Old Dominion University Research Foundation

THE APPLIED MARINE RESEARCH LABORATORY
COLLEGE OF SCIENCES
OLD DOMINION UNIVERSITY
NORFOLK, VIRGINIA 23529-0247

ORIGIN AND DISPERSAL OF POTENTIALLY CONTAMINATED SEA ICE IN THE ARCTIC OCEAN

By
Dr. Dennis A. Darby, Principal Investigator
Dr. Jens F. Bischof, Principal Investigator

Final Report
For the period ended August, 1995 to February, 1997

Prepared for
Program Manager/Officer ONR: 322
Attn: Robert Edson
Office of Naval Research
Ballston Tower One
800 North Quincy Street
Arlington, VA 22217-5660

Under
Contract N00014-95-1-1200
ODURF #253341

Submitted by the
Old Dominion University Research Foundation
P.O. Box 6369
Norfolk, VA 23508-0369

May 1997

REPORT DOCUMENTATION PAGE

FORM APPROVED
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	May 13, 1997	Final Report Aug. 1995-Feb. 1997

4. TITLE AND SUBTITLE OF REPORT
Origin and dispersal of potentially contaminated sea ice in the Arctic Ocean

5. FUNDING NUMBERS
N00014-95-1-1200

6. AUTHOR(S)
Dennis A. Darby and Jens F. Bischof

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Applied Marine Research Lab
Old Dominion University
Norfolk, VA 23529

8. PERFORMING ORGANIZATION REPORT NUMBER:

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
High Latitude Dynamics
800 North Quincy Street, Arlington, VA 22217-5660

10. SPONSORING/MONITORING AGENCY REPORT NUMBER:

11. SUPPLEMENTARY NOTES:

12a. DISTRIBUTION AVAILABILITY STATEMENT
UNCLASSIFIED: UNLIMITED

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)
see attached

14. SUBJECT TERMS
sea ice
ice-rafted detritus
Fe oxide grains

15. NUMBER OF PAGES: 12

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT:	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED

THE APPLIED MARINE RESEARCH LABORATORY
COLLEGE OF SCIENCES
OLD DOMINION UNIVERSITY
NORFOLK, VIRGINIA 23529-0247

ORIGIN AND DISPERSAL OF POTENTIALLY CONTAMINATED SEA ICE IN THE ARCTIC OCEAN

By
Dr. Dennis A. Darby, Principal Investigator
Dr. Jens F. Bischof, Principal Investigator

Final Report
For the period ended August, 1995 to February, 1997

Prepared for
Program Manager/Officer ONR: 322
Attn: Robert Edson
Office of Naval Research
Ballston Tower One
800 North Quincy Street
Arlington, VA 22217-5660

Under
Contract N00014-95-1-1200
ODURF #253341

Submitted by the
Old Dominion University Research Foundation
P.O. Box 6369
Norfolk, VA 23508-0369

May 1997

FINAL REPORT

ORIGIN AND DISPERSAL OF POTENTIALLY CONTAMINATED SEA ICE IN THE ARCTIC OCEAN

Introduction

The Arctic Ocean is unique because of its perennial ice cover and restricted water mass exchange with the other World's oceans. It is almost entirely surrounded by continents and broad shelves and possesses only one deep connection to the Norwegian and Greenland Seas, the Fram Strait. Ice is covering almost all of the Arctic Ocean during the winter months, but in the summer a large portion of the ice melts and a marginal ice-free zone opens up (Barry, 1989). The ice cover is relatively thin (2-4m) and consists of one- and multi-year old sea ice floes and pressure ridges (Koerner, 1973; Wadhams, 1981, 1983). Occasional fragments of icebergs and ice islands also are present (Clark and Hanson, 1983; Bogdanov et al. 1994; Eicken et al., 1994b; Fütterer 1994), but sea ice is the dominant ice type under the present interglacial conditions. Most sea ice forms on the shelves by freezing of seawater in contact with supercooled air during the fall (Colony and Thorndike, 1985). Depending on the location of sea ice formation, variable quantities of clastic debris can be entrained. The best conditions for sediment entrainment exist when sea ice forms during storm events (frazil-ice formation) on shallow shelves, as along the north coast of Alaska or on the broad Russian shelves. The sea-floor sediment is stirred up by a storm, and the suspended lithic particles are lifted to the surface by the newly formed ice crystals before settling. Enclosed in sea ice, the debris is then rafted away with the ice drift and drops to the sea-floor when the ice floes melt. Sediment can also directly freeze on to the bottom of an ice floe, or it can freeze to the keel of ice pileups, which can reach thicknesses of up to 30m. The preferred regions of sediment entrainment in sea ice are shallow shelves with less than 30m water depth (Reimnitz et al., 1987, 1992, 1993; Kempema et al. 1993).

Ice in the eastern Arctic Ocean is usually less than 5 years old and consistently exits into the Norwegian, Greenland, and Barents Seas (Pfirman et al. 1989, 1991). Satellite tracking of individual ice floes has shown the complexity of the short-term ice movement, which on a day-to-day scale can deviate significantly from the overall general direction (Vinje 1977, 1982). At times, ice can drift perpendicular if not opposite to the main direction of ice drift, which represents the long-term resultant of all short-term movements. Interference between the Eurasian and the Amerasian ice drift regimes probably occurs along their boundaries, possibly north of Greenland, where ice from the Beaufort Gyre can enter the Transpolar Drift and leave the Arctic Ocean via the Fram Strait and ice from the Transpolar Drift can become part of the Beaufort Gyre. This implies the possibility that ice from the eastern Arctic Ocean can enter the western part (Amerasian Basin) and contribute to sedimentation there.

The primary objective of this research was to determine whether sediment is transported by sea ice from the various Russian rivers and arctic shelf areas to the western Arctic Ocean and, in particular, the Beaufort Sea. Knowledge of the precise sources of sediment entrainment by sea ice is important if the potential for contaminated sediment known to occur in parts of the Russian shelves to move into the Alaskan waters is to be assessed. Equally important is the quantification of the amounts of sediment in the Beaufort Sea pack ice and bottom sediment that was derived from various parts of the Russian Arctic.

Tasks Completed

The origin of the lithic particles was determined by matching the composition of sea ice samples that contained sufficient coarse particles from the Beaufort Sea, the central Arctic Ocean along the track of the Arctic Ocean Section 1994 Trans-Polar Expedition, and Polarstern samples from the eastern Arctic Ocean to groups of samples with similar lithic composition from the entire Arctic data base using the classifying powers of discriminant function analysis (DFA) (Darby and Bischof, 1996). The proportions of sediment from each source were determined by matching individual Fe-oxide grain compositions from sea ice samples with adequate numbers of Fe oxide grains to groups of very similar compositions for each mineral type in source areas by DFA (Darby and Bischof, 1996). Before this could be accomplished, the Arctic source data base had to be supplemented by samples from the East Siberian Shelf, Laptev Sea, Russian rivers including the Ob and Yenesey Rivers, and the Pechora Sea.

The shape and surface textures of quartz grains were analyzed in order to find additional criteria for matching sediment to possible Russian sources and distinguishing between Eurasian and Amerasian sources. Quartz grains constitute the major portion of the sand fraction, and their shape and degree of roundness reveal the general transport history prior to entrainment in sea-ice. In addition, the clay mineral content of ice floes has been shown to be useful for identifying sources (Pfirman et al., 1996), so this was determined in 37 sea ice samples.

After the sources and the proportions from each source were established for ice floes in the various parts of the Arctic Ocean, the dispersal pathways were interpreted. All available information about past and present ice movements in the Arctic Ocean was used in conjunction with our data to generate ice trajectories and to quantify the chances for ice from Russia and the Eurasian Arctic to reach the North American Arctic.

Materials and Methods

A total of 31 sea ice samples (Fig.1) were studied and analyzed for various sediment parameters. A total of 1,329 Fe oxide grain sources were determined in 23 sea ice samples using the 12 elements analyzed by electron microprobe (see Darby and Bischof, 1996 for procedures). The clay mineralogy (<2μm) and silt fraction (2-63μm) mineralogy was determined for 22 and 8 sea ice samples, respectively. The sources of the lithic component >250μm were determined for 15 sea ice samples where sufficient coarse material existed. An additional 48 samples from Russian rivers and shelf areas were analyzed for the source data set plus six new samples from the Queen Elizabeth Islands. Lithic grain counts and over 3,000 Fe oxide grains were analyzed from these new source samples.

The mineralogy and geochemistry of opaque Fe-oxide detrital minerals (>45-250μm) were analyzed for grains extracted by hand magnet and the Frantz magnetic separator set at 0.3 Amp and a 30° slope. The Fe-oxide grains were mounted in Epofix epoxy plugs, ground, and polished. The mineralogy of each Fe-oxide grain was optically identified by reflected light microscopy and the grain numbered on a photomicrograph for later analysis by electron microprobe for 12 element oxides (TiO_2, FeO, MnO, MgO, SiO_2, Al_2O_3, Cr_2O_3, V_2O_3, CaO, ZnO, Nb_2O_5, and TaO; Darby and Bischof, 1996; Bence and Albee 1968). The electron beam size was set at half the diameter of the smaller grains analyzed in a sample to measure average compositions of heterogeneous mineral grains. This avoids time-consuming replicate analyses of each multiphase grain. Because the proportions of different phases in multiphase grains are unknown, Fe is reported as FeO instead of FeO and Fe_2O_3. The interference of the Ti K_β x-ray emission peak with the V K_a peak was corrected by the proportional overlap method (Snetsinger et al. 1968).

The lithic and Fe-oxide data were matched between the sea-ice and the source areas using a combination of statistical methods (Darby and Bischof, 1996). First, the lithic clast composition (73 variables) in the source areas was grouped by cluster analysis (Davis 1986, SAS Institute 1989). Each cluster in which the samples had less than 0.5 average distance was assigned a source group. In cases where samples from geographically separate areas clustered together, the samples were separated into subgroups that do not cross the boundaries of major geologic provinces like the Sverdrup Basin, the Franklinian Foldbelt, Russian rivers, or geographic regions on the Russian shelves such as the Laptev Sea. The validity of the group assignments was tested with stepwise discriminant function analysis (DFA), which determines the probability of a sample belonging to its assigned group. If a sample classifies into a previously clustered group at less than 0.95 probability, it is taken out of the old group and the changed groups are re-analyzed by DFA. This procedure was repeated until all groups were unique at ≥ 0.95 probability of group membership and a probability of ≥ 0.1 that an actual member of the source group occurs as far from the source group centroid as the sample in question (Klecka 1975, Darby 1990). This second probability, herein referred to as the similarity probability, prevents samples from being forced into a group because the group is more similar to the sample than any other group under consideration, when in actuality the lithic sample should be grouped differently or left as an outlier group by itself.

In a second step, the pack ice and Beaufort Sea bottom sediment data were matched to the source area data with DFA, resulting in certain probabilities for each ice sample to belong to a previously established source group. DFA is the preferred multivariate statistic because it is insensitive to closed data or correlated variables unless they are perfectly correlated, and it provides probabilities of group membership (Klecka 1980). The highest correlation coefficient between any variables in previously analyzed source areas was -0.8 for quartz and carbonates.

The procedure for grouping and matching the opaque Fe-oxide minerals was similar except that individual grains are matched to source areas and not the entire sample. Each of the nine detrital Fe-oxide mineral types (fresh and altered ilmenite, titanomagnetite, magnetite, magnetite with inclusions, titanohematite, ferrohematite, hematite, and chromite) found in the samples from each source area were clustered separately using the standardized chemical content of individual grains. The clustered groups were tested by step-wise DFA as were the lithics. Each Fe-oxide mineral type was treated separately. All Fe-oxide grains from pack ice or Beaufort Sea bottom samples were classified into their proper sources by the same DFA procedure used to test the source group membership. Grains that did not fulfill the probability criteria of group membership and similarity were considered as originating from unknown sources. From past experience, even a tightly clustered group of source Fe-oxide grain compositions can have similarity probabilities as low as 0.1 and group membership probabilities of >0.95. When grains from the Arctic Ocean are matched to source groups from the rivers along the U.S. east coast (see Darby, 1990 for sample locations), more than 40% match with membership probabilities of >0.95, but only about 10-13% of these grains have similarity probabilities >0.1. The use of both of these probabilities provides much greater insurance against errors of misclassification than membership probability alone.

Results

The sea ice clay and silt mineralogy are generally different for samples taken from near the Russian shelves as opposed to samples from the central Arctic Ocean (Fig. 2 and 3). The sea ice samples from the Laptev Sea and Barents Sea near Svalbard contain much higher smectite, kaolinite, and feldspar and less illite, dolomite, and calcite than the central Arctic Ocean or Alaskan shelf samples. Still the mineralogy is not always clearly distinctive for individual samples because some Alaskan shelf and central Arctic Ocean sea ice contains high smectite, kaolinite, and feldspar and some Laptev Sea samples contain 6% dolomite in the silt fraction.

The lithic grain type percentage data was used to determine the most probable source (i.e., the source area most similar in composition to the sample in question) (Table 1).

Table 1. Lithic source matches at >0.95 probability for sea ice samples. Only samples with sufficient coarse grains could be used.

SAMPLE	MATCHED SOURCE (>0.95 PROB.)
PS89-18	W. Victoria Island
ARK-IX-225-1	E. Siberian Sea + E. Laptev Sea
AOS94-207-1	Mackenzie Delta
AOS94-215-E3	E. Siberian Sea
AOS94-215-1	W. Banks Island
AOS94-226-1	?
AOS94-227-1	E. Siberian Sea
71-APB-15	Queen Elizabeth Islands + Alaskan Shelf
72-APB-18	W. Banks Island
PS89-5b	W. Victoria Island
93-230-1-1b	E. Siberian Sea (Kolyma R.)
93-230-1-1a	Alaskan Shelf
72-APB-54	W. Ellesmere Island ?
PS89-12	Wellington Channel - Barrow Strait

The Fe oxide grain matches are shown in Figure 1 along with the dispersal trajectories to show the net transport of sea ice and not the latest drift path. For example, if a sea ice sample contained Fe oxide grains from several sources, then the dominant source is shown as the origin of the dispersal and the trajectory is shown moving close to the other sources present. If sources were from Russian and Canadian or Alaskan sources, as was often the case, then two paths are shown, both traversing the Chukchi Shelf before ending at the sample site because this is the most probable area for the immediate entrainment of detritus from these sources. This important potential source area needs to be studied with many bottom samples in order to test this hypothesis.

The hypothesized drift tracks are currently being compared to satellite back trajectories. This will provide additional information on the last entrainment source area and net dispersal of sea ice sediment in the Arctic Ocean.

Important Findings and Conclusions

All of the sea ice samples contained Fe oxide grains from several sources. Even the lithic particles could not be matched to sources with identical compositions suggesting that more than one source area may have contributed coarse material. This probably indicates that the exact area where sea ice last entrained bottom sediment was not included in our source area samples. The dominant sources for the Fe oxide grains in sea ice samples with more that 25 Fe oxide grains were (in order of importance): the East Laptev Sea (source 18, Fig. 1), Banks & Victoria Islands (source 8), the East Siberian Shelf (especially source areas 20 & 21), and the Alaskan Shelf (source 13) (Fig. 4). Multiple sources for every sea ice sample suggest that sea ice is depositing Fe oxide grains from primary sources onto other shelves such as the Chukchi Shelf from where it is entrained by the sea ice sampled here. This is direct evidence that sea ice has a major role in both the erosion and deposition of sediment on Arctic shelves. Alternatively, multiple sources could be obtained by sequential entrainment at several different locations. This would have to occur under the pack ice with currents instead of waves stirring-up the sand.

Net sea ice drift pathways appear more complex than would be predicted by the generally accepted surface currents. The presence of sea ice samples from the Alaskan Shelf and the western Arctic Ocean with Fe oxide grains from the Laptev Sea indicates that Russian shelf sediment is transported into the American shelf waters. The general absence of Laptev Sea Fe oxide grains on the Canadian shelf areas suggests that the sea ice transport from the Laptev Sea does not move east across the Lomonosov Ridge area and then into the Beaufort Gyre but instead moves counter to the Beaufort Gyre and general Trans Polar Drift. Sea ice probably is transported eastward from the Laptev Sea to the East Siberian Sea before being entrained by sea ice and transported into the western part of the Beaufort Gyre (Fig. 1). The sea ice samples collected from near the Laptev Sea contain significant amounts of Fe oxide grains from Canadian sources, especially Banks Island. Thus sea ice from the Beaufort Gyre is transported into Russian shelf areas also.

Impact on Education

During the course of this project five graduate students (all masters degree candidates) and three undergraduate geology majors were supported. Two of the graduate students have finished their masters degrees and two are to finish within the next six months. The graduate students include: Steven Marshall, Steven Herman, Gita Dunhill, Vladimir Ispolatov (graduated), and Duan Li (graduated). The undergraduates include Brian Burdette, Shonia Becraft, and Marcella Ripich. Three of these students were female and one was Asian. All of the students gained valuable experience working on this project including training for two of them on the ETEC electron microprobe. All students were trained in sample preparation, polishing grain mounts, and microscopy. Rarely do students at this stage in their education get experience on sophisticated equipment such as the electron microprobe and reflected-light microscopy.

References

Barry, R.G., 1989. The Present Climate of the Arctic Ocean and Possible Past and Future States. In: Herman, Y. (ed.) The Arctic Seas. Climatology, Oceanography, Geology, and Biology. Van Nostrand Reinhold, New York: 1-46.

Clark, D.L. & Hanson, A. 1983. Central Arctic Ocean Sediment texture: a key to ice transport mechanisms. In: Molnia, B.F. (ed.) Glacial Marine Sedimentation, Plenum, 301-330.

Colony, R. and Thorndyke, A.S. 1984. An estimate of the mean field of Arctic ice motion. J. Geophys. Res. **89** (C6): 10,623-10,629.

Darby, D.A., 1990. Evidence for the Hudson River as the dominant source of sand on the U.S. Atlantic Shelf. Nature, v.346, p.828-831.

Darby, D.A. and Bischof, J.F., 1993. The ice-rafted dispersal history for the eastern Alpha Ridge, Arctic Ocean over the last 700 ka: evidence for changes in the Beaufort Gyre. Supplement to EOS, Oct. 1993, 1993 Fall Meeting of the Amer. Geophy. Union, Abstract Volume, p. 360.

Darby, D.A. and Bischof, J.F.,1996. A statistical approach to source determination of lithic and Fe-oxide grains - an example from the Alpha Ridge, Arctic Ocean. Journal of Sedimentary Research, **66**:599-607.

Ehrlich, R., Brown, J.P., and Yarus, J.M., 1980, The origin of shape frequency distributions and the relationship between size and shape. Journal of Sedimentary Petrology, v. 50, p.475-484.

Eicken, H., Martin, T., and Reimnitz, E. 1994a. Sea-Ice Studies and Sampling. Chapter 6 in:

Fütterer, D.K. (ed.) The Expedition ARCTIC '93 Leg ARK-IX/4 of RV "POLARSTERN". Berichte zur Polarforschung - Reports on Polar Research, **149**, Alfred Wegener Institute for Polar and Marine Research: 42-78.

Eicken, H., Alexandrov, V., Bogdanov, V., Martin, T., Reimnitz, E., and Syrtsov, S. 1994b. Iceberg Observations. Chapter 6.7 in: Fütterer, D.K. (ed.) The Expedition ARCTIC '93 Leg ARK-IX/4 of RV "POLARSTERN". Berichte zur Polarforschung - Reports on Polar Research, **149**, Alfred Wegener Institute for Polar and Marine Research: 76-78.

Fütterer, D.K. (ed.) 1994. The Expedition ARCTIC '93 Leg ARK-IX/4 of RV "POLARSTERN". Berichte zur Polarforschung - Reports on Polar Research, **149**, Alfred Wegener Institute for Polar and Marine Research, 244 pp.

Herman, Y. (ed.), 1989. The Arctic Seas. Climatology, Oceanography, Geology, and Biology. Van Nostrand Reinhold, New York, 888 pp.

Kerr, J.W., 1981. Evolution of the Canadian Arctic Islands: A transition between the Atlantic and Arctic Oceans. In: Nairn, Alan E.M., Churkin, Michael Jr., and Stehli, Francis G. (eds), The Ocean Basins and Margins. Plenum, New York: 105-200.

Koerner, R.M. 1973. The mass balance of the sea ice in the Arctic Ocean. J. Glaciol. **12** (65): 173-185.

Nairn, A.E.M., Churkin, M.Jr., and Stehli, F.G. (eds) 1981. The Ocean Basins and Margins. Plenum, New York, 672 pp.

Pfirman, S., Gascard, J.-C., Wollenburg, I., Mudie, P. & Abelmann, A. 1989. Particle-laden Eurasian Arctic sea ice: observations from July and August 1987. Polar Research, **7**, p.59-66.

Pfirman, S., Wollenburg, I., Goldschmidt, P., Bischof, J. & Lange, M. 1991. Sediment in Barents Sea Ice. Chapter 1.3.8. in: Krause, G., Meincke, J. & Schwartz, H.J. (eds.) Reports on Polar Research, Scientific Cruise reports of Arctic Expeditions ARK VI/1-4 of RV "Polarstern" in 1989: 33-35.

Ruddiman, W.F. 1977. Late Quaternary deposition of ice-rafted sand in the subpolar North Atlantic (lat. 40° to 65° N). Geol. Soc. Am. Bull. v. **88**, p. 1813-1827.

Snetsinger, K.G., Bunch, T.E., and Keil, K., 1968. Electron microprobe analysis of vanadium in the presence of titanium: American Mineralogist, v. **53**: 1770-1773.

Trettin, H.P., Frisch, T.O., Sobczak, L.W., Weber, J.R., Niblett, E.R., Law, L.K., de Laurier, I., and Whitham, K.1972. The Innuitian Province; In: Variations in tectonic styles in Canada, R.A.

Price and R.J.W. Douglas (eds.); Geological Association of Canada, Special Paper 11: 83-180.

Vinje, T.E., 1977. Sea ice conditions and drift of Nimbus-6 buoys in 1977. Norsk Polarinstitutt Arbok 1977, Pre-Print.

Vinje, T. E. 1982. The drift pattern of sea-ice in the Arctic Ocean with particular reference to the North Atlantic approach, In: Rey, L. (ed.) The Arctic Ocean: 82-96.

Wadhams, P. 1981. The ice cover in the Greenland and Norwegian Seas. Rev. Geophys. Space Phys. **19**: 345-393.

Wadhams, P. 1983. Sea ice thickness distribution in Fram Strait. Nature **305**: 108-111.

Publications Resulting From This Project

Darby, D.A. and Bischof, J.F.,1996. A statistical approach to source determination of lithic and Fe-oxide grains - an example from the Alpha Ridge, Arctic Ocean. Journal of Sedimentary Research, **66**:599-607.

Darby, D.A. and Bischof, J.F., 1996. Sources of ice-rafted detritus and iceberg tracks in the Arctic Ocean. In: Tucker, W. and Cate, D., eds, The 1994 Arctic Ocean Section; The First Major Scientific Crossing of the Arctic Ocean, U.S. Army Cold Regions Research and Engineering Lab, Hanover, NH, p. 89-91.

Darby, D.A. and Bischof, J.F., 1996. Sources of ice-rafted detritus and iceberg tracks in the Arctic Ocean. In: Tucker, W. and Cate, D., eds., The 1994 Arctic Ocean Section, U.S.Army Cold Regions Research and Engineering Laboratory, Special Report 96-23, Hanover, NH, pp. 89-91.

Meese, D.A., Reimnitz, E., Tucker III, W.B., Gow, A.J., Bischof, J.F., and Darby, D.A., in press, Evidence for radionuclide transport by sea ice. Science of the Total Environment.

Darby. D.A., Bischof, J.F., and Jones, G.A., in press. Radiocarbon chronology of depositional regimes in the western Arctic Ocean. Deepsea Research.

Darby, D.A., in review. Mysterious iron-nickel-zinc Arctic spherules. Canadian Journal of Earth Sciences,

Berger, G.W., Jones, G.A., Darby, D.A., and Bischof, J.F., in review. Test of thermoluminesence dating of sediment from the western Arctic Ocean.

Paleoceanography,

Reimnitz, E., McCormick, M., Bischof, J., darby, D.A., in review. Sediment sorting by sea ice entrainment in the Beaufort Gyre, Arctic Ocean. Journal of Sedimentary research,

Bischof, J.F. and Darby, D.A., in review. The role of the western Arctic Ocean in global climate. Science,

Bischof, J.F. and Darby, D.A., 1995. Pleistocene North American ice sheet dynamics and Arctic Ocean circulation. First SEPM Congress on Sedimentary Geology, Abs. with Prog., p. 29-30.

Darby, D.A. and Bischof, J.F., 1995. Statistical linkage of Alpha Ridge ice-rafted detritus to Pleistocene ice sheets. First SEPM Congress on Sedimentary Geology, Abs. with Prog., p. 43.

Jones, G.A., Darby, D.A., and Bischof, J.F., 1995, Holocene vs. last glacial maximum sedimentation in the central Arctic Ocean. 5th International Conference on Paleoceanography, Halifax, Nova Scotia, Canada, Program with Abstracts, p.162.

Darby, D.A., Bischof, J.F., and Li, D., 1995, Late Pleistocene ice transport in the Queen Elizabeth Islands. 5th International Conference on Paleoceanography, Halifax, Nova Scotia, Canada, Program with Abstracts, p.156.

Darby, D.A. and Bischof, J.F., 1995, Mid to Late Pleistocene variations of the western Arctic Ocean's ice drift regime recognized in the changing composition of ice-rafted debris. 5th International Conference on Paleoceanography, Halifax, Nova Scotia, Canada, Program with Abstracts, p.156.

Darby, D.A. and Bischof, J.F., 1996, History of Holocene and Late Pleistocene ice-rafting events. Proceedings of the Arctic System Science (ARCSS) All-Hands Workshop, Snowbird, Utah.

Bischof, J. and Darby, D., 1996, Changing origin of ice-rafted clastic debris for the Northwind Ridge, western Arctic Ocean, during the Late Wisconsin-Holocene transition. Proceedings of the Arctic System Science (ARCSS) All-Hands Workshop, Snowbird, Utah.

Darby, D.A. and Bischof, J.F., 1997, Neoglaciation event recognized in AMS radiocarbon-dated box cores from the Arctic Ocean. 27th Arctic Workshop, Prog. and Abs., Ottawa, Canada, p. 42.

Darby, D.A., Bischof, J.F., ans Jones, G.A., 1997, The Arctic Ocean: long intervals of slow

sedimentation interspersed with short, coarse intervals of high rates. ARCSS/OAII All Hands Meeting & Planning Workshop, Va. Beach, VA, p.25.

Bischof, J.F. and Darby, D.A., 1997, Is the Beaufort Gyre an exceptional and potentially unstable feature of the Arctic Circulation? ARCSS/OAII All Hands Meeting & Planning Workshop, Va. Beach, VA, p.12.

Bischof, J.F. and Darby, D.A., 1997, Origin of sea ice sediment in the Western Arctic Ocean. ARCSS/OAII All Hands Meeting & Planning Workshop, Va. Beach, VA, p. 13.

Presentations

Bischof, J.F. and Darby, D.A., 1995. Pleistocene North American ice sheet dynamics and Arctic Ocean circulation. First SEPM Congress on Sedimentary Geology, St. Petersberg, Florida.

Darby, D.A. and Bischof, J.F., 1995. Statistical linkage of Alpha Ridge ice-rafted detritus to Pleistocene ice sheets. First SEPM Congress on Sedimentary Geology, St. Petersberg, Florida.

Jones, G.A., Darby, D.A., and Bischof, J.F., 1995, Holocene vs. last glacial maximum sedimentation in the central Arctic Ocean. 5th International Conference on Paleoceanography, Halifax, Nova Scotia, Canada.

Bischof, J.F. and Darby, D.A., 1995, Changing origin of ice-rafted clastic debris for the Northwind Ridge, western Arctic Ocean, during the Late Pleistocene - Holocene transition. 5th International Conference on Paleoceanography, Halifax, Nova Scotia, Canada.

Darby, D.A., Bischof, J.F., and Li, D., 1995, Late Pleistocene ice transport in the Queen Elizabeth Islands. 5th International Conference on Paleoceanography, Halifax, Nova Scotia, Canada.

Darby, D.A. and Bischof, J.F., 1995, Mid to Late Pleistocene variations of the western Arctic Ocean's ice drift regime recognized in the changing composition of ice-rafted debris. 5th International Conference on Paleoceanography, Halifax, Nova Scotia, Canada, Program with Abstracts, p.

Darby, D.A. and Bischof, J.F., 1996, History of Holocene and Late Pleistocene ice-rafting events. Arctic System Science (ARCSS) All-Hands Workshop, Snowbird, Utah.

Darby, D.A. and Bischof, J.F., 1997, Neoglaciation event recognized in AMS radiocarbon-dated box cores from the Arctic Ocean. 27th Arctic Workshop, Prog. and Abs., Ottawa, Canada, p. 42.

Darby, D.A., Bischof, J.F., ans Jones, G.A., 1997, The Arctic Ocean: long intervals of slow sedimentation interspersed with short, coarse intervals of high rates. ARCSS/OAII All Hands Meeting & Planning Workshop, Va. Beach, VA, p.25.

Bischof, J.F. and Darby, D.A., 1997, Is the Beaufort Gyre an exceptional and potentially unstable feature of the Arctic Circulation? ARCSS/OAII All Hands Meeting & Planning Workshop, Va. Beach, VA, p.12.

Bischof, J.F. and Darby, D.A., 1997, Origin of sea ice sediment in the Western Arctic Ocean. ARCSS/OAII All Hands Meeting & Planning Workshop, Va. Beach, VA, p. 13.

SEA ICE SOURCES AND PROBABLE DRIFT PATHS

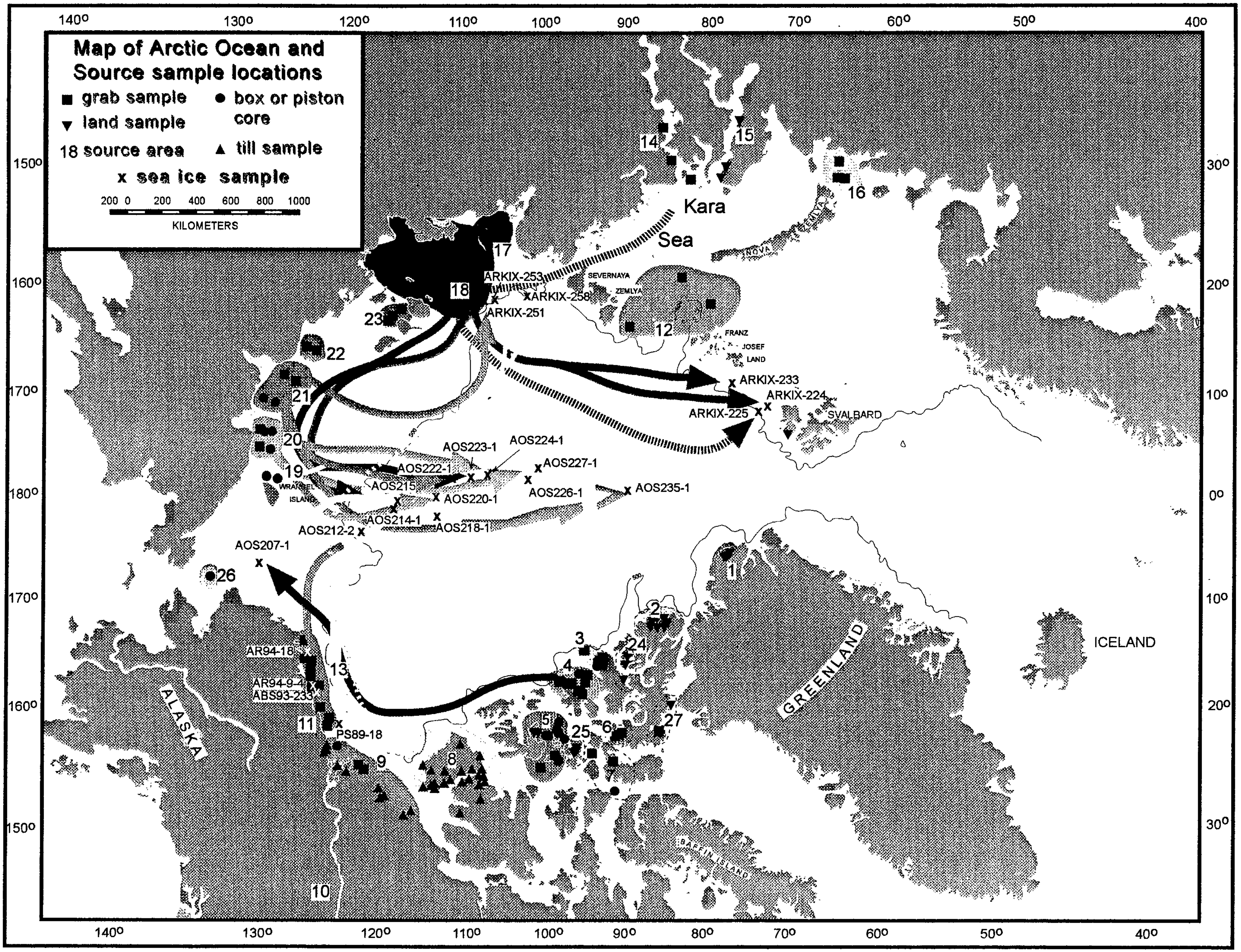
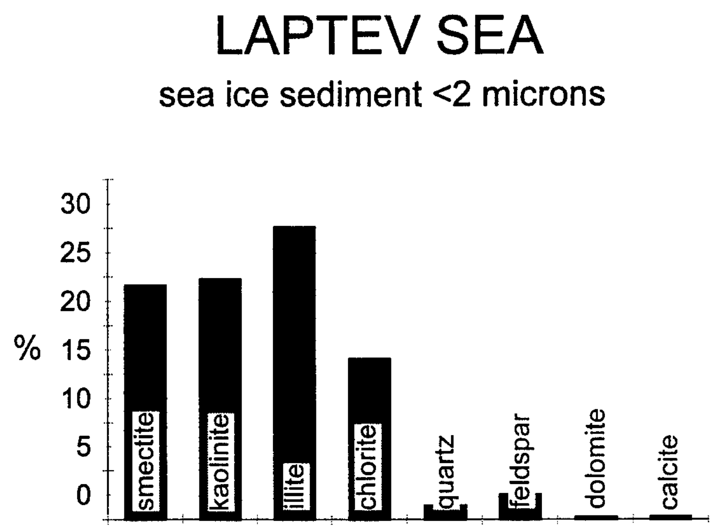
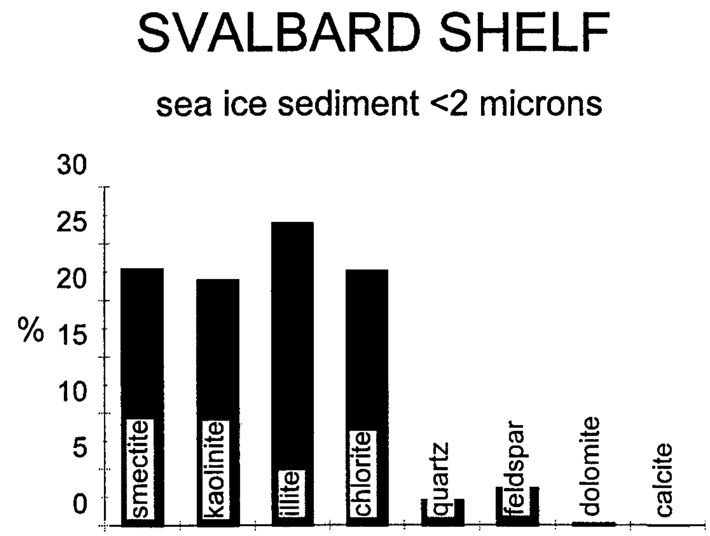
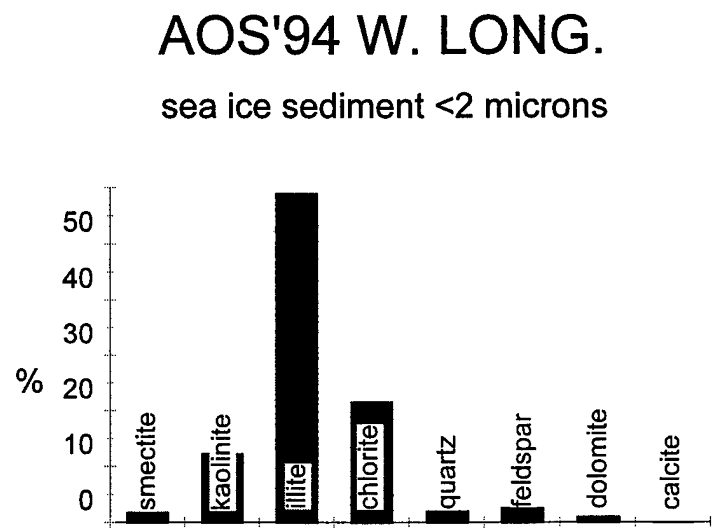
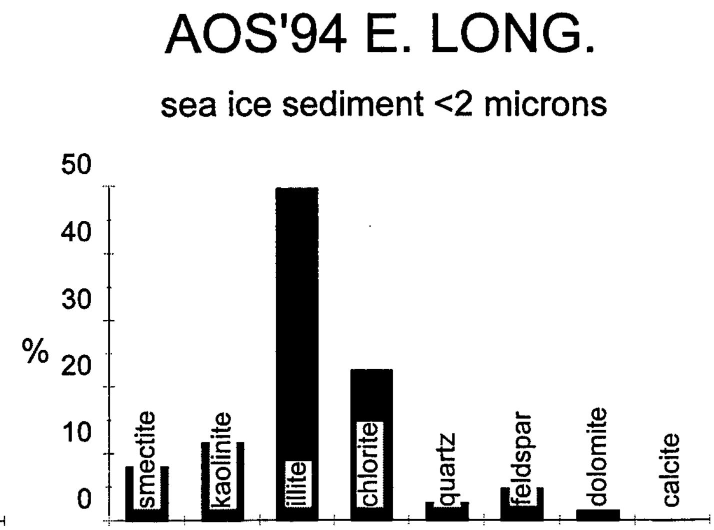


Figure 1. Source samples and sea ice samples for Fe oxide grain source matches. Drift tracks show the net drift based on the dominant sources for each sea ice sediment sample.









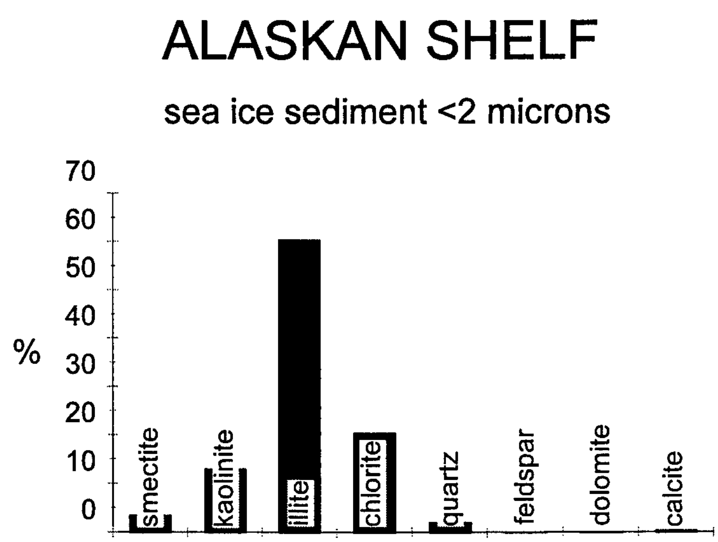


Figure 2. Average sea ice sediment mineralogy in the clay fraction for different Arctic areas. The smectite and kaolinite are significantly higher near the Russian shelves.

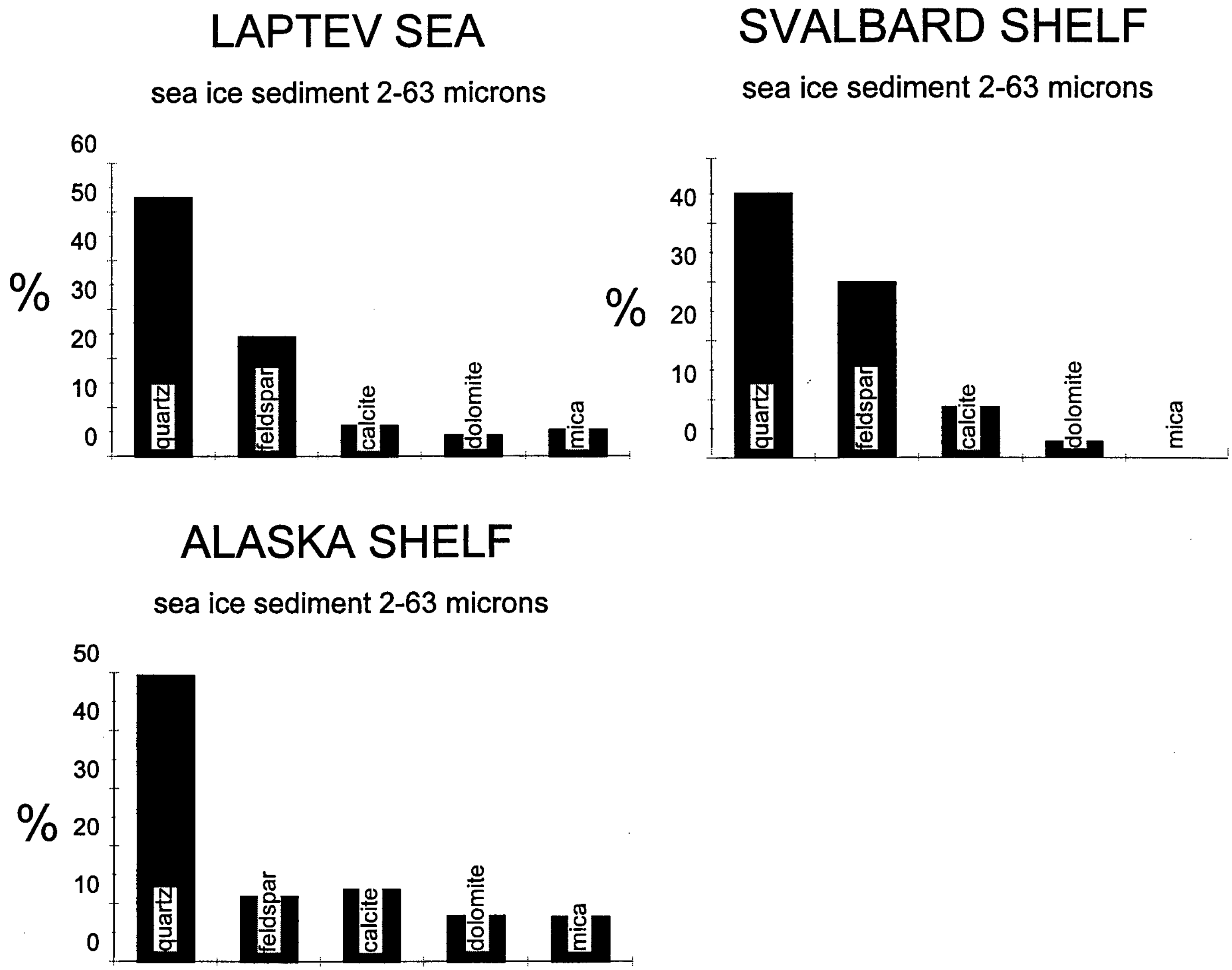
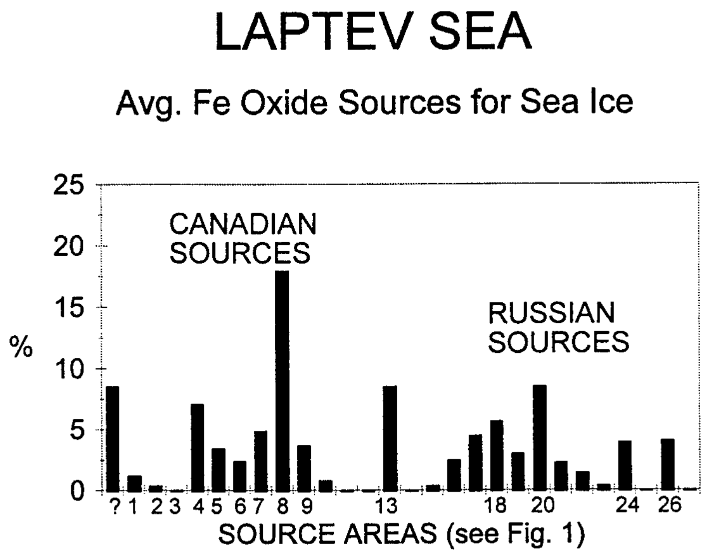
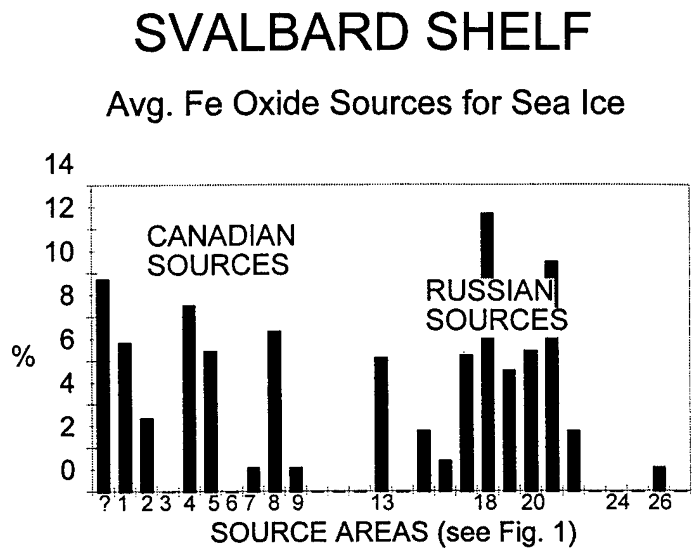
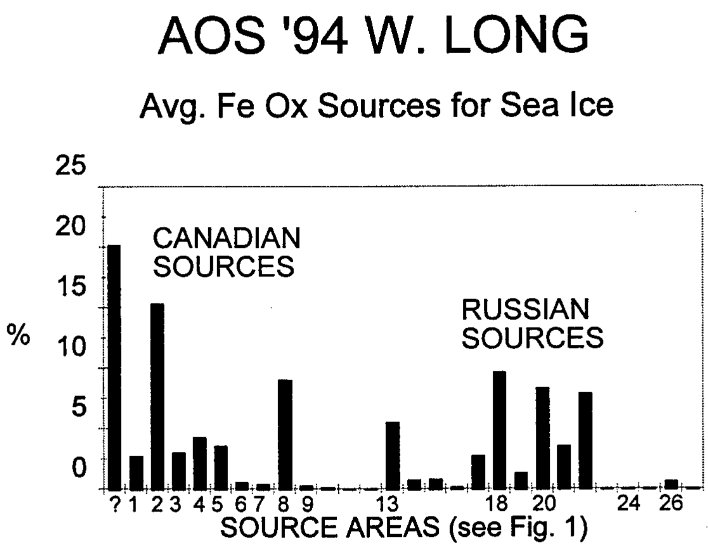
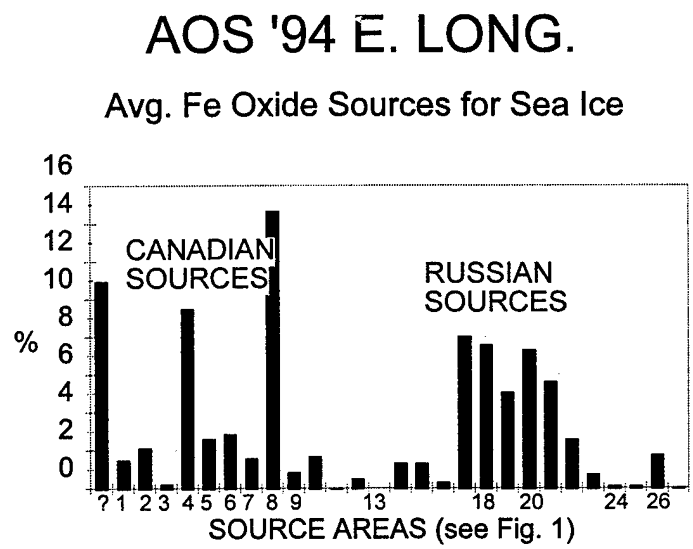


Figure 3. Average silt mineralogy of sea ice samples from different areas in the Arctic Ocean. Note the similar dolomite percentages on the Russian shelves and Alaskan Shelf despite the absence of a known source in Russia.









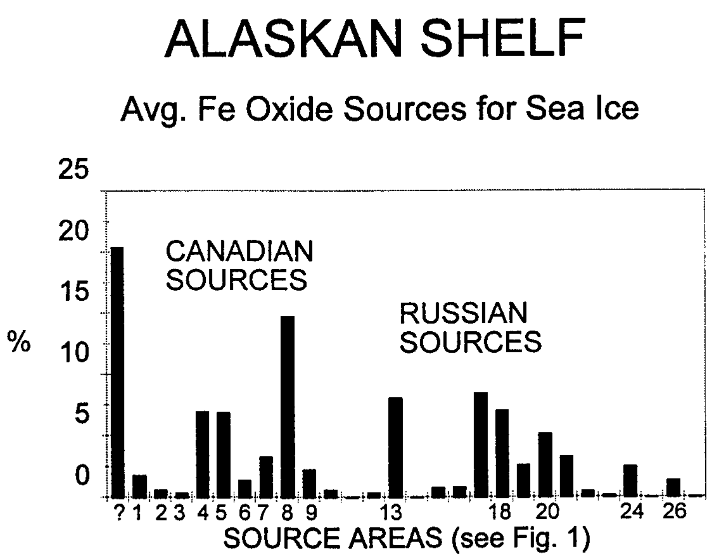


Figure 4. Average Fe oxide grain percentages from Arctic source areas defined in Figure 1 for sea ice samples from different areas of the Arctic Ocean. The dominant source areas are Banks Island (8), Ellef Ringnes Island (4), the Laptev Sea (17 and 18), the Alaskan Shelf (13), and the E. Siberian Shelf (19-23).