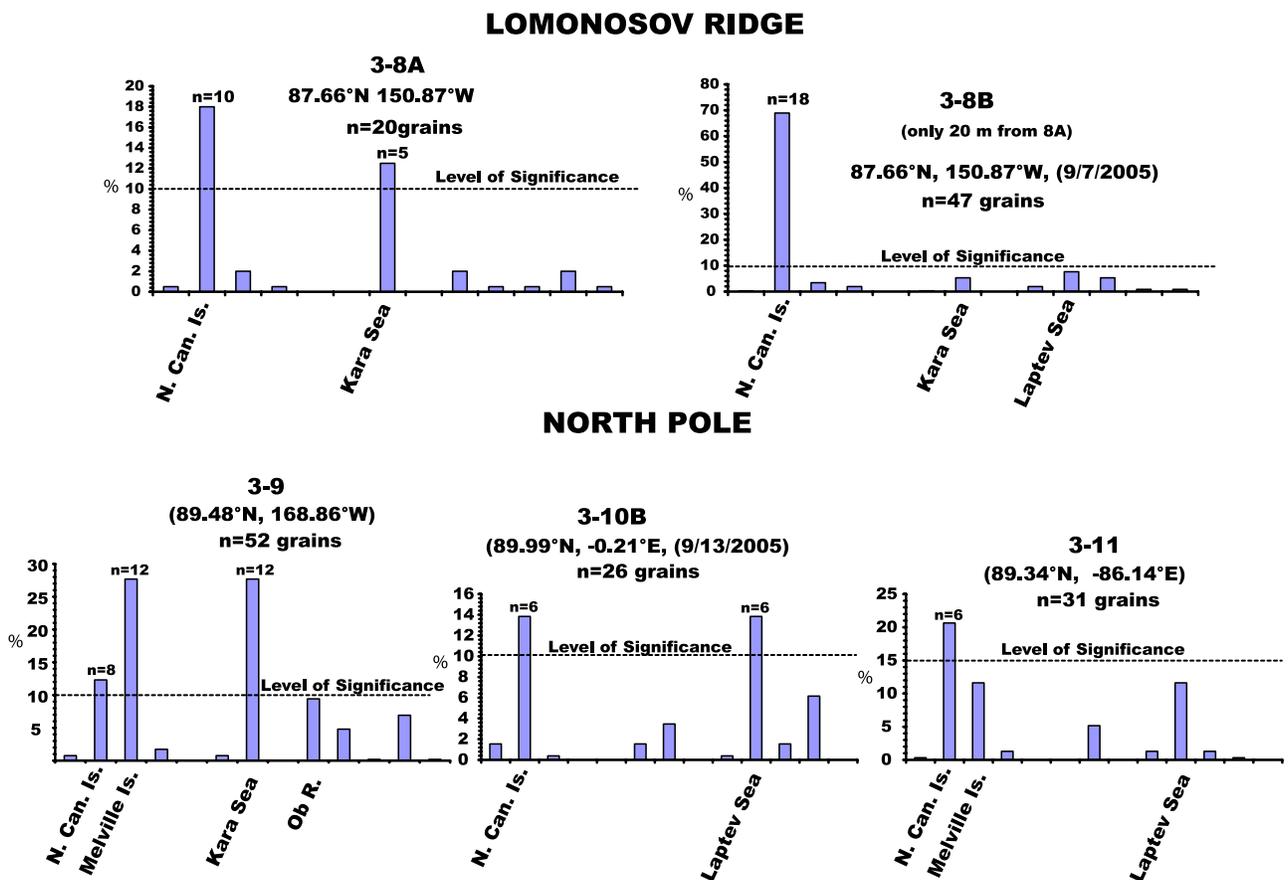


Figure 4. Fe grain sources from dirty sea ice collected during the Healy Oden Trans_Arctic Expedition of 2005 [*Darby et al.*, 2005]. The prevalence of northern Canadian Island (NCI) sources in all five samples from four locations is even more striking because the Melville Island source can be combined with this NCI source area. In the same way the Ob River source could be considered part of the Kara Sea.

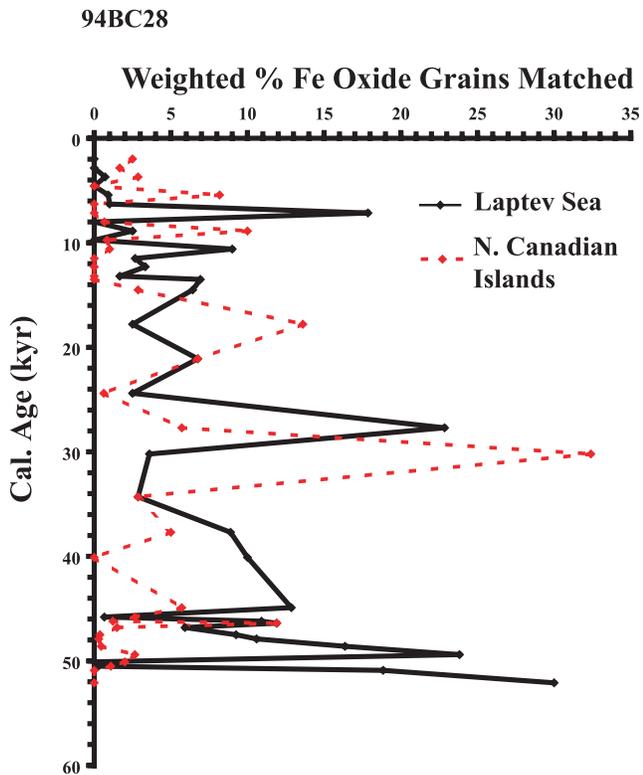


Figure 5. Comparison of Fe grains matched to the Laptev Sea and the northern Canadian Islands over the last 52,000 years in core 94BC28 from the Lomonosov Ridge near the ACEX site. The age model of this core is based on 15 accelerator mass spectrometry radiocarbon dates corrected for a reservoir time of 440 years and converted to calendar age using the radiocarbon calibration program Calib. 4.1 and extrapolated to 52 ka [Darby *et al.*, 1997].

calendar age of 52 ka (Figure 5) [Darby *et al.*, 1997]. PS1230 is 47 cm with an extrapolated calendar age of 34 ka [Darby *et al.*, 2002]. The northern Canadian Islands are the single largest source of Fe grains in both of these box cores and the composite ACEX core (average 21.3%, 19.1%, and 33.5%, respectively). This source is nearly equal or higher than the combined Barents, Kara, and Laptev seas, which only average 19.2% in 94BC28, 20.6% in PS1230, and 30.8% in the ACEX core (Table 2). The dominant sources are the same in all three cores, except for the Barents Sea and Kara Sea sources. Both are lower in 94BC28 possibly because it is located closest to Greenland and to the western margins of the TPD drift path where ice from these sources is primarily transported (Figure 1a). These cores and the ACEX core show significant contributions from both North American and Russian sources (Figures 2a and 5 and Table 2).

[23] There is a significant shift in the dominant sources within the northern Canadian Islands (NCI) from the more recent Pleistocene records of 94BC28 and PS1230 to the much older ACEX record (Table 2). In the ACEX record, Ellesmere Island is the primary NCI source and in the last 52 ka record of 94BC28 or 34 ka record of PS1230, Ellef

Ringnes Island dominates. This might indicate a change in ice drift paths near the NCI or a change in the abundance of sand-sized grains available for entrainment at these two sites.

[24] For most of the last 14 Ma, Fram Strait was narrower than it is today. This could have slowed drift rates and allowed Ellesmere Fe grains to move into the center of the Arctic instead of east along the northern Greenland coast as often occurs today (Figure 1a). Of course, some Ellesmere ice does drift west into the Beaufort Gyre and then into the center of the Arctic, where the TPD might bring it near the ACEX core site. The ice island T-3 from Ellesmere Island drifted into the Beaufort Gyre but eventually exited the Arctic nearer the coast of Greenland than the ACEX site. Overall, a different pattern of drift than today involving ice originating near Ellesmere Island and then drifting into the center of the Arctic Ocean must have occurred more frequently in the distant past than in the last 50 ka. Ellef Ringnes Island is west of Ellesmere Island and ice from this island would likely drift west into the Beaufort Gyre, from where it too should drift into the TPD and across the ACEX site. So if drift patterns are the cause of this difference, then a very different drift pattern is required to explain the abundance of Ellesmere grains relative to Ellef Ringnes grains in the ACEX core.

[25] Peary Channel on the west side of Ellef Ringnes Island was one of the main conduits for ice from the Innuitian Ice Sheet that covered the NCI during the glacial intervals [Atkinson, 2003] and thus the shelf just offshore of this channel would be an important site for glacial deposition during the Pleistocene. Reentrainment of these deposits by sea ice might produce abundant dirty ice containing sand that would drift westward into the Beaufort Gyre (BG) before merging with the TPD and arriving at the ACEX core site following a Modern drift pattern (Figure 1a). Prior to the Innuitian Ice Sheet, Ellef Ringnes Island might not have contained abundant coarse deposits on its shelf and thus could not contribute significant Fe grains to the ACEX core.

[26] Furthermore, prior the existence of the Innuitian Ice Sheet, Ellesmere Island may have had sand delivered to its coast and shelf by mountain streams because of its higher relief than the northern Canadian Islands to the west such as Ellef Ringnes Island. Also, Ellesmere might have spawned small glaciers sooner than the lower lying islands to the west. Both of these possibilities might explain the greater contribution of Fe grains from Ellesmere Island in the older ACEX core.

4. Conclusions

[27] The overwhelming numbers of Fe grains from circum-Arctic shelves and coastal sources that are more than a year drift time from the ACEX core site, even assuming a faster than probable drift, indicates that a perennial ice cover has persisted for at least the last 14 Ma. The likelihood that every ACEX sample missed a time of seasonal ice is very low. This suggests that the perennial ice cover has been a stable feature of the Arctic Ocean. Thus its predicted demise in the next 50 years is indeed cause for concern. Ongoing work on the ACEX core samples below 164 m core depth

will hopefully discover the initiation of the perennial ice cover, but it might occur during the 26 Ma hiatus in this core [Backman *et al.*, 2006, 2008; Moran *et al.*, 2006]. This underscores the need for additional drilling in the Arctic Ocean.

[28] During the last 14 Ma there has been a subtle but possibly significant shift in the sources of ice-rafted Fe grains, especially compared to the more recent record of the last 50 ka. This change is from a much larger contribution from Ellesmere Island in the distant past to an increased input from near Ellef Ringnes Island more recently. Because a change in drift patterns would probably affect ice drift from both of these nearby sources in a similar fashion, the

most reasonable explanation for this source change is the possible increased delivery of sand to the Ellef Ringnes shelf area by glaciers in the Pleistocene.

[29] **Acknowledgments.** This research was funded by the NSF (ODP) grant 0550109. Thanks are extended to M. Jakobsson and I. Rigor for their help and discussions on ice drift distance calculations at 15 Ma and drift trajectories today. D. Piper, M. Jakobsson, and T. Yerace made helpful suggestions for the improvement of the paper. ACEX samples were provided by K. Moran, and the preview of the ACEX core age model was provided by J. Backman. J. Rand and S. Miles helped with the Fe grain size determinations.

References

- Aagaard, K., and E. C. Carmack (1989), The role of sea ice and other fresh water in the arctic circulation, *J. Geophys. Res.*, *94*, 14,485–14,498.
- Atkinson, N. (2003), Late Wisconsinan glaciation of Amund and Ellef Ringnes islands, Nunavut: Evidence for the configuration, dynamics, and deglacial chronology of the northwest sector of the Innuitian Ice Sheet, *Can. J. Earth Sci.*, *40*, 351–363.
- Backman, J., K. Moran, D. B. McInroy, L. A. Mayer and the Expedition 302 Scientists (2006), *Proceedings of the Integrated Ocean Drilling Program*, *302*, Integr. Ocean Drill. Program Manage. Int., Inc., doi:10.2204/iodp.proc.302.
- Backman, J., *et al.* (2008), Age model and core-seismic integration for the Cenozoic ACEX sediments from the Lomonosov Ridge, *Paleoceanography*, doi:10.1029/2007PA001476, in press.
- Bischof, J. A., and D. A. Darby (1997), Mid to Late Pleistocene ice drift in the western Arctic Ocean: Evidence for a different circulation in the past, *Science*, *277*, 74–78.
- Colony, R., and A. S. Thorndike (1984), An estimate of the mean field of Arctic sea ice motion, *J. Geophys. Res.*, *89*, 10,623–10,629.
- Comiso, J. C. (2006), Abrupt decline in the Arctic winter sea ice cover, *Geophys. Res. Lett.*, *33*, L18504, doi:10.1029/2006GL027341.
- Darby, D. A. (1998), Mysterious iron-nickel-zinc spherules, *Can. J. Earth Sci.*, *35*, 23–39.
- Darby, D. A. (2003), Sources of sediment found in sea ice from the western Arctic Ocean, new insights into processes of entrainment and drift patterns, *J. Geophys. Res.*, *108*(C8), 3257, doi:10.1029/2002JC001350.
- Darby, D. A., and J. F. Bischof (1996), A statistical approach to source determination of lithic and Fe-oxide grains: An example from the Alpha Ridge, Arctic Ocean, *J. Sediment. Res.*, *66*, 599–607.
- Darby, D. A., and J. F. Bischof (2004), A Holocene record of changing Arctic Ocean ice drift, analogous to the effects of the Arctic Oscillation, *Paleoceanography*, *19*, PA1027, doi:10.1029/2003PA000961.
- Darby, D. A., J. F. Bischof, and G. A. Jones (1997), Radiocarbon chronology of depositional regimes in the western Arctic Ocean, *Deep Sea Res., Part II*, *44*, 1745–1757.
- Darby, D. A., J. F. Bischof, R. F. Spielhagen, S. A. Marshall, and S. W. Herman (2002), Arctic ice export events and their potential impact on global climate during the late Pleistocene, *Paleoceanography*, *17*(2), 1025, doi:10.1029/2001PA000639.
- Darby, D. A., M. Jakobsson, and L. Polyak (2005), Icebreaker expedition collects key Arctic seafloor and ice data, *Eos Trans. AGU*, *86*(52), 549.
- deBoer, A. M., and D. Nof (2004), The exhaust valve of the North Atlantic, *J. Clim.*, *17*(3), 417–422.
- Eicken, H., E. Reimnitz, V. Alexandrov, T. Martin, H. Kassens, and T. Viehoff (1997), Sea-ice processes in the Laptev Sea and their importance for sediment export, *Cont. Shelf Res.*, *17*, 205–233.
- Eicken, H., J. Kolatschek, J. Freitag, F. Lindemann, H. Kassens, and I. Dmitrenko (2000), Identifying a major source area and constraints on entrainment for basin-scale sediment transport by Arctic sea ice, *Geophys. Res. Lett.*, *27*, 1919–1922.
- Eicken, H., H. R. Krouse, D. Kadko, and D. K. Perovich (2002), Tracer studies of pathways and rates of meltwater transport through Arctic summer sea ice, *J. Geophys. Res.*, *107*(C10), 8046, doi:10.1029/2000JC000583.
- Eicken, H., R. Gradinger, A. Gaylord, A. Mahoney, I. Rigor, and H. Melling (2005), Sediment transport by sea ice in the Chukchi and Beaufort seas: Increasing importance due to changing ice conditions?, *Deep Sea Res., Part II*, *52*, 3281–3302.
- Gladenkov, A. Y., A. E. Oleinik, L. Marinovich Jr., and K. B. Barinov (2002), A refined age for the earliest opening of Bering Strait, *Paleogeogr. Palaeoclimatol. Palaeoecol.*, *183*, 321–328.
- Holland, M. M., C. M. Bitz, and B. Tremblay (2006), Future abrupt reductions in the summer Arctic sea ice, *Geophys. Res. Lett.*, *33*, L23503, doi:10.1029/2006GL028024.
- Jakobsson, M., *et al.* (2007), The early Miocene onset of a ventilated circulation regime in the Arctic Ocean, *Nature*, *447*, 986–990, doi:10.1038/nature05924.
- Marinovich, L., and Y. G. Andrey (1999), Evidence for an early opening of the Bering Strait, *Nature*, *397*, doi:10.1038/16446.
- Moran, K., *et al.* (2006), The Cenozoic palaeoenvironment of the Arctic Ocean, *Nature*, *441*, 601–605.
- Nørgaard-Pedersen, N., R. F. Spielhagen, H. Erlenkeuser, P. M. Grootes, J. Heinemeier, and J. Knies (2003), Arctic Ocean during the Last Glacial Maximum: Atlantic and polar domains of surface water mass distribution and ice cover, *Paleoceanography*, *18*(3), 1063, doi:10.1029/2002PA000781.
- Nürnberg, D., I. Wollenburg, D. Dethleff, H. Eicken, H. Kassens, T. Letzig, E. Reimnitz, and J. Thiede (1994), Sediments in Arctic sea ice: Implications for entrainment, transport and release, *Mar. Geol.*, *119*, 185–214.
- Polyak, L., W. B. Curry, D. A. Darby, J. F. Bischof, and T. M. Cronin (2003), Contrasting glacial/interglacial regimes in the western Arctic Ocean as exemplified by a sedimentary record from the Mendeleev Ridge, *Paleogeogr. Palaeoclimatol. Palaeoecol.*, *203*, 73–93.
- Reimnitz, E., E. W. Kempema, and P. W. Barnes (1987), Anchor ice, seabed freezing, and sediment dynamics in shallow arctic seas, *J. Geophys. Res.*, *92*, 14,671–14,678.
- Reimnitz, E., P. W. Barnes, and W. S. Weber (1993a), Particulate matter in pack ice of the Beaufort Gyre, *J. Glaciol.*, *39*, 186–198.
- Reimnitz, E., M. McCormick, K. McDougall, and E. Brouwers (1993b), Sediment export by ice rafting from a coastal polynya, Arctic Alaska, U.S.A., *Arct. Alp. Res.*, *25*, 83–98.
- Reimnitz, E., M. McCormick, J. Bischof, and D. A. Darby (1998), Comparing sea-ice sediment load with Beaufort Sea shelf deposits: Is entrainment selective?, *J. Sediment. Res.*, *68*, 777–787.
- Rigor, I. (1992), Arctic Ocean buoy program, *Argos Newsl.*, *44*(July), 1–3.
- Rigor, I. G., and J. M. Wallace (2004), Variations in the age of Arctic sea-ice and summer sea-ice extent, *Geophys. Res. Lett.*, *31*, L09401, doi:10.1029/2004GL019492.

D. A. Darby, Department of Ocean, Earth, and Atmospheric Sciences, Old Dominion University, 4600 Elkorn Avenue, Norfolk, VA 23529, USA. (ddarby@odu.edu)