7-26-2017

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Kristen E. St. John
James Madison University

Sandra Passchier
Montclair State University, passchiers@montclair.edu

Brooke Tantillo

Dennis Darby
Old Dominion University

Lance Kearns
Old Dominion University

Published Citation
St John, K., Passchier, S., Tantillo, B., Darby, D., & Kearns, L. (2015). Microfeatures of modern sea-ice-rafted sediment and implications for paleo-sea-ice reconstructions. ANNALS OF GLACIOLOGY, 56, 83-93. doi:10.3189/2015AoG69A586

Microfeatures of modern sea-ice-rafted sediment and implications for paleo-sea-ice reconstructions

Kristen ST JOHN,[1] Sandra PASSCHIER,[2] Brooke TANTILLO,[3] Dennis DARBY,[4] Lance KEARNS[1]

[1]*Department of Geology and Environmental Science, James Madison University, Harrisonburg, VA, USA*
E-mail: stjohnke@jmu.edu
[2]*Department of Earth and Environmental Studies, Montclair State University, Montclair, NJ, USA*
[3]*Halliburton, Laramie, WY, USA*
[4]*Department of Ocean, Earth & Atmospheric Sciences, Old Dominion University, Norfolk, VA, USA*

ABSTRACT. Distinguishing sea-ice-rafted debris (SIRD) from iceberg-rafted debris is crucial to an interpretation of ice-rafting history; however, there are few paleo-sea-ice proxies. This study characterizes quartz grain microfeatures of modern SIRD from the Arctic Ocean, and compares these results with microfeatures from representative glacial deposits to potentially differentiate SIRD from ice-rafted sediments which have been recently subjected to glacial processes. This allows us to evaluate the use of grain microfeatures as a paleo-sea-ice proxy. SIRD grains were largely subrounded, with medium relief, pervasive silica dissolution and a high abundance of breakage blocks and microlayering. The glacial grains were more angular, with lower relief and higher abundances of fractures and striations/gouges. Discriminate analysis shows a distinct difference between SIRD and glacial grains, with <7% of the SIRD grains containing typical glacial microtextures, suggesting this method is a useful means of inferring paleo-sea-ice presence in the marine record. We propose that differences in microfeatures of SIRD and glacial ice-rafted debris reflect differences in sediment transport and weathering histories. Sediment transported to a coastal setting and later rafted by sea ice would be subject to increased chemical weathering, whereas glaciers that calve icebergs would bypass the coastal marine environment, thus preserving their glacial signature.

KEYWORDS: Arctic glaciology, icebergs, paleoclimate, sea ice, sedimentology

BACKGROUND

Ice-rafted debris, and the importance of glacial ice and sea ice in the climate system

Terrigenous sands in pelagic sedimentary sequences in the mid- to high-latitude oceans are commonly interpreted as being transported from land by floating ice. This 'ice-rafted debris' (IRD) interpretation is most robust when these records come from offshore bathymetric highs, as deposition of coarse grains by river input and/or turbidity flows is therefore eliminated. Additionally, transport of terrigenous sands by aeolian processes is unlikely beyond the coastal setting given the large particle size. The particle size of deep-sea terrigenous-sourced sediments typically matches that of dust, and is in clay to silt size range (Kennett, 1982). However, large proportions of well-rounded 'aeolian'-type sand grains found by Damiani and others (2006) in some IRD layers relatively far offshore in the Southern Ocean have been difficult to reconcile with an iceberg-rafted origin for the grains. Because icebergs are known to transport sediment thousands of kilometers from its terrigenous sources (Ruddiman, 1977; Bond and others, 1992; Stuart and Long, 2011), changing abundances of IRD have traditionally been equated with iceberg transport, and thus used to infer changes in regional glacial histories. For example, evidence for onset of widespread Antarctic glaciation includes a sharp increase of terrigenous sands in the Southern Ocean in the early Oligocene (Zachos and others, 1992; Scher and others, 2011). Likewise, the expansion of Northern Hemisphere glaciation at ~2.7 Ma is marked by widespread deposition of terrigenous sands across the northern and mid-Atlantic Ocean (Ruddiman, 1977). Moran and others (2006) used variations in the percentage of sand on the Lomonosov Ridge to infer Neogene glacial/interglacial cycles in the central Arctic Ocean.

However, in glaciomarine settings such as the Arctic Ocean, where sea ice is an additional transport mechanism, the need to differentiate between iceberg- and sea-ice-transported sediments becomes important. This is because glacial ice (from which icebergs originate) and sea ice have different roles in climate-system feedbacks, and have different formation and transport histories. As sea-ice extent diminishes, there is an increase in ocean heat loss to the atmosphere (Serreze and others, 2009); this warming drives further sea-ice (and glacial ice) melting, and the warming–melting positive ice-albedo feedback cycle ensues. There is a differential impact on eustatic sea level by continental ice vs sea ice, with a decrease in continental ice volume resulting in an increase in sea level, and changes in sea-ice volume have no effect on sea level. In contrast, both ice-sheet and sea-ice melt reduce the surface albedo and thus increase surface warming (Perovich and others, 2002). In addition to the albedo and insulating effects of sea ice on the climate system, there are effects on the hydrologic cycle and ocean circulation. As sea ice melts there is an increase in moisture transfer from the ocean to the atmosphere, which can impact regional air pressures and precipitation patterns (DeConto and others, 2007). A reduction of sea surface salinity as a result of sea-ice melt and input of glacial meltwater has been shown to increase ocean water stratification and suppress thermohaline convection, with potentially global consequences (Holland and others, 2001; Clark and others, 2002; Peterson and others, 2006; Polyak and others, 2010).

Sedimentological proxies for paleo-sea ice

While the importance of sea ice in the ocean–atmosphere climate system is well documented, reconstruction of the timing and extent of paleo-sea ice is a relatively new field in paleoceanography and paleoclimatology. The most robust paleo-sea-ice proxies come from marine sediments in regions that either are currently or were in the past covered by sea ice. The presence of sea ice impacts the physical, biological and chemical conditions in the oceans, and these conditions in turn influence the depositional record. Furthermore, the transport capability of sea ice in the Arctic is well established (Eicken and others, 1997; Reimnitz and others, 1998; Darby and others, 2009, 2011).

Grain size, provenance and microfeatures are the three primary sedimentological means by which the presence of paleo-sea ice in the Arctic has been inferred. A review of paleo-sea-ice proxy methods and the history of sea ice in the Arctic is provided by Polyak and others (2010). Studies of sediment collected from modern sea-ice floes in the Arctic indicate that the majority (89–95%) of terrigenous grains are <63 m (silt/sand boundary) in diameter (Nürnberg and others, 1994; Darby, 2003; Darby and others, 2009). The entrainment of fine sediment results from frazil-ice formation which incorporates suspended sediment during the freeze-up process. Therefore, high-latitude marine sediment records from offshore bathymetric highs dominated by sand-sized sediment have often been interpreted as iceberg-derived rather than sea-ice-derived (Polyak and others, 2010).

Using grain size as a criterion to differentiate iceberg- and sea-ice-rafted sediment is complicated, however, by the fact that the sand-sized fraction is the least representative size fraction in typical glacial sediments (Drewry, 1986). In addition, there are situations in which coarse grains can be entrained in sea ice. Erosion of coastal cliffs and river transport of sediment to landfast sea ice could include a coarser fraction (Reimnitz and Bruder, 1972; Rachold and others, 2000; Reimnitz and Wolf, 2000; Lisitzin, 2002). For example, there are many coarse glacial-outwash fans in the Brooks Range, coastal Alaska (Reimnitz and Wolf, 2000); past progradation of these fans, coupled with high seasonal meltwater discharge, could have transported coarse sediment to the coast where landfast sea ice could entrain it. In addition, in modern times, erosion of high cliffs along the Laptev Sea transports more sediment to the sea than does the Lena River. These cliffs are dominated by permafrost, and organic-rich silts and silty sands (Rachold and others, 2000). Furthermore, anchor ice formation, which occurs during supercooled conditions, is an important process in mobilizing bed sediments of all grain sizes in both continental shelves and rivers (Reimnitz and others, 1987, 1993, 1998; Nürnberg and others, 1994; Mager and others, 2013). When anchor ice lifts from the bed, it becomes a form of sediment-laden sea ice. Recent studies show that anchor ice is more extensive and transports more sediment in the Arctic than previously thought, perhaps rivaling other forms of sea-ice entrainment (Darby and others, 2011). While the direct observation of anchor ice is rare, it can be inferred from the inclusions of benthic marine flora and fauna in sea ice and from high concentrations of sediment overall in 'dirty sea ice' (Darby and others, 2011; Mager and others, 2013). These studies show that grain size alone cannot be used as a criterion to differentiate iceberg- and sea-ice-rafted sediment.

Identification of sea-ice-rafted debris (SIRD) sediment provenance is an important tool for reconstructing paleo-sea-ice drift history provided that the source area has independent evidence (e.g. lack of terrestrial glacial deposits or glacial erosional landscapes) of no glaciation so that iceberg rafting can be ruled out. In the Arctic, iron-oxide mineral sources (Darby and others, 2002; Darby, 2003) and clay mineral source compositions (Vogt, 1997, 2009; Vogt and Kines, 2008; Darby and others, 2011) are well established. In general, it appears that the iron-oxide minerals have a more distinctive source area fingerprint than do clay minerals. For example, Darby and others (2011) were able to identify Russian and Canadian source areas for modern sea-ice sediment collected in the central Arctic Sea, but clay mineralogy on the same suite of samples was found to match many different source areas. The iron-oxide method has successfully been used to reconstruct Arctic paleo-sea-ice histories as old as the middle Eocene (e.g. Darby, 2008, 2014). However, if the glacial history of source areas is uncertain or if sources were involved in both sea-ice and iceberg transport, more than provenance is required to distinguish these two transport modes.

Given the limitations of grain-size and provenance methods for distinguishing paleo-sea-ice and iceberg transport, the analysis of grain microfeatures as an additional sea-ice proxy is worth considering, and is the focus of this paper. Historically, the majority of grain microfeature studies of marine sediments have focused on reconstructing glacial histories, with very little attention to sea-ice drift histories. The analysis of surface textures of quartz grains in continental deposits (e.g. Helland and Diffendal, 1993; Mahaney, 1995, 2002; Mahaney and others, 1996; Passchier and others, 1997) has successfully been used as a method to infer regional glacial histories and glacial dynamics because the mechanical abrasion and crushing of sediments during glacial transport is a well-documented process (Krinsley and Doornkamp, 1973). No studies have characterized grain microfeatures of sediment directly sampled from icebergs; but the common working assumption is that iceberg-rafted debris would have the same sedimentological properties as the continental glacial deposits, especially tills and the glaciofluvial sediments that melt out from debris-rich basal ice (Lawson and others, 1998). The grain microfeatures of ice-proximal sediments include high relief, angular edges, straight grooves (striations) and a wide range of fracture types, including conchoidal, sub-parallel fractures, arc and straight step fractures, and sometimes breakage blocks (Helland and Diffendal 1993; Mahaney, 1995, 2002; Passchier and others, 1997). Similar features on quartz grains from the middle Eocene in the ACEX core on the Lomonosov Ridge indicate the possibility of glacial ice (St John, 2008). Increased mechanical surface textures on quartz grains from this core were evidence of Arctic cooling trends in the Middle Miocene (Immonen and others, 2009; Immonen, 2013). Similarly, surface features on quartz IRD provided evidence of glaciation in southern Greenland in the late Miocene (Helland and Holmes, 1997). Also, an increase in mechanical microtextural changes provided further evidence of the expansion of circum-Arctic ice sheets in the Late Pleistocene (Strand and Immonen, 2010). Patterns in Pleistocene glacial dynamics of the Eurasian ice sheet have also been inferred from glacial and non-glacial microfeatures of IRD (Immonen, 2014).

In contrast to grain microfeature analysis for use in glacial ice-rafting reconstructions, the analysis of grain microfeatures for modern and paleo-sea-ice studies is rare. To date, there is only one published study that characterizes grain microfeatures of sediment directly sampled from sea-ice floes. Based on qualitative analyses of grain surface textures, and quantitative analysis of grain surface shape (roundness and relief) of sediment from modern sea-ice floes in the Beaufort Sea and from Northwind Ridge piston cores, sea-ice- and iceberg-transported sediments were differentiated by the abundance or absence of specific groups of grain surface microfeatures (Dunhill, 1998). This study found that modern SIRD displayed rounded edges and chemical features of silica dissolution and silica reprecipitation, whereas the Pleistocene sediment grains (which were assumed to be iceberg-rafted debris) displayed more mechanical features such as angular edges, breakage blocks, high relief, step-like fractures, and conchoidal fractures. The mechanical features identified were generally consistent with those identified as characteristic of sands in glacial tills (e.g. Krinsley and Doornkamp, 1973; Margolis and Krinsley, 1974; Helland and Diffendal, 1993; Mahaney, 1995; Passchier and others, 1997).

Preliminary efforts to reconstruct the Arctic sea-ice history using the grain microfeatures characterized by Dunhill (1998) have been made. St John (2008) and Stickley and others (2009) applied this method to a key interval of the middle Eocene Arctic record. They found a dominance of SIRD, an increase in iceberg-rafted debris concurrent with the oldest dropstone (pebble), and increases in the proportion of iceberg-rafted debris that generally correlated with increases in total terrigenous sand abundance. Importantly, the interpretation that sea ice was present in the Arctic in the middle Eocene was consistent with robust data of sea-ice dependent fossil diatoms (Stickley and others, 2009). More recently, Immonen (2013) used a similar suite of grain microfeatures to suggest ephemeral glacial ice in the Paleogene Arctic, and outline the changing relative importance of iceberg and sea-ice transport in the Arctic in the Miocene through Pleistocene.

This study

While these modern and paleo-sea-ice studies show some promising results, there is a need for verification and refinement of the methodology. The single study (Dunhill, 1998) distinguishing sea-ice-rafted from iceberg-rafted grain microfeatures has not been reproduced. In addition, statistical analysis of that study was limited to grain shape. Therefore the purpose of our study is twofold: (1) to evaluate whether Dunhill's (1998) SIRD grain microfeature results are reproducible given a new sample suite from modern sea-ice floes in the central Arctic Ocean; and (2) to evaluate whether analyses of grain microfeatures is a useful proxy for discriminating between sea-ice and glacial transport, by comparing these results with microfeatures of sand grains in a representative ice-marginal deposit. Specific research questions in support of these goals include: *Is there a suite of microfeatures that characterize sea-ice transported sediment? Are SIRD microfeatures statistically distinct from glacially derived microfeatures? Does this methodology supply quantitative or qualitative evidence of the importance of sea-ice vs iceberg transport that is useful for paleo-sea-ice reconstruction?* Answers to these questions can provide a more robust assessment of grain microfeatures as a paleo-sea-ice proxy.

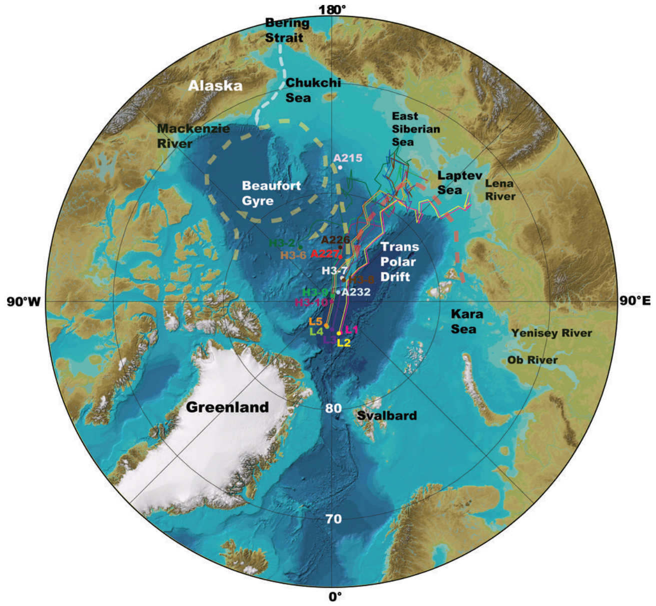

Fig. 1. Location of sea-ice samples (H: HOTRAX expedition in 2005; L: LOMROG expedition in 2007; A: AOS expedition in 1994), back trajectories for sea-ice drifts (solid lines) based on the date and location of each dirty ice sample, and major drift patterns (dashed lines) of the Beaufort Gyre and Trans-Polar Drift. Net drift paths based on buoy drift and circulation models of Rigor and Wallace (2004). The bathymetry is from the International Bathymetric Chart of the Arctic Ocean (Jakobsson and others, 2008). Modified from Darby and others (2011).

MATERIALS AND METHODS

Sea-ice-rafted sediment samples

Fifteen samples collected from modern sea-ice floes in the Arctic Ocean during the 1994 Arctic Ocean Sections (AOS-94) expedition, the 2005 Healy Oden Trans-Arctic Expedition (HOTRAX) and the 2007 Lomonsov Ridge Off Greenland (LOMROG) expedition were included in this study (Table 1; Fig. 1). Samples were collected from surface sediment concentrations on the ice floes generally within a $\sim$50 m sampling area (Darby and others, 2011). Ice-floe locations were concentrated in the central Arctic, most north of 84° N. Based on observations, modern drift rates and paths (Rigor and Wallace, 2004), all were multi-year ice. Samples were sieved, and up to 20 grains were randomly selected from each >250 m fraction. If fewer than 20 quartz grains were present then all of the >250 m quartz grains were included. A total of 253 quartz grains collected from sea ice were analyzed.

Surface microfeatures were analyzed using a LEO 1430VP scanning electron microscope (SEM). The energy-dispersive spectrometer (EDS) was used to verify that grains included in the study were quartz. A checklist approach following the methods of Williams and Morgan (1993) and Dunhill (1998) was used, in which the presence and absence of different grain microfeatures was noted. Classifications of grain roundness, form, relief and textures were

Table 1. Arctic sea-ice floe samples used in this study

Sample ID assigned color*	Sample ID	Latitude	Longitude	Ice-floe age	Number of quartz grains in this study
	Hotrax 3-2	84.31	–149.09	Multi-year, >2 years	14
	Hotrax 3-6	84.17	–151.02	Multi-year, >2 years	13
	Hotrax 3-7B	87.62	156.09	Multi-year, >2 years	19
	Hotrax 3-8B	87.66	150.87	Multi-year, >2 years	19
	Hotrax 3-9	89.48	168.86	Multi-year, >3 years (near pole)	16
	Hotrax 3-10B	89.99	–0.21	Multi-year, >3 years (near pole)	19
	Lomrog-07 DICE-1	86.98	16.01	Multi-year, >2 years	20
	Lomrog-07 DICE-2	86.97	12.69	Multi-year, >2 years	20
	Lomrog-07 DICE-3A	87.41	1.11	Multi-year, >2 years	20
	Lomrog-07 DICE-4E+D	87.62	10.07	Multi-year, >2 years	20
	Lomrog-07 DICE-5B	87.72	13.13	Multi-year, >2 years	20
	AOS-94-226-1	84.83	170.70	Multi-year	20
	AOS-94-227-1	85.90	166.83	Multi-year	19
	AOS-94-232-1	89.00	137.66	Multi-year	14
	AOS-94-215-E3	78.07	176.73	Multi-year	

*Sample ID color corresponds to Figures 1 and 3.

made by comparison to grain images in Krinsley and Doornkamp (1973) and Powers (1953) and calculated as a percentage for the whole population (Table 2; Fig. 2) and for each sample (Fig. 2). Three additional types of microtextures were included in the study: microlayering (Fig 2r), isolated cusps (Fig 2p) and isolated fractures (a single fracture, not as part of a step-like pattern). In addition, due to the variable degree of surface dissolution on different quartz grains, the textural category of silica dissolution included a four-tiered ranking of absent or rare (0–2% of the visible surface), present (2–25%), common (25–75%) and pervasive (>75%), rather than simple presence–absence as was used in all other checklist categories.

Proximal glacial sediment samples

In order to address the question of whether SIRD and iceberg-rafted debris have distinct suites of grain microfeatures, we included observations on 105 quartz grains collected from Pleistocene tills and fluvioglacial sediments in the analysis. The glacial sediments are part of an ice-marginal complex composed of a lower till, a glaciofluvial sediment and an upper till, exposed in a coastal cliff along the Gulf of Gdansk, northern Poland. While it would be preferable to include sediment samples collected directly from icebergs, or from ice-proximal glacial sediments in source areas rimming the Arctic, the observations on the Gulf of Gdansk glacial sediments were immediately available to us and represent glacial deposits laid down by the Eurasian ice sheets advancing south from the land areas surrounding the Arctic during the Last Glacial Maximum. These samples were part of a previous study on regional sediment supply and transport as revealed by microfeatures of these grains (Passchier and others, 1997). Extracting the equivalent microfeatures from this dataset and including them in the analysis provided an opportunity to statistically compare SIRD grain microfeatures and representative glacial grain microfeatures.

Statistical and multivariate data analyses

After SEM observations and a qualitative analysis were complete, the data of grain microfeatures were analyzed using multiple phases of principal component analysis (PCA), using the covariance matrix and discriminant analysis (DA) (Davis, 2002). The software package PAST (Hammer and others, 2001) was used to carry out the multivariate and statistical analyses. The PCA simplifies the data matrix and helps to highlight particular sets of variables (i.e. grain microfeatures) that co-occur on grain surfaces in the dataset. DA is used to look for differences between populations based on multiple variables. Our first null hypothesis ($H1_0$) is that surface textures on populations of grains sampled from different ice flows are the same at probability $p<0.05$. Our second null hypothesis ($H2_0$) is that populations of sea-ice-rafted grains can be distinguished from glacially derived grains at $p<0.05$, because they exhibit sets of microfeatures that are distinct from those typical for glacially derived grains. Because the previous study (Dunhill, 1998) did not use grain form as a checklist category, and we wanted to compare our results to that study, we did not include grain form in the statistical analyses.

The initial multivariate analyses focused only on the SIRD. PCA of the SIRD samples focused first on the presence and absence of sets of mechanical grain microtextures, and later added the components of dissolution, grain roundness and relief to determine which of these components best represents sea-ice-rafted sediment. Although qualitative observations differentiated by the degree of dissolution, for the PCA any grain with dissolution (common to pervasive) was assigned a score of 1 and grains with absent to rare dissolution were assigned a score of 0, which is consistent with the recorded observations for other textural variables. Similarly, grain roundness and relief was scored as a 1 (presence) or 0 (absence) despite the fact that these are range variables. This is because a normalized scale between 1 and

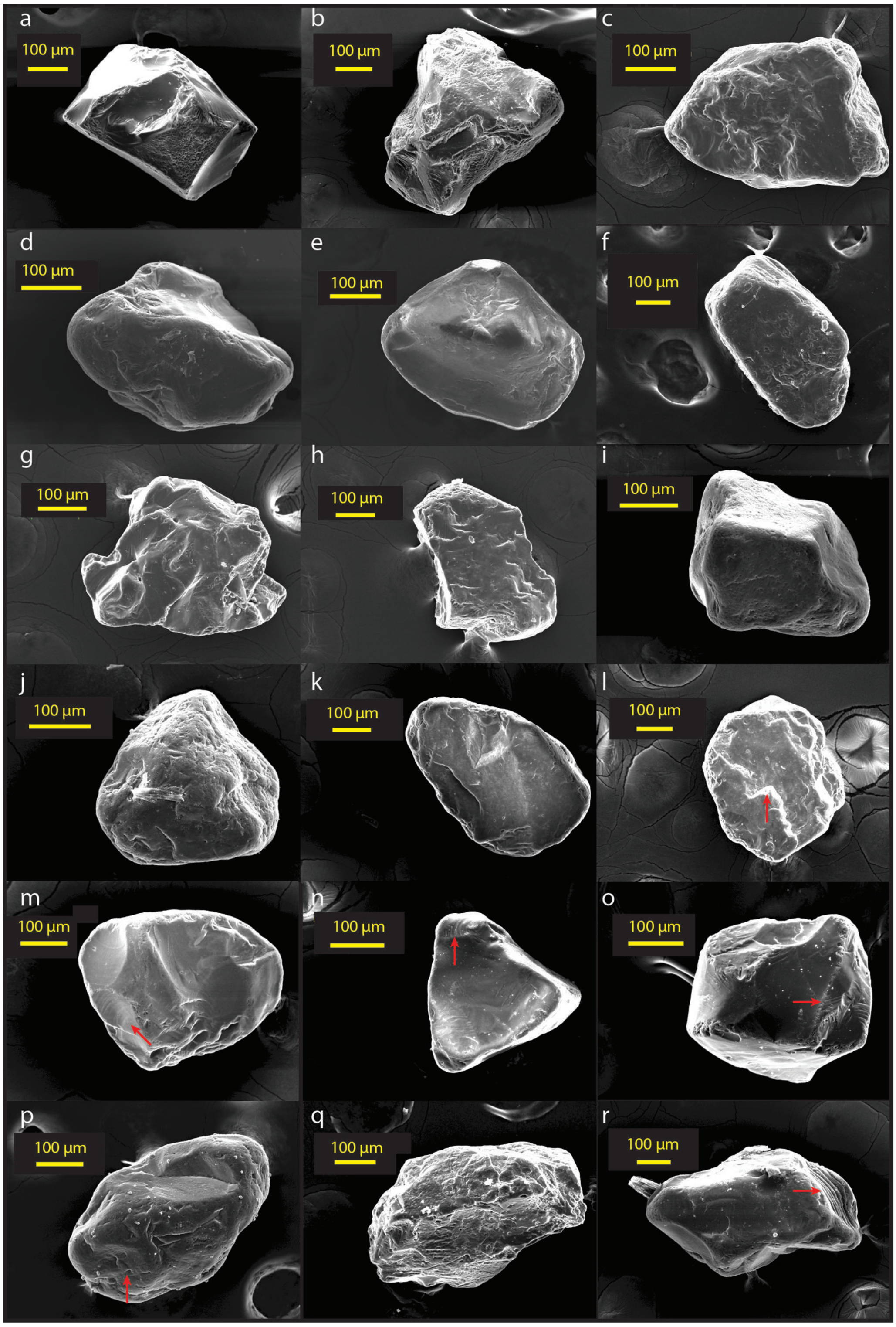

Fig. 2. Example SEM secondary electron photos of grain surface features from the sea-ice sediment: (a) angular shape; (b) subangular shape; (c) subrounded shape; (d) rounded shape; (e) equant form; (f) elongate form; (g) irregular form; (h) tabulate form; (i) high relief; (j) medium relief; (k) low relief; (l) breakage block; (m) conchoidal fractures; (n) arc step-like fractures; (o) straight step-like fractures; (p) isolate cusp; (q) dissolution (abundant, >75% of visible surface); and (r) microlayering.

0 (with 0.5 for medium relief, for example) would put medium values at a lower importance and would overly emphasize the extremes. DA of these samples was performed with the goal of determining if spatial (geographic) or temporal (sampling dates) patterns existed in the data. Samples AOS 232 and 215 were excluded for this first phase of statistical analysis because we could not verify the locations for each of the grains. This complication arose due to an error in sample preparation, where grains from both samples were combined on the same SEM stub.

The second phase of the statistical analysis was a comparison of the sea-ice-rafted sediment samples and the proximal glacial sediment samples. All 15 sea-ice-rafted samples were used in this analysis because location or expedition was not being directly addressed. DA-2 was carried out to test the second null hypothesis ($H2_0$) that

Table 2. Grain microfeatures included in this study

Grain microfeature category	Microfeature* (Dunhill's (1998) SIRD (**bold**) or IRD (*italic*) interpretations of these features)	Percent abundance of microfeatures in SIRD samples (this study; see Fig. 3) as determined from SEM observations
Grain roundness†	*Very angular*	0
	Angular	4
	Subangular	30
	Subrounded	55
	Rounded	10
	Well rounded	0
Grain form‡	Equant	21
	Elongate	8
	Irregular	63
	Tabulate (flat)	8
Grain relief	*High*	1
	Medium	87
	Low	12
Grain surface texture	*Breakage blocks*	87
	Conchoidal fracture	3
	Straight step-like fractures	11
	Arc step-like fractures	9
	Isolated cusps	42
	Isolated fracture	1
	Striations/gouges	4
	Silica dissolution	
	Absent or rare (0–2%)	2
	Present (2–25%)	55
	Common (25–75%)	38
	Pervasive (>75%)	6
	Microlayering	64

*Examples of these microfeatures are shown in Figure 2.
†Roundness was determined by comparing to Powers' (1953) roundness classifications.
‡Not included in the statistical analyses.

sea-ice-rafted sediment and glacial sediment can be discriminated, and based on which variables.

RESULTS

Sea-ice-rafted sediment: SEM observations

Based on the checklist observations the grains transported by sea ice are dominated by a general suite of characteristics (Table 2; Fig. 3). They are subrounded (55%) to subangular (30%), partially dissolved (98%), have medium relief (87%) and contain breakage blocks (87%), isolated cusps (42%) and microlayering (64%). Most grains were irregular (63%) in form. Also important is the observation that certain textures and shapes were not present, or only rarely present. None of the grains was either very angular or well rounded, and very few were angular (4%) or rounded (10%). Only 1% of the grains had high relief. Only low percentages of striations (4%), conchoidal fracture (3%), isolated fractures (1%), straight (11%) and arc (9%) step-fractures were observed.

Sea-ice-rafted sediment: statistical and multivariate data analysis results

PCA of mechanical microtextures on SIRD (excluding grain shape and dissolution) shows that the first principal component (PC) is very much controlled by the presence of isolated cuspate features, and the second PC by microlayering (Supplemental Table 1). (All supplementary material is available at http://www.igsoc.org/hyperlink/69A586.pdf.) The breakage blocks are a negative loading in the third PC and anticorrelate to step fractures. It is logical that the breakage blocks do not show up in the first two PCs as they are present in a large number of samples (Table 2; Fig. 3) and therefore so common that they are not discriminatory. Similarly, when silica dissolution is included in the analysis and microlayering excluded, and all step-like fractures are merged into one class (to later match the categories of the glacial ice margin complex dataset), the results of the PCA do not change substantially (Supplemental Table 2) because silica dissolution is present on all grains. When PCA is carried out on the SIRD data with inclusion of grain shape and relief parameters, the first PC is controlled by grain shape (Supplemental Fig. 1a). However, because we find high PC scores in adjacent, very similar, grain shape classes, it is important to be cautious in evaluating the relative importance of grain shape among the mechanical microtextures. It is likely that the high PC scores are an artifact of the high abundance of grains with subangular to subrounded shape relative to other grain shapes. The second PC again identifies isolated cusps, which is in agreement with the first PCA results (Supplemental Fig. 1b).

DA of the sea-ice sediment microtextures based on expedition (Supplemental Fig. 2) indicates there is no significant difference between the expedition-based grouping of samples. The percentage of grains classified correctly by expedition via DA was only 59–64% (with 50% being chance). These results indicate that the grain microtextures

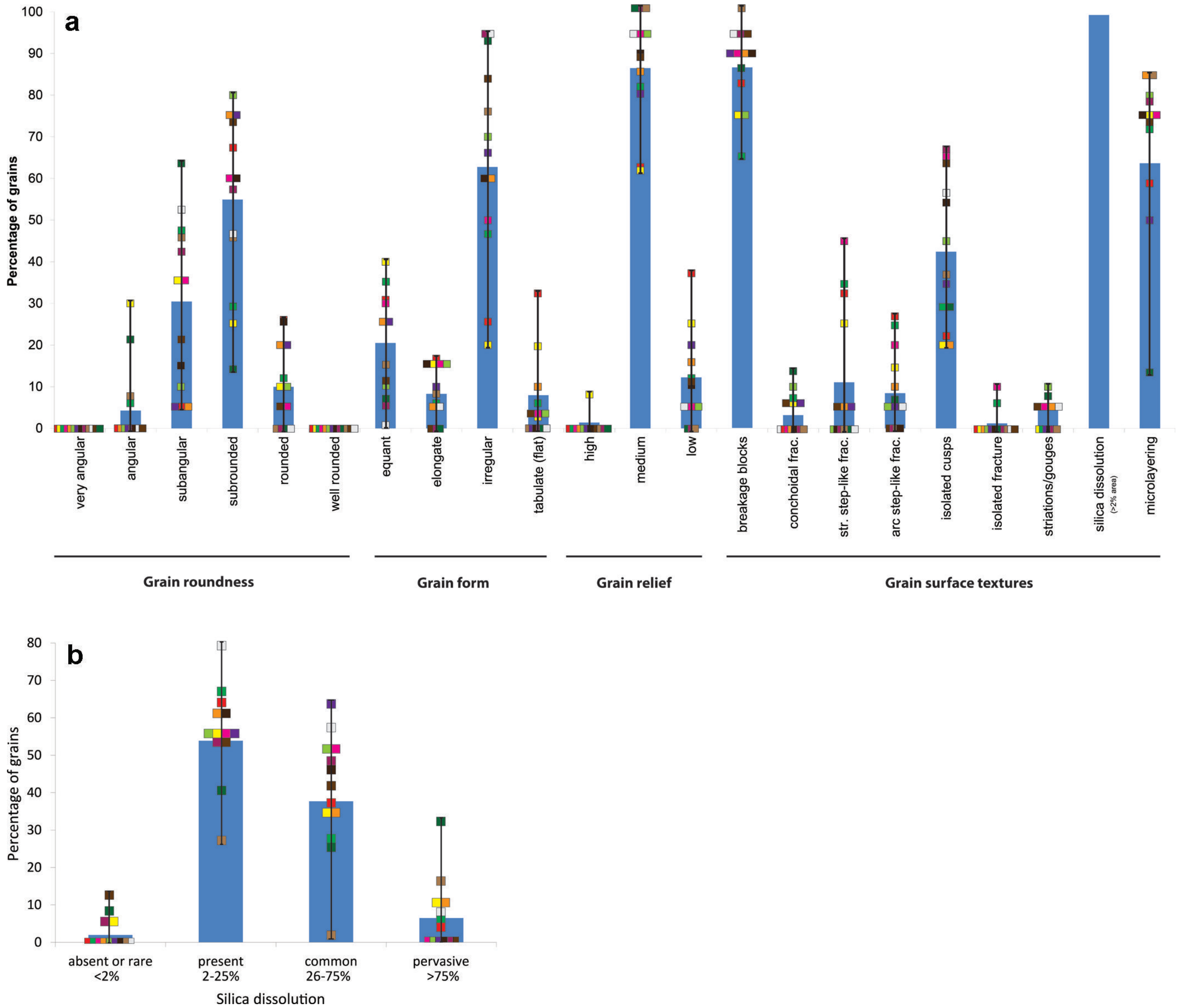

Fig. 3. Bar graphs showing the mean (blue bars) and range (black lines) of the microfeature percentages in the sea-ice sediment samples. Colored boxes correspond to specific samples (Table 1). (a) All microfeatures; and (b) the percentage of grains with silica dissolution broken down by subcategories. Samples AOS-94-232-1 and AOS-94-215-E3 were included in calculating the mean and range, but their sample averages (colored boxes) are not displayed here because grains from these samples were combined during preparation for SEM analysis.

are most likely randomly distributed among the samples, with no significant patterns in expedition location or time (i.e. sampling date). We also tested the hypothesis of similarity between samples derived from sea ice potentially influenced by the Beaufort Gyre (AOS samples, plus HOTRAX 2, 6, 7) vs the Transpolar Drift (LOMROG samples, plus HOTRAX 8, 9, 10). These groupings are tentative, however, as the Transpolar Drift can be broad and variable in location based on the buoy drift patterns (Rigor and Wallace, 2004; Fig. 1). Interestingly, we found that the first null hypothesis ($H1_0$), that the surface textures on grains from each of the two possible source areas were the same, can be rejected at $p<0.001$ and with 69% of samples classified correctly (Supplemental Fig. 3). When comparing microtextures for these two groups of sea-ice samples, we find a slightly higher incidence of conchoidal or step-like fractures, isolated cusps, and isolated fractures or striations in the Transpolar Drift group than in the Beaufort Gyre group. The Transpolar Drift samples also exhibit microlayering on 75% of the grains, whereas 47% of grains in the Beaufort Gyre group show this feature. The other textures (breakage blocks, silica dissolution) are present on >85% of grains in both source groups, and grain shape and form factors (not included in the DA) show very similar distributions. Based upon these results, we treated the 253 SIRD grains as one population and compared the observations to the results on 105 glacial proximal grains from Passchier and others (1997).

Sea-ice-rafted sediment compared with proximal glacial sediment: SEM observations

SEM observations of microfeatures of the glacial proximal sediment grain dataset (Passchier and others, 1997) included all of the categories used in the SIRD analysis except grain form and microlayering. In addition, straight and arc step-like fractures were combined as one category, and silica dissolution was recorded as presence vs absence (not degree of dissolution as in the SIRD observational checklist). A comparison of the percentages of grains with microfeatures common to both SIRD and glacial IRD analyses shows that

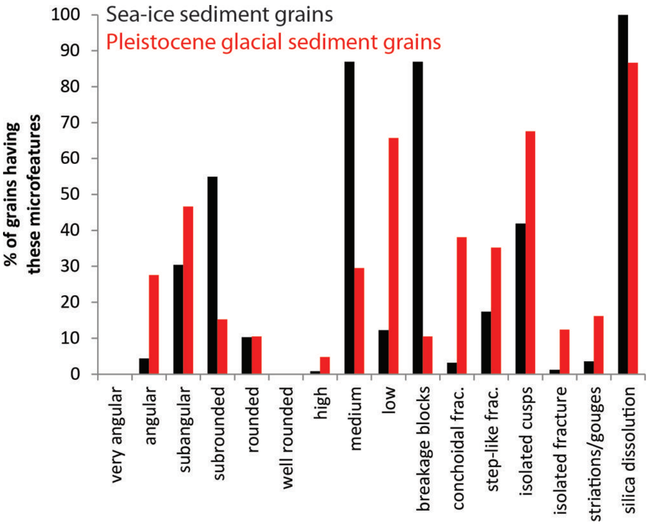

Fig. 4. Bar graph comparing microfeature percentages in the sea-ice-rafted grains (black) vs the Pleistocene glacial sediment grains (red). Only categories common to both datasets are compared, which includes all SEM-observed microfeatures except grain form and microlayering. Straight and arc step-like fractures are combined as one category. Dissolution is categorized by presence vs absence, not degree of dissolution (as in Fig. 3b).

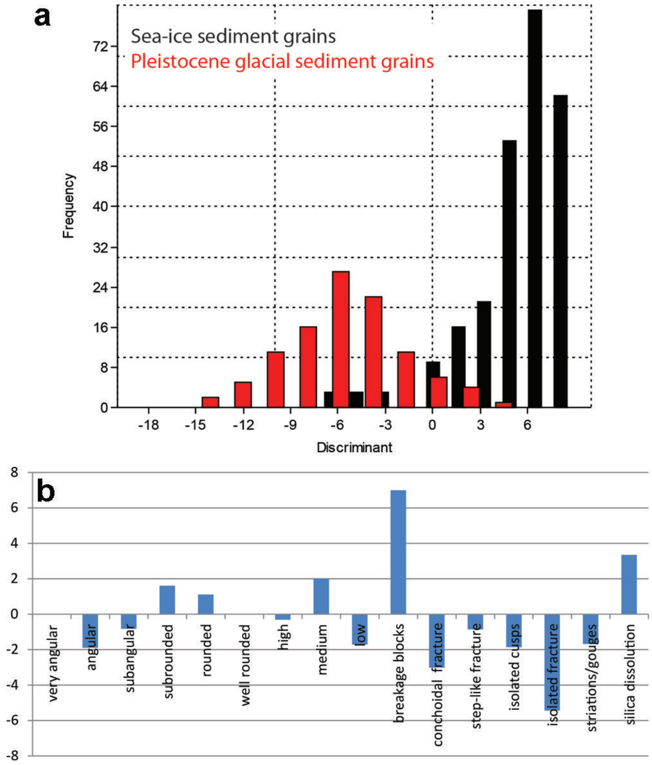

Fig. 5. DA results for SIRD and Pleistocene glacial sediment samples including all SEM grain microfeature observations, except grain form: (a) multivariate data matrix plotted on the discriminant axis that represents the largest difference between the two grain populations: sea-ice (black) vs glacial grains (red); and (b) loadings of different variables on the discriminant function that defines the position of discriminant axis in multidimensional space. Greater positive or negative loadings correspond to greater importance of these variables in distinguishing the SIRD and Pleistocene glacial grain populations. Note the negative loadings for typical 'glacial' features.

most grains show some evidence of dissolution, but more so in SIRD (Fig. 4). There is a distinction in grain roundness, with SIRD generally more rounded (subrounded) than glacial proximal grains. SIRD and glacial proximal grains show distinctly different grain relief, dominated by medium and low relief, respectively. Mechanical microtextures (e.g. fractures and gouges) were all more prevalent in glacial sediment grains than in the SIRD. In contrast, SIRD had a much higher abundance of breakage blocks. That most of the glacial ice-proximal grains had more mechanical microtextures (e.g. fractures) yet still low relief was surprising, as increases in mechanical features and relief have been shown to co-vary in glacial sediments and be a function of increasing ice thickness (Mahaney, 1995).

Sea-ice-rafted sediment compared with proximal glacial sediment: statistical and multivariate data analysis results

PCA of microtextures only for the SIRD and Pleistocene glacial sediment samples in one dataset provides a complex picture with an anticorrelation between breakage blocks and isolated cusps on the first PC-axis, but a positive correlation between these variables on the second PC-axis. When grain shape and relief are also included in the analysis, we see two groupings: one group of subrounded grains with medium relief, breakage blocks and silica dissolution, and an opposite group of low-relief angular and subangular grains with conchoidal fractures, steps and isolated cusps (Supplemental Fig. 4). The latter are generally characteristic of glacial environments.

The DAs accept the second null hypothesis ($H2_0$) that sea-ice and Pleistocene glacial sediment grains are distinguishable based on surface microtextures. SIRD grains are distinguished from glacial proximal grains by subrounded grain shape, with medium relief, high relative abundance of breakage blocks and silica dissolution (Fig. 5). Sea-ice-rafted grains have low abundance of conchoidal fractures, steps, isolated cusps, fractures and striations/gouges. Using all grain characteristics, >93% of grains are correctly classified by the discriminant function and the analysis is highly significant, with $p < 0.01$. This means that very few (<7% of) SIRD grains contain typical glacial microtextures.

DISCUSSION

Is there a suite of microfeatures that characterize sea-ice transported sediment?

One of the goals of this research was to evaluate the reproducibility of the single previous study of SIRD grain microfeatures (Dunhill, 1998), given this new sample suite from modern sea-ice floes in the central Arctic Ocean. Our results largely confirm Dunhill's (1998) findings, but with a few important differences. In both studies SIRD grains are shown to have more rounded than angular edges, medium to low relief rather than high relief, and have strong evidence of chemical alteration (e.g. silica dissolution). They also have few fractures (e.g. conchoidal fractures) and striations compared to glacial ice-proximal sediment grains. However, a large difference between Dunhill (1998) and our study is the dominance of breakage blocks on 87% of SIRD grains in our study. In contrast, Dunhill (1998) found a low abundance of breakage blocks on SIRD compared to her glacial samples. It is important to note that Dunhill's (1998) 'glacial' samples are derived from glaciomarine mud with IRD and not a land-based till, and that the 'glacial' samples could contain a mixture of SIRD and glacial IRD (Dunhill, 1998, p. 33). Although breakage blocks were considered a typical glacial mechanical texture and have been identified on the IRD grains observed by Dunhill (1998), these textures are not consistently observed on glacial sediment grains elsewhere. For example, large (>1 m) breakage blocks were found to be abundant in quartz sands in tills from Nebraska, USA (Helland and Diffendal, 1993), but breakage blocks or fracture faces were present in low abundance in till samples from Antarctica (Mahaney and others, 1996). Only 10% of the Pleistocene glacial and glaciofluvial sediment grains from Poland (Passchier and others, 1997) discussed in this study exhibit breakage blocks. However, moraine-sourced barrier beach sands from Long Island, New York, USA, show a considerable abundance of small and large breakage blocks (Williams and Morgan, 1993). It is hence unclear whether the breakage blocks that we observed on SIRD are inherited from an ice-contact glacial environment that ultimately sourced the grains or are a result of coastal marine and periglacial processes acting on the grains prior to incorporation in the sea ice.

Another important difference between our findings and Dunhill (1998) is that microlayering was observed in 64% of the SIRD grains in our study. Microlayering was not included as an observational category in Dunhill (1998). The prevalence and sheet-like orientation of the microlayering in our SIRD samples suggests a relationship between crystallography and weathering. Microfractures in quartz grains of plutonic rocks, sediments and soils have been examined by others (Moss and Green, 1975) and found to be present in nearly all samples, and only weakly related to crystallography. Residual strain in quartz grains may manifest itself as surface microfeatures long after mineral formation (Moss and Green, 1975). Therefore, we suggest that weathering may preferentially take place where these internal planes of weakness intersect the surface of the quartz grains, producing the microlayering texture. A recent study of Arctic marine muds has also reported microlayering in 6% of quartz IRD (Immonen, 2013), although it was termed 'layered breakage'. In that study, the microlayering was attributed to chemical and mechanical layer separation, and co-occurred with glacial microtextures. In our study, microlayering is most abundant in the sea-ice grains sourced via the Transpolar Drift (75% of grains), and these grains also exhibit a slightly higher incidence of other mechanical textures generally attributed to glacial action (conchoidal or step-like fractures, isolated cusps, fractures or striations). However, given the high percentage of microlayering in our SIRD samples, it is difficult to reconcile it as purely indicative of glacial action. Rather, as in the case of breakage blocks, microlayering may be derived from a complex history of formation and environmental conditions, possibly including, initially, glacial erosion and transport, followed by subaqueous or aeolian sediment transport, and surficial weathering processes.

Are sea-ice-rafted debris microfeatures statistically distinct from glacially derived microfeatures?

The second goal of the research was to evaluate whether analysis of grain microfeatures is a useful proxy for discriminating between sea-ice and glacial transport. Statistical analyses show that some variation is noticeable with respect to grain shape, the presence or absence of isolated cusps, and microlayering within the SIRD population. This variability is not correlated to expedition, but there is some variability with respect to sea-ice source (i.e. sources for the Beaufort Gyre vs the Transpolar Drift), and this probably represents specific processes within the periglacial environment acting on some grains and not others, before being incorporated into sea ice.

The DA shows that ~7% of the grains in SIRD show features typical of ice-proximal glacial sediment. This result suggests that glacially sourced grains can be affected by different types and intensities of marine and periglacial processes before being incorporated into sea ice. It also shows that the vast majority (93%) of the grains in SIRD are statistically distinct from the ice-proximal samples, the distinction being that SIRD is dominated by grains that are largely subrounded, with medium relief, breakage blocks, and pervasive evidence of silica dissolution. The results comparing Arctic SIRD and ice-proximal grains should be verified by a follow-up study that looks more narrowly at grain populations from the Arctic source areas of the SIRD. This may be possible by combining provenance work from Fe grain studies (e.g. Darby, 2003) with quartz grain microfeature analyses from the same sample populations. Ideally the SIRD sample locations should also be more clearly differentiated by drift patterns and thus ocean current influence (e.g. Beaufort Gyre vs Transpolar Drift). In addition, it would be important to expand the analyses to include samples from multiple locations from both polar oceans to have broader geographic representation, and to develop a method to provide an error estimate of the small overlap in SIRD and glacial-proximal population characteristics.

IMPLICATIONS FOR PALEO-SEA-ICE RECONSTRUCTION

Does this methodology supply quantitative or qualitative evidence of the importance of sea-ice vs iceberg transport that is useful for paleo-sea-ice reconstruction?

The implications of this study of modern SIRD in paleo-sea-ice reconstructions are twofold. First, the results suggest that analysis of quartz grain microfeatures is a suitable method for general characterization of paleo-IRD in terms of iceberg vs sea-ice transport. Goldschmidt and others (1992) stated that there is no definitive way to determine whether sediment samples in sea-floor sediment cores are deposited from sea ice or icebergs; this study helps close that gap. The difference between sea-ice and glacial microfeatures likely lies in the fact that iceberg-derived sand grains have bypassed the periglacial environment, and therefore preserve the glacial signature, whereas a majority of the sea-ice-derived sand grains are overprinted by a periglacial or marine sediment signature. Second, the results emphasize the need to make observations on large populations of grains; the discovery of a few typical 'glacial' grains in a paleo-IRD study may not signify iceberg-derived IRD, as these grain types can occur in sea-ice populations, albeit in low numbers. Therefore, while stratigraphic changes in IRD grain microfeatures can be used to help us infer the relative changes in the importance of sea-ice vs iceberg transport in the past, we cannot yet use this method to quantify the absolute proportions of sea-ice and iceberg deposition. Despite these limitations, the outcome of this study can shed light on unusual variability in surface textures of ice-rafted sand in the polar oceans (e.g. Damiani and others, 2006).

We have demonstrated here that sea-ice transport and deposition could be the responsible mechanism for the transport of glacially sourced, but periglacially modified, sand-sized grains. The marine sedimentary record from which we reconstruct ice histories is not a simple one in terms of iceberg vs sea-ice contributions, although the different roles of glacial ice and sea ice in the climate system are significant. Thus, like grain size and grain provenance analyses, grain microfeature analysis is now proven to be insightful for reconstructing sea-ice histories, but also with limitations. The best approach would be a multi-proxy one, in which each of these approaches is used, and when available augmented with micropaleontological sea-ice proxies (e.g. Stickley and others, 2009).

ACKNOWLEDGEMENTS

We thank the editor, associate editor and two anonymous reviewers for their critical reading and constructive comments, which helped improve the manuscript.

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