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Sources of Sediment Found in Sea Ice From the Western Arctic Ocean, New Insights Into Processes of Entrainment and Drift Patterns

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Sources of sediment found in sea ice from the western Arctic Ocean, new insights into processes of entrainment and drift patterns

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[1] The geochemical fingerprint of entrained Fe oxide mineral grains in Arctic Ocean sea ice is used to determine precise sources of this sediment. This approach substantiates the importance of the Laptev Sea as a source of sea ice and even the presence of Russian ice in the Beaufort Sea off Alaska. Fe oxide grains from the Laptev Sea were found in floes in the Beaufort Sea, Chukchi Borderland, and central Arctic Ocean, demonstrating the importance of sea ice in distributing itself throughout the Arctic Ocean and the potential of transporting sediment from Russian rivers to North American shelves. Banks Island shelf is the most important source of sediment sampled from ice floes in the Beaufort Sea, northern Chukchi Sea, and Chukchi Borderland area. Although most of the entrained sediment fits the criteria for suspension freezing in shallow water, the presence of winter polynyas with offshore winds and not the size of shallow areas appears to be the critical factor for sea ice entrainment. Seven of the 18 ice floes sampled contained Fe oxide grains from more than one source area. The two most common sources that are found in the same ice floes are Banks Island and the Laptev Sea. Multiple sources in ice floes suggest that either mingling of fragmented ice floes occurs or that a source area containing grains from both these sources has yet to be located. The addition of fine, sand-sized, windblown sediment is not thought to be significant. *INDEX TERMS:* 4207 Oceanography: General: Arctic and Antarctic oceanography; 4219 Oceanography: General: Continental shelf processes; 3349 Meteorology and Atmospheric Dynamics: Polar meteorology; 4558 Oceanography: Physical: Sediment transport; 3339 Meteorology and Atmospheric Dynamics: Ocean/atmosphere interactions (0312, 4504); *KEYWORDS:* Arctic Ocean, sea ice, provenance, Fe oxide minerals, surface circulation, ice drift

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1. Introduction

[2] The origin and drift pattern of Arctic sea ice impacts coastal erosion, bio-productivity, weather, and environmental contamination where polluted sediment is entrained by ice. Because of its importance, several attempts have been made to better understand where sea ice forms, how it entrains sediment, its drift pattern, and eventual deposition by melt out [*Pfirman et al.*, 1997; *Reimnitz et al.*, 1998; *Tucker et al.*, 1999; *Dethleff et al.*, 2000]. Thus far only a handful of floes are traced to possible sources with limited confidence. The Kara Sea and the eastern Laptev Sea to the western East Siberia Sea are identified as important areas of sea ice formation and sediment entrainment [*Eicken et al.*, 1997; *Pfirman et al.*, 1997; *Tucker et al.*, 1999; *Darby et al.*, 2002]. This paper examines 18 sea ice sediment samples collected from ice floes in the western Arctic Ocean during the last 30 years that contain abundant fine sand and silt-sized sediment. A new tracer is employed that provides more specific source information than those previously used; that is, the chemical fingerprint of nine Fe oxide mineral grain types that are compared to a large data set from circum-Arctic shelves and coastal areas [*Darby and Bischof*, 1996; *Darby et al.*, 2002]. This approach to provenance uses microprobe analyses of individual grains in the 45–250 μm range that can be matched to similar grain types in sampled source areas (Figure 1). The findings help to confirm the importance of the eastern Laptev Sea for sea ice production and sediment entrainment but also suggest other unsuspected areas as well as new insights into ice drift and entrainment processes.

2. Materials and Methods

[3] Sediment samples collected from the surface of ice floes by various means were usually composite samples from several melt ponds or ice within a small area of a few hundred meters. Except for the floes sampled in the Beaufort Sea, most of the floes sampled were multiyear floes as determined from ice characteristics (Table 1) [*Reimnitz et al.*, 1993c; *Tucker et al.*, 1999]. About 65 samples were examined but only 18 contained adequate numbers of Fe oxide grains for a statistically meaningful match to sources.

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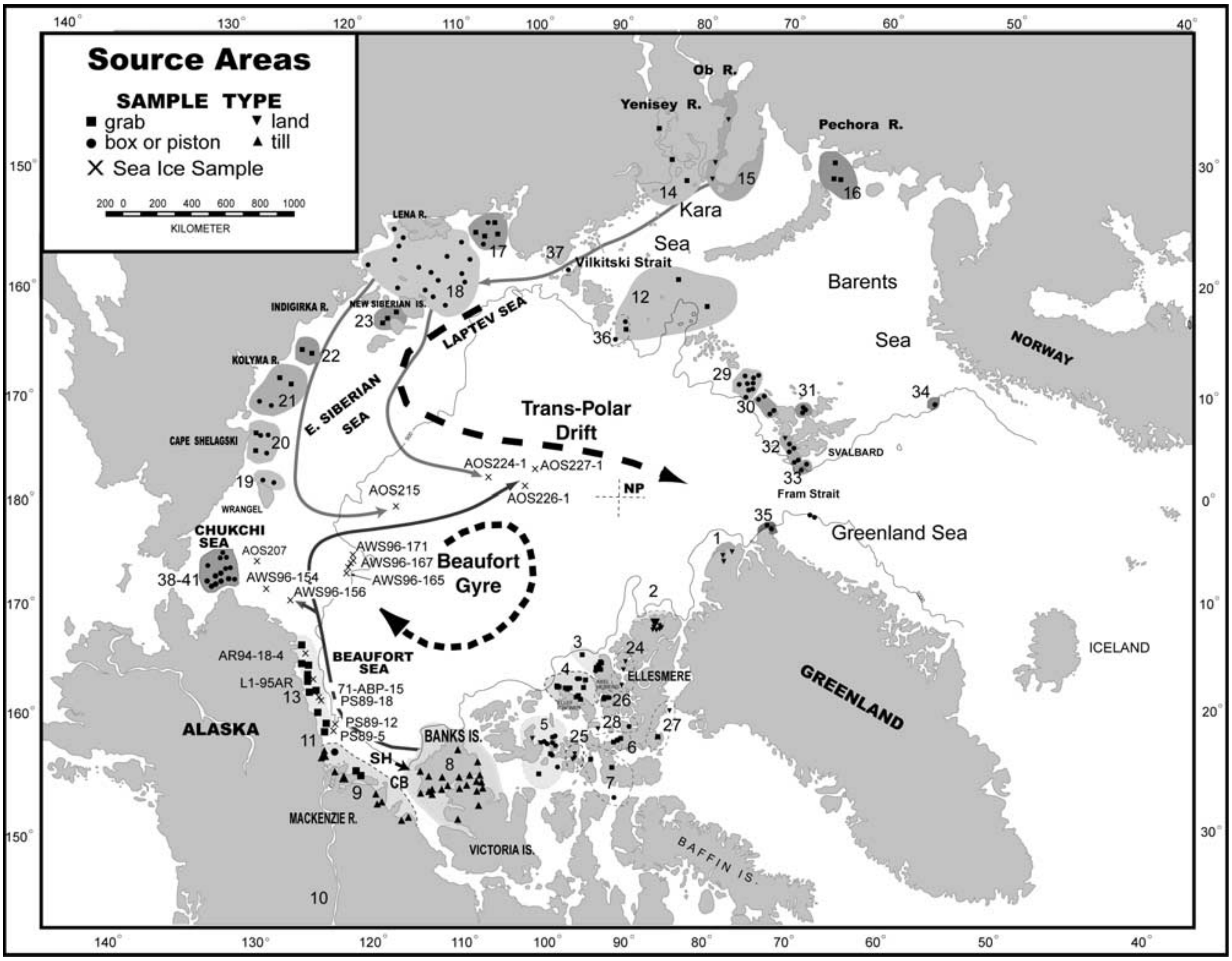

Figure 1. The sea ice sample locations and the general sea ice circulation (bold dashed arrows) in the Arctic Ocean. The proposed drift trajectories (gray arrows) shown are for the general areas where floes were sampled and are based both on the Fe oxide grain sources and buoy backtrajectories with known or general surface currents. Samples from Sachs Harbor (SH) are too close together to show. The Cape Bathurst (CB) Polynya generally occurs in the coastal waters between Banks Island and the Mackenzie Delta.

Table 1. Location and Collection Date for Sea Ice Samples[a]

Floe ID	Latitude	Longitude	Date	Floe Age	AO Index	Comments
71-ABP-15	70°36.5′N	146°2.3′W	Aug. 1971	FY?	−0.15	one floe, sampled area ±50 m
PS89-5	70°15′N	140°22′W	Aug. 1989	FY	0.3	one floe, sampled area ±50 m
PS89-12	70°17′N	143°34′W	Aug. 1989	FY	0.3	one floe, sampled area ±200 m
PS89-18	70°31′N	142°13′W	Aug. 1989	FY	0.3	one floe, sampled area ±50 m
AR94-18-4	71°5′N	152°12′W	Aug. 1994	FY?	0.15	one floe, sampled area ±50 m
L1-95AR-3	70°46.5′N	149°51.3′W	Aug. 1995	FY?	0.1	one floe, sampled area ±50 m
AWS96-154C[b]	70°50.2′N	164°57′W	2 June 1996	FY	0.1	several locations on same floe ±100 m
AWS96-156-2-1	71°52.2′N	163°30.5′W	4 June 1996	FY	0.1	one floe, sampled area ±50 m
AOS207-1	70°0′N	168°44′W	26 July 1994	FY	0.15	one floe, sampled area ±50 m
AWS96-165[b]	75°9.9′N	160°15.8′W	13 June 1996	MY	0.1	combined samples from two floes >20 km apart
AWS96-166	75°36.1′N	161°31.2′W	14 June 1996	MY	0.1	combined samples from two floes >6 km apart
AWS96-167	75°51.7′N	163°49.6′W	15 June 1996	MY	0.1	several locations on same floe ±100 m
AWS96-170C[b]	75°57.9′N	167°36.7′W	18 June 1996	MY	0.1	combined samples from three floes >11 km apart
AWS96-171C[b]	76°24.2′N	168°0.1′W	19 June 1996	MY	0.1	combined samples from two floes >39 km apart
AOS215	78°7′N	176°44′W	3 Aug. 1994	MY	0.15	one floe, sampled area ±50 m
AOS224	83°10′N	174°5′E	12 Aug. 1994	MY	0.15	one floe, sampled area ±50 m
AOS226-1	84°50′N	170°42′E	14 Aug. 1994	MY	0.15	one floe, sampled area ±50 m
AOS227-1	85°54′N	166°50′E	15 Aug. 1994	MY	0.15	one floe, sampled area ±50 m

[a]The interpretation of first year (FY) or multiyear (MY) ice is by W. Tucker (AWS and AOS samples) and E. Reimnitz (all others). The Arctic Oscillation vorticity index is from *Mysak* [2001].
[b]Samples combined from same general location.

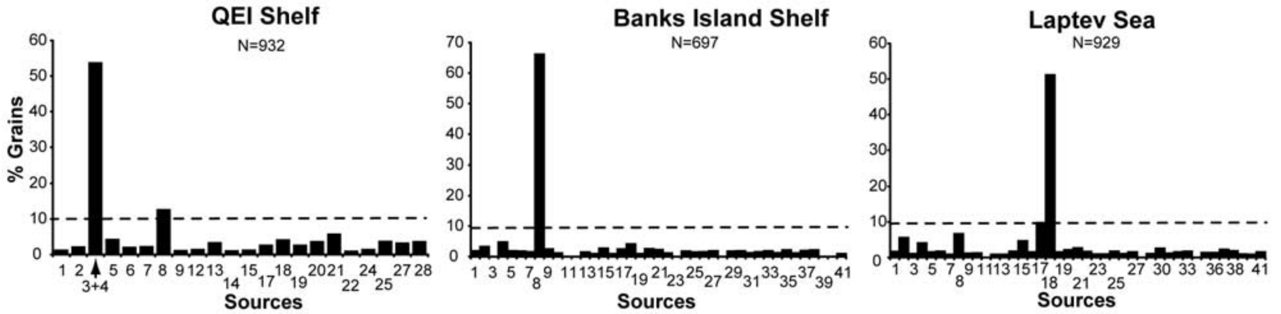

Figure 2. Matches of grains from three important source areas to all other source areas in the circum-Arctic. N is the number of grains matched, and the dashed line indicates the minimum percentage of grains for a match, which is a function of N (see text for discussion).

None of the reported floes showed clear indications of a fast (anchor) ice origin.

[4] All samples were wet-sieved into 45–63 μm and 63–250 μm fractions for ease of magnetic separation. The magnetic Fe oxide minerals were separated by hand magnet and then a Frantz magnetic separator set at 0.3 amp. The magnetic minerals from both size fractions were combined and mounted in epoxy plugs, ground to expose the grains, polished, photographed, and identified with reflected light ore microscopy (1000x). Each identified grain was numbered on the photograph of the mount and analyzed for 12 elements by an automicroprobe. This analysis counted each element for 20 s or 20,000 counts and standards were Fe oxides similar to the minerals analyzed [*Darby and Bischof*, 1996]. The 12 elements are all known to occur in one or more of the nine mineral types (Fe, Ti, Mn, Mg, Ca, V, Cr, Si, Al, Zn, Nb, and Ta). The mineral types are fresh ilmenite (TiO_2 < 51%), altered ilmenite, magnetite, magnetite with other phases, hematite, ferric-ilmenite (ilmenite with <50% exsolved hematite), titano-hematite (hematite with <50% exsolved ilmenite), titanomagnetite, and chromite. Special care was taken to avoid altered parts of grains such as weathered rims.

[5] The analyzed grains in the source area data set were grouped by mineral type and clustered into composition groups for each mineral. The range for each element in a source group is nearly as low as replicate analyses of the same grain (i.e., approximately ±5% of the analyzed value). Nearly 2,000 composition types were recognized for all minerals among the 41 source areas, but fewer than 100 of these contained more than 10 grains (maximum in any composition group is 150 grains). These larger composition groups account for more than 80% of the matched grains in the sea ice samples. Groups with 2–3 grains were excluded unless they were the only grain groups for a particular mineral in a source area.

[6] The source groups were tested using discriminant function analysis (DFA) where the probability of group membership exceeded 0.95 and the probability of each grain being closer than any other grain to the group centroid exceeded 0.1. About 30% of the analyzed source area grains failed these tests and were not used. Attempting to match all of the grains from a source area to all other circum-Arctic sources tested the robustness of these groupings. The results of this match for the important source areas, those to which most of the sea ice grains matched, indicate that grains from these source areas do not match into groups from other areas in significant numbers (Figure 2). To match grains to a source area, each grain in a sea ice sample was compared to all source area composition groups for that mineral using DFA. For a grain to be matched to a source, this technique requires that the 12 elements be closer to the source group mean composition than half of the source grains comprising that source mineral group [*Bischof and Darby*, 1997]. This reduces considerably the error associated with confusing similar source groups, but it also causes about 40% of the analyzed grains to fail in matching to a source. Because of the time involved in each analysis and the low percentage of accepted matches, matched grain numbers in any given sample rarely exceeded 100. Only the number of grains that were matched to a source is reported, not the total number of grains analyzed. No matches with less than 25 grains were used.

3. Results

[7] Most of the grains analyzed were single-phase Fe oxide minerals (ilmenite, titanomagnetite, or magnetite) and 60% of these were successfully matched to source area composition groups. Because of the complexity of Fe oxide grains with exsolved phases and inclusions, such grains are more difficult to match to source grain compositions. This is because the analyzed spot on each grain varies in the amount of either mineral phase that is analyzed, significantly affecting the chemical composition. For these mineral types, 22% were matched to a source compared to the overall average of 55%. Not only did compositions differ for a mineral type among source areas, but also the mix of Fe oxide minerals varied widely [*Bischof and Darby*, 1999]. This plays an important role in this provenance approach. Nearly all source areas contained ilmenite, titanomagnetite, and magnetite and these minerals have the greatest variability in composition. Some magnetite grains have up to the maximum 40% substitution of Fe by other elements [*Darby*, 1998] and combinations of Fe, Ti, Mn, Mg, Si, Al, and Nb are important in ilmenite (Table 2). Even trace amounts (<1%) of some elements, however, were useful in matching grains to specific sources. The range of compositions among each Fe oxide mineral in the circum-Arctic source data set is quite remarkable (Table 2). It is this wide variability in these minerals that makes matches to specific source areas possible. When all of the grains from each of

Table 2. Range of Chemical Oxide Values for Each Fe Oxide Mineral in the Major Composition Groups From the Circum-Arctic Source Areas[a]

	Fresh Ilmenite	Altered Ilmenite	Titano- Magnetite	Hematite	Titano- Hematite	Ferro-Ilmenite	Magnetite	Magnetite + Others	Chromite
N	5147	1076	2188	256	415	1160	1654	991	75
TiO_2	30.0–51.0	51.0–98.1	1.1–46.6	0–25.8	5.0–73.9	30.2–86.8	0–50.2	0–56.0	0–8.4
FeO	1.4–67.5	0.7–47.8	2.6–70.0	37.8–95.5	1.6–90.6	4.0–66.1	31.1–99.3	30.1–99.0	21.3–64.0
MnO	0–20.2	0–14.9	0–6.3	0–2.0	0–18.2	0–16.1	0–2.2	0–8.4	0.3–8.8
MgO	0–6.9	0–3.7	0–19.7	0–9.0	0–8.0	0–8.7	0–20.4	0–9.4	0.2–12.8
$Si0_2$	0–51.0	0–15.8	0–48.5	0–60.2	0–20.7	0–20.4	0–30.5	0–24.1	0–7.6
$Al2O_3$	0–25.6	0–8.9	0–19.7	0–8.0	0–14.4	0–12.7	0–16.0	0–9.3	0–18.3
$Cr2O_3$	0–4.5	0–0.8	0–12.7	0–7.4	0–5.1	0–0.6	0–13.0	0–15.3	30.3–58.5
ZnO	0–10.0	0–6.4	0–6.0	0–8.7	0–8.9	0–9.0	0–25.0	0–6.6	0–6.4
$V2O_3$	0–2.8	0–1.4	0–4.1	0–2.0	0–2.2	0–1.7	0–2.9	0–3.4	0–0.9
CaO	0–27.0	0–28.3	0–46.9	0–10.3	0–22.1	0–20.1	0–11.7	0–19.2	0–1.9
$Nb2O_5$	0–5.4	0–4.7	0–6.7	0–2.3	0–5.5	0–2.2	0–3.2	0–3.3	0–1.9
TaO	0–0.9	0–1.1	0–2.1	0–0.7	0–1.3	0–0.7	0–1.1	0–0.8	0–0.8

[a]Analyses include grains with inclusions of other mineral phases.

these sources are matched to every other source area, the results indicate that each source is remarkably unique (Figure 2). Normally fewer than five percent of the grains from three important source areas for sea ice samples matched to any other source area, except for the Queen Elizabeth Islands shelf area, where 12% of the grains matched to the nearby Banks Island area. Including grains that were originally excluded from the composition groups in these areas as well as those comprising these groups, 52–65% of all these grains matched correctly to the source area in which they were sampled. This is very good considering the conservative probabilities required for a match.

[8] The sea ice samples are divided into general regional locations so as to better evaluate sources and provide details of source and drift direction from source to sampling site. These regions are: the shelf off northern Alaska (Beaufort Sea), the northern Chukchi Sea, the Chukchi Borderland including the Northwind Ridge area, and the west-central Arctic Ocean between the Chukchi Borderland and the North Pole (Figure 1).

[9] Because of the relatively low number of grains matched to sources from each sample (less than the minimum number of 300 for statistical significance in point counts), percentages could be misleading. To avoid this, a weighted percentage is used where the percentage matched to a source is multiplied by 10% of the grains matched to that source [*Darby et al.*, 2002]. Thus the weighted percent increases in the case where more than 10 grains are matched to a source and decreases where fewer grains are matched (more commonly the case). This emphasizes the matches that are more significant because of larger numbers of grains matched. Although 10 grains matched to a single source is somewhat arbitrary, the large occurrence of sources with fewer than 5 grains indicates that 10-grain matches constitutes a significant source and 5 is the minimum for a positive source identification [*Darby et al.*, 2002].

3.1. Beaufort Sea

[10] The six sea ice samples taken from the Beaufort Sea show that Banks Island is a major source of sediment (source 8, Figures 1 and 3). Grains from north Ellesmere Island in the Ward Hunt ice shelf area dominate one floe, PS89-18. Both of these sources are east of the Beaufort Sea and indicate westward drift typical of the net motion of the Beaufort Gyre [*Kwok*, 2000]. Four of the six floes contained grains from Russian shelves in addition to grains from northern Canada. In the oldest of these samples, 71-ABP-15 (collected in 1971), the eastern Laptev Sea is the most important source matched (source 18). The Russian sources are primarily the Laptev Sea or the Ob River, which empties into the Kara Sea. The floes with significant numbers of grains from the Ob River were sampled in the Beaufort Sea in 1971 and 1989 and peak suspended sediment discharges (double the average) from this river occurred in 1969 and 1986 [*Meade et al.*, 2000]. Only two of the Beaufort Sea ice floes contain grains from primarily one source, Banks Island. Both of these floes were sampled in 1994–1995 and are the youngest samples from this area. None of the floes contain significant numbers of grains from northern coastal Alaska (source 13, Figures 1 and 3).

3.2. Chukchi Sea

[11] Only three floe samples contained adequate numbers of Fe oxide grains from the northern Chukchi Sea but the source matches all indicate that Banks Island is the dominant source (Figure 4). Only the westernmost floe (AOS207-1) contained significant numbers of grains that matched to the eastern Laptev Sea in addition to grains that matched to Banks Island. The number of grains from the Chukchi Sea (sources 38–41) is insignificant, but none of the Chukchi Sea floes are from the coastal belt of dirty ice often observed along the Arctic coast of Alaska [*Reimnitz et al.*, 1993c; *Tucker et al.*, 1999] where one might expect a local source.

3.3. Chukchi Borderland

[12] Grains from Banks Island dominate four of the five floes from this area (Figure 5). Of particular interest is one floe matched to the Laptev Sea as its sole source (AWS96-167). One other nearby floe sample, AWS96-165, also contained notable amounts of grains matched to the Laptev Sea. Otherwise, the grains in these floes indicate sources to the east in northern Canada. Two floe samples in this group contained some grains (below significant levels) from the Chukchi Sea to the south.

3.4. Central-Western Arctic Ocean

[13] Dirty sea ice is less common 100 km beyond the coast [*Tucker et al.*, 1999]. Yet four floes sampled during the Trans-Arctic joint Canadian-US icebreaker expedition in 1994 in the central Arctic had adequate amounts of fine

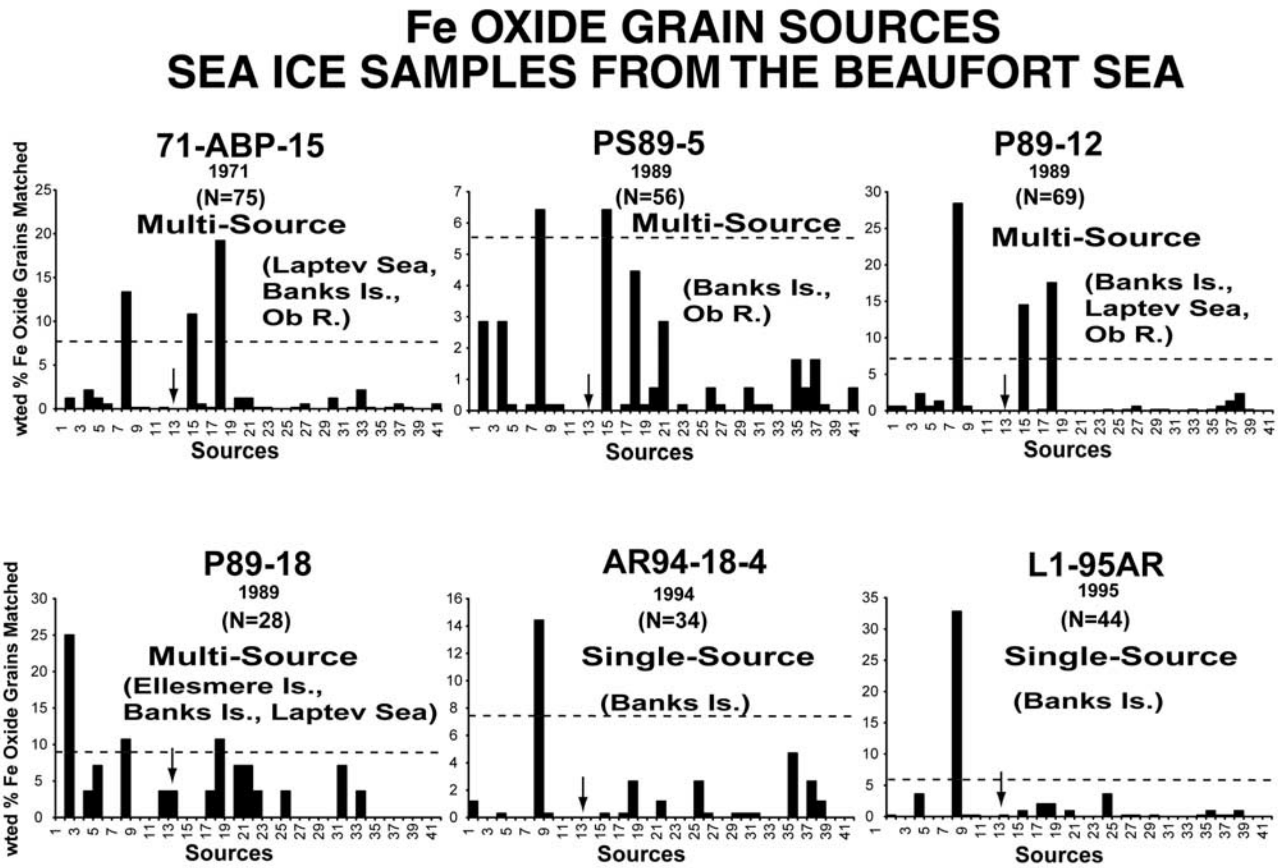

Figure 3. The weighted percent of Fe oxide grains from sea ice floes in the Beaufort Sea matched to circum-Arctic source areas. Arrows show the local northern Alaska shelf source area (source area 13). The Banks Island source (source area 8) is significant in every sample.

sand and coarse silt for significant source matches. Three of these matched solely to Russian shelves and one to Banks Island (Figure 6). Grains from the Laptev Sea dominate two of these Russian floes and grains from Cape Shelagski (source 20) in the East Siberian Sea (Figure 1) dominate another. This sample (AOS226-1), dominated by Cape Shelagski grains but with significant matches (13 grains) to the Ob River (area 15, Figure 1) is one of two multisource floe samples in the central Arctic area. The other multisource sample (215) matches primarily to the Laptev Sea with 9 grains matched to the Kolyma River mouth area (source area 21, Figure 1) on the East Siberian Sea.

4. Discussion

4.1. Robustness of Matches

[14] In the 11 floe samples with a single dominant source, there are no other sources with 10 or more grains and

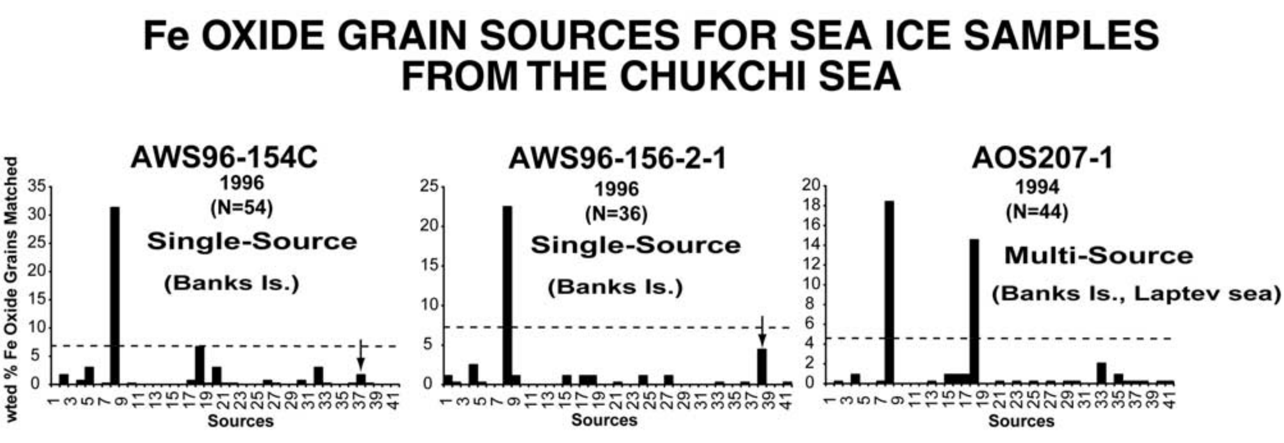

Figure 4. Source matches for three floes sampled in the northern Chukchi Sea. Arrows indicate the local Chukchi Sea source.

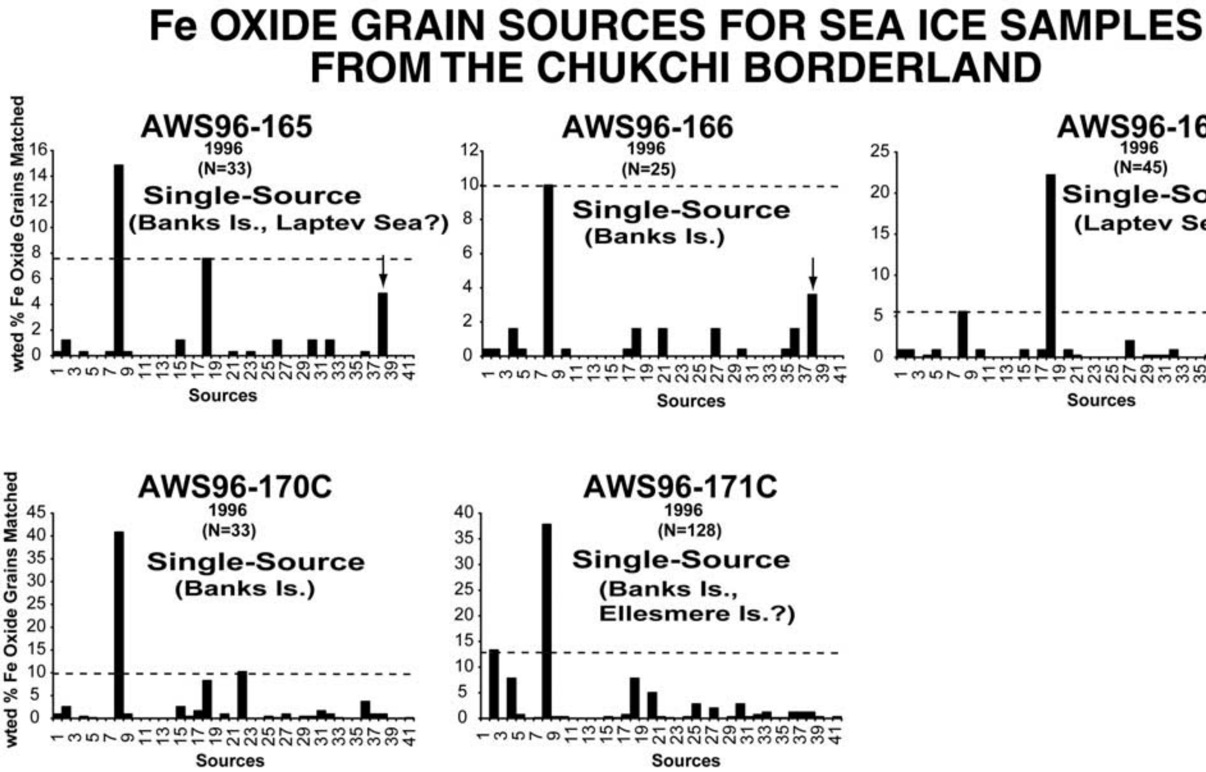

Figure 5. Source matches for five floes sampled in the Chukchi Borderland area in 1996. Arrows indicate the local Chukchi Sea source.

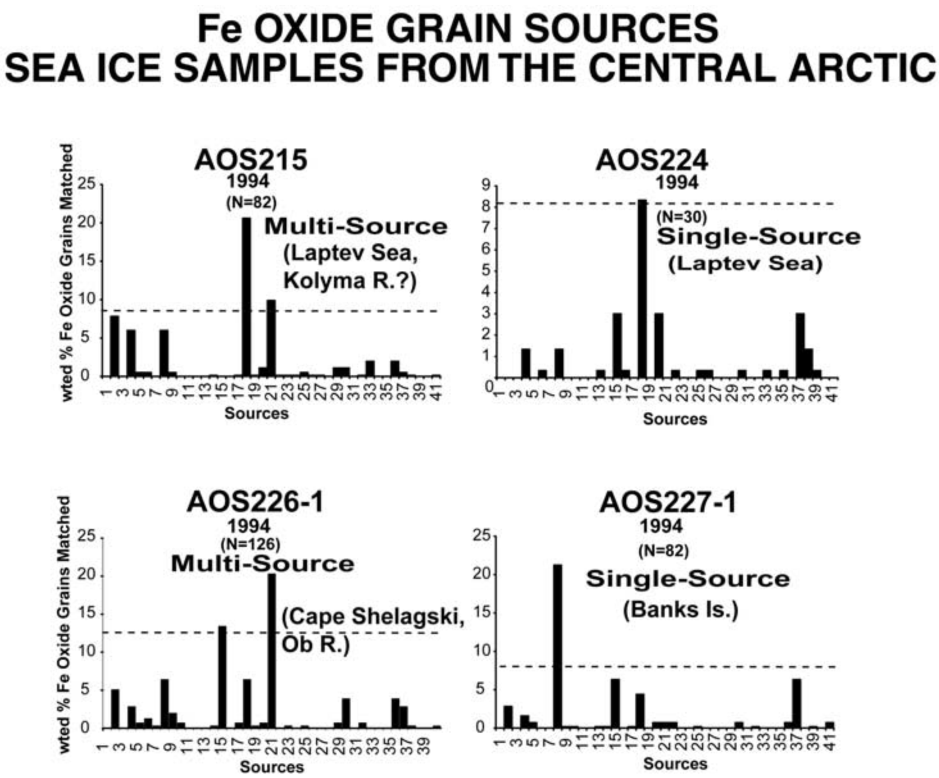

Figure 6. Source matches for four floes sampled in the west-central Arctic in 1994.

usually no other source with more than 5 grains. Even floe samples matched to multiple sources contain low numbers of grains from several other sources, normally less than 3–5 grains from any source area. Thus the pervasiveness of this background of grains matched to sources with fewer than 5 grains suggests that a level of significance for the primary source or sources should be set at a somewhat higher limit and 5 grains (about 10% of most samples) seems reasonable judging from the difference between dominant and minor sources. The cause of such a large number of sources found in each sample, each source represented by less than five grains, might be either low numbers of grains transported to and deposited on foreign shelves by sea ice [*Bischof and Darby*, 1999], or low numbers of grains in different areas with similar compositions (Figure 2). Neither of these can be discounted. The fact that the dominant sources contain far greater numbers of matched grains than the minor sources with less than 3–5 grains indicates that this is not a serious problem in using this provenance approach. In fact a test of the robustness of the matches was made by attempting to match the 3,227 Arctic Ocean sea ice Fe oxide grains from all 18 samples to a large data set that could not be the source. The source area groups used for this test contain 2,171-grain analyses from five important US East Coast rivers (Hudson, Susquehanna, Potomac, James and Roanoke rivers) comprising a wide variety of source rock types and Fe oxide grain compositions. These Fe oxide grains were analyzed and grouped in the same manner as the circum-Arctic source area groups. Only 8% of the sea ice grains matched to these rivers using the same probability criteria as used in matching them to circum-Arctic sources. More than 10 sea ice grains matched to only a few of the 200 source groups from these U.S. rivers. This demonstrates that this provenance approach will not randomly match significant numbers of grains to an incorrect source and that the Fe oxide grains in at least these two large source area data sets (East Coast US and circum-Arctic) are quite different. Thus the minimal level of significance for a source match is set at 5 grains or 10% of the total matched grains in a sample, whichever is larger (Figures 2–6).

[15] Another test of the source matches is based on a comparison of the available sea ice International Arctic Buoy Programme results. Tracked floes from the Beaufort Sea have back drift trajectories that indicate an origin somewhere along the Northeastern Alaska coast or near Banks Island [*Pfirman et al.*, 1997]. This generally agrees with the closest source area based on matched Fe oxide grains. The drift buoy trajectories are based on average monthly drift trajectories and are run back in time until the floe intersects a coastline or shallow water [*Rigor and Heiberg*, 1995; *Rigor and Colony*, 1997]. Thus the nearest source would most likely be the one determined by this calculation. For example, ice samples 71-ABP-15 and PS89-5 to 18 from the Beaufort Sea have back trajectories that suggest an origin near northeast Alaska or the Mackenzie area and perhaps Banks Island [*Pfirman et al.*, 1997]. These floes have a significant number of Fe oxide grains from Banks Island as well as Russian sources such as the Laptev Sea (Figure 3).

[16] The 1989 floe samples are suspected to have originated in a coastal polynya north of Alaska [*Reimnitz et al.*, 1993c] but the Fe oxide data indicate Banks Island and the Laptev Sea as the sources. Although the grains in these six floe samples do not match sources on the shelf north of Alaska, there is a possibility that unsampled areas of this shelf might contain Fe oxide grains from Banks Island and even Russia because of earlier ice transport (see discussion below). Such deposits would indicate a dual source such as the sampled floes from 1989. Several floes from the AOS-94 cruise across the central Arctic show back trajectories to the Siberian coast [*Tucker et al.*, 1999]. This also is in general agreement with the sources from Fe oxide matches despite some inconsistencies in individual floes discussed later.

4.2. Origin of Sea Ice, Important Sediment Entrainment Areas, and Implications for Entrainment Processes

[17] The sampled floes over the last 30 years in the western Arctic Ocean reaffirm the importance of the Laptev Sea both as a center of ice production and sediment entrainment by sea ice. *Pfirman et al.* [1997] identified this region as the main source of sediment-laden ice in the Eurasian Arctic on the basis of clay mineralogy coupled with back trajectories. The grains matched to the Laptev Sea indicate that the primary source area for sediment matched to the Laptev Sea is the eastern part, east of the Lena Delta. Fe oxide grains from this area are found in significant numbers in eight of the 18 sampled floes from the western Arctic. Besides this Russian source, grains were matched to the Ob River as well as to the Cape Shelagski and Kolyma River areas on the East Siberian Sea. The shelf here is one of the widest and shallowest in the Arctic Ocean. Despite having large areas with depths favorable for suspension entrainment, neither this study nor earlier studies [*Nürnberg et al.*, 1994; *Pfirman et al.*, 1997; *Tucker et al.*, 1999; *Eicken et al.*, 1997, 2000] indicate that the East Siberian Shelf is an important source of sea ice entrainment except for the very western area near the Laptev Sea. Apparently other factors play an overriding role.

[18] Satellite observations of dirty ice in this part of the Arctic indicate that the area southeast of the New Siberian Islands is an important entrainment area [*Eicken et al.*, 2000]. This is just east of the Fe oxide source area 18 in the eastern Laptev Sea (Figure 1). Because the two areas are so close, both the Fe oxide source matches and the satellite tracking techniques used by *Eicken et al.* [2000] compliment one another in determining this general area to be important for sea ice sediment entrainment.

[19] Banks Island grains are found in significant numbers in 14 of the 18 sampled floes. This source area was not previously suspected to be such an important source of sediment entrainment. While the exact manner of entrainment for all of these floes is difficult to determine, the fact that nine of these floes matched to a single source, Banks Island, and that all of the grains were very fine sand- or silt-sized suggest that suspension freezing was responsible [*Reimnitz et al.*, 1993a, 1993b]. Aeolian deposition onto the pack ice, however, is also possible, although field evidence for such a process is very scant [*Darby et al.*, 1974; *Pfirman et al.*, 1989; E. Reimnitz, U.S.G.S., personal communication, 2001]. Redistribution of the Fe oxide grains by wind is highly unlikely because sediment entrained by sea ice is encased in ice during the winter or

in melt ponds in summer and thus not normally available for aeolian transport. All of the samples used to characterize Banks Island are from tills and outwash deposits on this or Victoria Island. Thus the grains in those floe samples matched to Banks Island were probably eroded onto the adjacent Arctic shelf where they could be entrained in sea ice. To test this, six samples were collected from the southwest Banks shelf near Sachs Harbour in water depths less than 50 m. Collectively, the grains from these samples matched primarily to the tills on Banks Island (63% of 481 grains analyzed) with less than 5% matching to any other individual source area.

[20] If suspension freezing during sea ice formation is the entrainment process for the floes matched to Banks Island, not only is this an important sediment entrainment area, but also it's a more important sea ice formation area than previously believed. The frequent polynya, known as the Cape Bathurst Polynya [*Stirling*, 1997], or flaw leads (open water at the boundary of fast ice and the moving packice offshore) that occur in this area [*Winsor and Björk*, 2000; *Carmack and McDonald*, 2002], would be conducive to sea ice formation, especially when offshore winds prevail [*Reimnitz et al.*, 1993c]. The typical scenario would be that as frazil ice forms with entrained bottom sediment and is blown offshore or westward out of the area, more ice forms and the process repeats itself several times over the fall and winter. Compared to the area of the East Siberian Sea that is shallower than the 30 m depths needed for suspension entrainment, the Banks Island Shelf contains less than one percent of this vast shallow sea. Both the East Siberian Sea and the Chukchi Sea are of minor importance for suspension entrainment in sea ice but are largely ice-free at the end of each melt season and thus are important areas of sea ice formation [*Winsor and Bjork*, 2000]. The shallow areas of these shelves dwarfs even the important shallow entrainment area of the Laptev Sea. Thus polynya conditions with offshore winds in fall and winter appear to be more important than total shallow area or ice production for this entrainment process. Also total ice production does not equate with dirty ice production.

4.3. Multisource Floes

[21] The presence of more than one source in a floe is noteworthy. Multisource floes should be rare because sea ice usually does not entrain sediment after the packice forms, even apparently by grounding or aeolian deposition when close to shore [*Reimnitz and Barnes*, 1974; *Reimnitz et al.*, 1993a; *Nürnberg et al.*, 1994]. Processes that could add new sediment to a floe after the packice forms include: 1) windblown material from nearby land (usually less than a few kilometers if sand is involved) [*Pfirman et al.*, 1989]; 2) flood events where turbid river waters are flushed onto the packice [*Reimnitz and Bruder*, 1972; *Holmes and Creager*, 1974], or 3) some type of grounding that brings the packice into contact with unconsolidated bottom sediment [*Reimnitz and Barnes*, 1974]. No evidence for any of these processes was seen in the sampled floes based on observations by those collecting the samples (W. Tucker, CRREL, and E. Reimnitz, U.S.G.S., personal communication, 2001]. None of these floes contain significant numbers of grains from the major river in this area, the Mackenzie River, which excludes fluvial flood events or river ice as significant for the sampled floes. For sand entrainment by grounded ice to mix with sediment originally in the ice, it must work its way to the surface via multiple melting episodes where surface ice melts during the summer and new ice is added to the bottom of the packice in winter. Because they were less than 600 km from the Banks Island shelf, the Beaufort Sea floes would probably not have the time for this to occur.

[22] The floes in the Beaufort Sea are all thought to be first year ice (Table 1) and yet four of the six contain grains from multiple sources, Banks Island and the Laptev Sea plus the Ob River. A possible explanation for multisource floes, especially first year floes, involves the transport of sediment by sea ice across the Arctic to another shelf where the sediment is deposited by melt out. This permits mingling of sediment from multiple sources on certain shelves where this might occur.

[23] Up to 16% of the Fe oxide grains from the shelf off the Queen Elizabeth Islands (Ellef Ringnes and Axel Heiberg Islands) in northern Canada matched to Russian sources, with subequal amounts from the Laptev and East Siberian seas [*Bischof and Darby*, 1999]. In at least two of the multisource ice floes found in the Beaufort Sea, the Laptev Sea component is greater than 16% and grain numbers from the E. Siberian Sea are insignificant (Figure 3). The Canadian shelf Fe oxide grains do not match to the Ob River in significant numbers like the three floes containing such grains found in the Beaufort Sea. Thus, because of these differences, the northern Queen Elizabeth Islands shelf area does not appear to be a promising entrainment area for these sampled ice floes. The Laptev Sea does not appear to be a promising area for mixing of Banks Island grains with local grains either. There are insignificant amounts of grains matched to Banks Island in Russian source areas (Figure 2). Likewise, fewer than 4% of the Banks Island source area grains match to any source area other than Banks Island (Figure 2). The entire Laptev Sea area (sources 17 and 18) accounted for only 5% of these Banks shelf grains. These grains, however, are terrestrial and not from the Banks Island shelf where sea ice would entrain grains. Thus if the process of reentrainment of mixed assemblages occurs, the source area for this is yet to be discovered. Most of the Banks Island shelf or Mackenzie shelf are not sampled and more samples from these areas need to be collected and analyzed to test these areas for multisource deposits.

[24] The dominant sources found in multisource floes in the Beaufort Sea and Chukchi Sea (i.e., Banks Island) suggest a westward drift similar to the dominant clockwise circulation of the Beaufort Gyre. The most likely scenario for the transport of Russian sediments into the Beaufort Gyre occurs when a positive vorticity index for the Arctic Oscillation (+AO) favors strong advection of ice away from the Russian coast deep into the central Arctic followed by -AO conditions increasing the size of the Beaufort Gyre, which captures the dirty ice into the Gyre. All of the multisource floes are from 1971 to 1989 and the single-source floes from 1994–1995. Unfortunately, there is an inadequate number of sampled floes to indicate a temporal change in sources; nor do the multi and single-source floes occur in the same sampling year. Yet the years immediately preceding the sampled floes are almost always years of a positive vorticity index for the Arctic Oscillation [*Mysak*,

2001]. During these years, the TPD would be strengthened and pushed closer to the Beaufort Sea, making the transport of Laptev Sea ice into the Beaufort Gyre more likely [*Thompson and Wallace*, 1998; *Dickson et al.*, 2000].

[25] Thus a promising scenario for sea ice floes with multiple sources is the mingling of floes from discrete sources. Russian ice floes drift into the Beaufort Sea where they can break up and then mingle directly with fragmented floes or even frazil ice (first-year ice) originating from the Banks Island or Mackenzie shelves. This occurs as ice floes break apart and rejoin under changing wind regimes. In fact, sharp demarcations between different floes are observed where ice of different color (entrapped air content) or clarity (sediment content) is juxtaposed. Because floes were sampled within a 50–100 m area and several melt ponds were sampled in many cases from a single floe, the possibility of mingled floes being sampled is increased. All of the floe samples that were combined from floes more than 200 m apart for statistical reasons (i.e., low grain numbers) in this study were single-source floes (Table 1).

[26] The lack of grains from the Beaufort shelf north of Alaska in proximity to the sampling locations is noteworthy. While the number of samples is not adequate to generalize, this suggests that this shelf area is not a significant entrainment area for the sea ice found farther offshore, at least for the years that the floes were sampled there. Possibly, floes that originate from the shallow parts of the Beaufort Sea, close to shore, drift west instead of north and avoid the area where the floes were sampled.

[27] Two of the three sampled floes from the Chukchi Sea contain grains from a single source, Banks Island. The other floe contains grains from both this Canadian source and a Russian source, the Laptev Sea. All three of these floes were located well outside the coastal belt of dirty ice [*Reimnitz et al.*, 1993a], presumably of local origin. Thus, because of their offshore location and Fe oxide grain matches, the sampled floes from this area have a very similar drift history and probably similar origin as those sampled in the Beaufort Sea.

[28] Back trajectories for sample AOS207, a multisource, first year floe from the northern Chukchi Sea, indicate an origin east of Wrangel Island on the East Siberian Shelf [*Tucker et al.*, 1999]. Slight alterations to the monthly averaged trajectories could easily result in back trajectories from the east instead. The location of the sampled floe (207) is an area where floes from the Beaufort Gyre can merge with floes from the East Siberian Sea [*Pfirman et al.*, 1997; *Tucker et al.*, 1999]. The Fe oxide sources for this floe are Banks Island and the Laptev Sea. These sources suggest that this floe initially originated in the eastern Laptev Sea, traversed the central Arctic via the Trans Polar Drift, and was captured by the Beaufort Gyre. It drifted south to Banks Island where fragments of this floe mingled and rejoined with floes from this area before crossing the remainder of the Beaufort Sea via the Beaufort Gyre to reach the Chukchi Sea. Alternatively, Fe oxide grains from the Laptev Sea were rafted across the Arctic Ocean to the Banks Island area in the past, deposited there and mixed with grains from this island before entrainment in a new floe that drifted to where it was sampled in 1994. Both of these scenarios require a faster drift than normal to fit with a first year ice interpretation and origin near Banks Island, more than 1600 km from the location of floe 207. Because a net 6–10 km/day drift to the west is unlikely, either multiyear floes mingled with first year ice, or a mixed source deposit exists closer to the 207 site.

[29] Four of the five floes sampled from the Chukchi Borderland show a strong source signal from the Banks Island area and one floe matched to the Laptev Sea (Figure 5). Only one floe (AWS96-165) contains a secondary match to the Laptev Sea, which is borderline significant. Thus these floes suggest a similar pattern of net westward drift from the Banks Island area within the Beaufort Gyre. Even the floe originating in the Laptev Sea could be explained by this drift pattern where the Russian floe is captured in the Beaufort Gyre after crossing the Arctic in the TPD. All of these floes were located farther offshore than those from the Chukchi and Beaufort seas and they are all multiyear floes. They were sampled in 1996 while the multisource Beaufort Sea floes were all sampled in 1971 or 1989. This might indicate that these older, multisource floes originated in areas near Banks Island that are different from the single-source floes sampled more recently.

[30] In the west-central Arctic Ocean, multisource floe sample AOS226-1 matches source grains from both Cape Shelagski (source 20, Figure 1) and the Ob River (Figure 5). This combination of Russian sources suggests a counterclockwise drift originating in the Kara Sea near the Ob River mouth. A likely path for this floe based on the sources would be through Vilkitski Strait, across the Laptev Sea and E. Siberian Sea and then to Cape Shelagski via the East Siberian Sea coastal current before turning north toward the pole (Figure 1). Somewhere between Cape Shelagski and the location of AOS226-1, fragments of the floe that originated near the Ob River mingled with floes from off Cape Shelagski or grains from this river were deposited near Cape Shelagski earlier and reentrained along with local Fe oxide grains by the ice floe sampled. Back trajectories for a nearby floe (227) [*Tucker et al.*, 1999] indicated an origin near the New Siberian Islands, just east of the Laptev Sea. This drift path based on buoy drift data is similar to the one proposed above on the basis of Fe oxide grain matches, but shifted slightly offshore.

[31] Another floe (sample AOS215) originating in the Laptev Sea shows a similar pattern based on the combination of this source and the Kolyma River area in the E. Siberian Sea. Back trajectories for this floe suggest an origin near Barrow, Alaska; however, the drift trajectory for 215 is very close to and parallel to other floes such as 218 that originated in the East Siberian Sea [*Tucker et al.*, 1999]. Thus, with minor adjustments to the monthly averaged drift vectors, this floe (215) could very easily have originated in Siberia as indicated by the Fe oxide grain matches.

[32] On the basis of these two floes (226 and 215), a similar eastward drift pattern is suggested for the single-source floe from the Laptev Sea found in the central Arctic Ocean (AOS224). Although there is less than significant numbers of grains from the Cape Shelagski area in AOS224, this and other E. Siberian Sea sources are virtually absent in floes originating in Russia and found in the Beaufort Sea and Chukchi Sea areas. Thus the combination of Russian sources (Laptev Sea and E. Siberian Sea) in the central Arctic floes helps to establish an eastward drift pattern (counterclockwise) that is remarkably similar to that suggested by *Mysak*

[2001] for years with a strong positive vorticity index for the Arctic Oscillation (1987–1996, Table 1).

[33] The only floe in this part of the Arctic with a strong North American source signature (AOS227-1) originates off Banks Island. The presence of floes in the central Arctic from both Russian and North American sources, suggests that at least for the 1994 season, the transect of the AOS samples might be close to a line where floes from both these major source areas comingle (Figure 1).

5. Conclusions

[34] This study demonstrates the use of Fe oxide chemical "fingerprinting" in tracing sea ice floes and establishing their drift path back to their origin. The drift patterns confirm that the North American side of the Arctic Ocean is dominated by sea ice floes that drift west with the Beaufort Gyre. For those floes with significant Russian grains along with Banks Island grains, an origin on Siberian shelves (Laptev Sea) coincident with sediment entrainment is postulated followed by drift across the central Arctic via the TPD before capture in the Beaufort Gyre. Only in the west-central Arctic Ocean do ice floes occur with Russian sources that suggest an eastward drift across the E. Siberian Sea near the coast before turning north to where they were sampled. This study also demonstrates the importance of the shelf off Banks Island (e.g., the Cape Bathurst Polynya area) for sea ice entrainment, most likely by suspension freezing during ice formation. This is the first time that multiple sources are recognized in sea ice sediment. This indicates the importance of either trans-Arctic transport and deposition of Russian grains onto shallow North American shelves where they can later be entrained in sea ice or comingling of Russian and North American ice floes in the Beaufort Gyre or west-central Arctic Ocean. In either case, ice floes originating in shallow Russian seas are a regular occurrence in the Beaufort Gyre.

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