AN ABSTRACT OF THE THESIS OF

Kerry Anne Mammone for the degree Master of Science in Geology presented on May 19, 1997. Title: Sediment Provenance and Transport on the Siberian Arctic Shelf.

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Abstract Approved: ______________________________

Peter U. Clark

Continental shelf sediments were examined for grain size, clay mineralogy, and biogenic components in order to assess sediment provenance and transport on the Siberian Arctic shelf. Factor analysis of grain-size frequency data identifies four distinct sediment groups, with primary modes in the clay (8 ϕ), silt (5.5 ϕ), and fine sand (3 ϕ and 4 ϕ) ranges, that contribute to shelf sediments. Shelf sediments are predominantly clayey-silts with secondary silty-clays and sand-silt-clay mixtures. Fine sand is generally confined to shoals proximal to coastline and island sources. Fine sand, with secondary amounts of clay, also blankets the western Laptev Sea at depths >50 m. Sea-ice may play an important role in explaining this distinct grain-size distribution. Poorly-sorted and texturally varied sediments result from multiple source regions and intense reworking of sediments by currents, sea-ice, and bioturbation. Spatial distributions of clay mineral and grain size data indicate that local rivers that drain Siberia are the predominant source of silt and clay to the East Siberian and Laptev shelves. Organic carbon distributions and C/N ratios indicate that these rivers also supply terrigenous organic matter to shelf sediments. In contrast, rivers supply little sediment directly into the Chukchi Sea. Here, northward-flowing currents entering through the Bering Strait supply silt and smectite-rich clays from Yukon River and Aleutian Island sources. Biogenic components (total organic carbon and biogenic silica) comprise up to 16 % by weight of Chukchi shelf sediments. The distribution of organic matter and biogenic silica, which reflects surface primary productivity patterns, combined with C/N ratios of 6-7 indicate that this material is predominantly (>90 %) marine in origin. Physical, mineralogical, and biological measurements suggest that sediment dispersal processes (currents, and sea ice) and source regions result in distinct sediment signatures that may be used to interpret changing

sediment sources and transport pathways. Strong regional trends in these parameters indicate that sediments are generally dispersed offshore with currents and sea ice rather than along the shelf.

Sediment Provenance and Transport on the Siberian Arctic Shelf

by

Kerry Anne Mammone

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APPROVED:

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Major Professor, representing Geology

Redacted for Privacy

Chair of Department of Geosciences

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Dean of Graduate School

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Kerry Anne Mammone, Author

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CONTRIBUTION OF AUTHORS

These manuscripts have been completed in collaboration with three other authors. Carolyn Viscosi-Shirley assisted in the core sampling and the collection, analysis, and interpretation of the clay mineral data. Carolyn was also involved with the statistical analysis of the grain-size data. Dr. Peter U. Clark and Dr. Nicklas G. Pisias were responsible for the conception and financial support of the project. All authors provided invaluable reviews of the manuscripts.

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CHAPTER 1: INTRODUCTION

The potential for contamination of the Arctic from nuclear activities by the former Soviet Union is an issue of international concern. Dumping of nuclear waste directly onto and near rivers that drain into the broad Siberian shelves adds to the potential for future contamination. Because radionuclides, such as ^{137}Cs and $^{239,240}Pu$ are particle-reactive, identifying sources and transport pathways of sediment on these shelves is critical.

Sedimentation in the Arctic is strongly influenced by strong seasonal and spatial gradients in sea-ice distribution, circulation, river discharge, and biological productivity. Combined, the Lena, Yana, Indigirka, and Kolyma rivers account for 45 % (50.1×10^6 t) of the total suspended matter delivered annually to the Arctic Ocean from the Siberian continent (Gordeev et al., 1996). These shelves produce and export more ice than any other region in the Arctic, thus ice processes may play an important role in sediment transport and distribution (Dethleff, 1995; Pavlov and Pfirman, 1995). Recent studies of sediment in sea ice indicate that the Siberian shelves are an important source of sediment to the deep, central Arctic Ocean (Pfirman et al., 1990; Ablemann, 1992; Nürnberg et al., 1994, Stein and Korolev, 1994; Stein et al., 1994; Dethleff, 1995; Schubert and Stein, 1997; Eicken et al., 1997). Thus, identifying sedimentary processes on these shelves is critical for examining the linkage between particle-reactive pollutants delivered from the former Soviet Union to the Siberian shelves and central Arctic Basin (Fig. 1).

In order to better understand modern sedimentary processes on these Arctic shelves, we have examined surface sediments from the Chukchi, East Siberian, and Laptev seas for grain size, clay mineralogy, and biogenic components (Fig. 2). Factor analysis of grain-size data and semi-quantitative estimates of clay mineral abundances were used to identify the spatial distribution of sediments on these shelves. The distribution of biogenic phases and C/N ratios were also used to help delineate between terrigenous and marine sources. Although this research focuses on identifying sediment provenance and

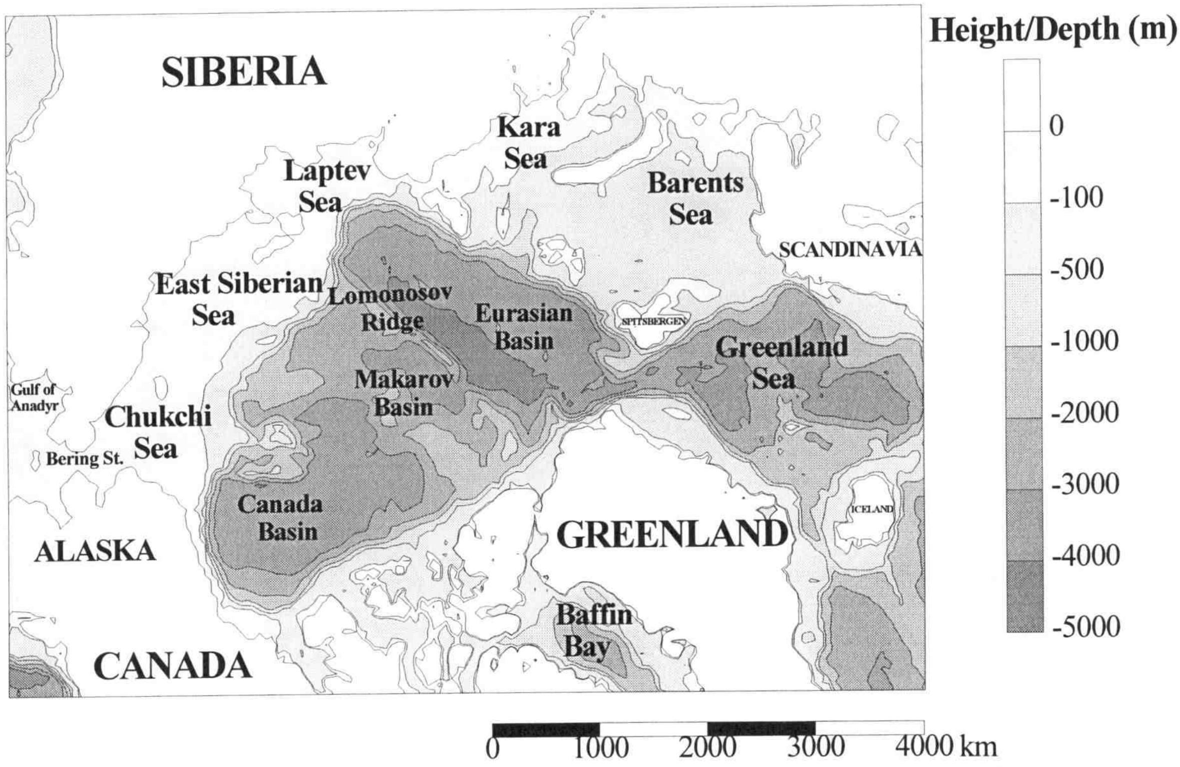

Figure 1. Bathymetric map of the Arctic Ocean.

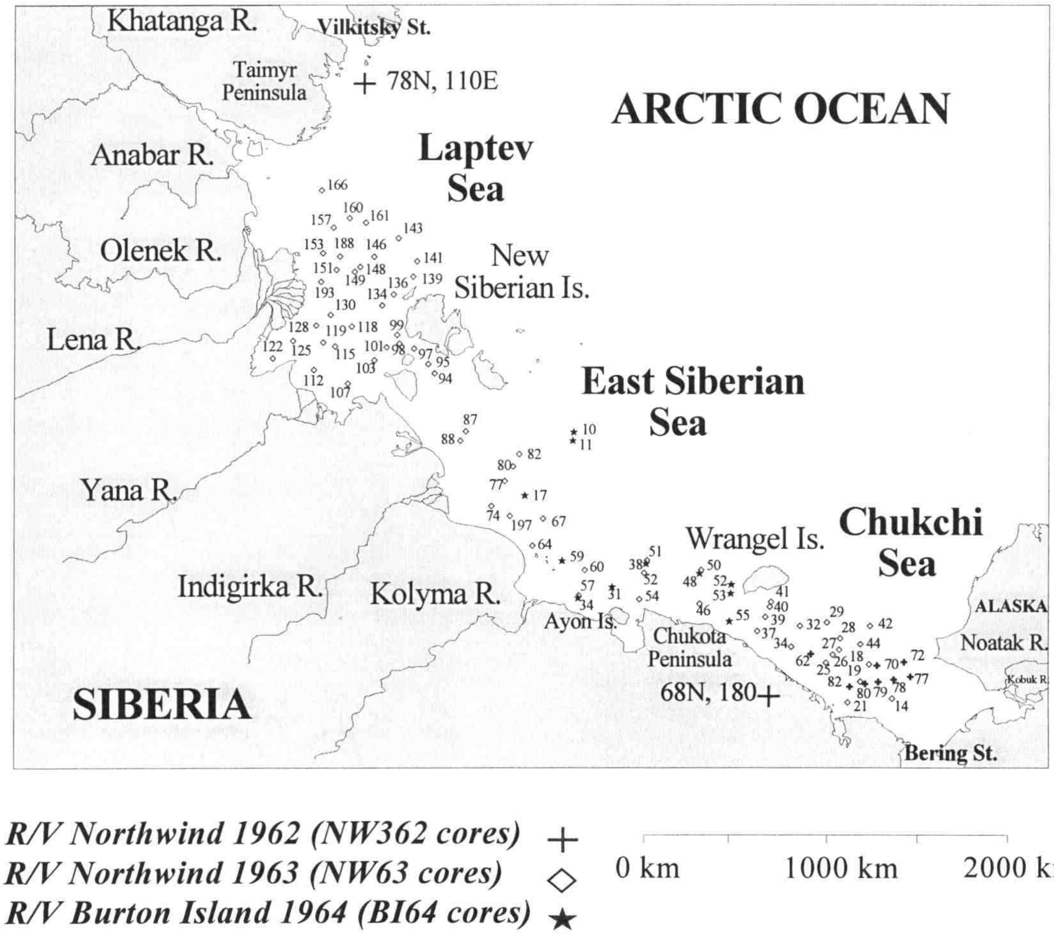

Figure 2. Map of the Siberian Arctic shelf showing the number and location of sediment cores used in this study.

dispersal pathways, we hope to evaluate the role of currents, sea-ice, and biological activity on surface sediment composition and distribution. A better understanding of modern sedimentary processes may also be a useful tool for evaluating past changes in source and transport pathways driven by climate as recorded in the Arctic sediment record.

CHAPTER 2: COMPOSITION AND SOURCE OF BIOGENIC MATTER ON THE SIBERIAN ARCTIC SHELF

K. A. Mammone[1], C. Viscosi-Shirley[2], P. U. Clark[1], and N. G. Pisias[2]
[1]Department of Geosciences, Oregon State University, Corvallis, OR 97331
[2]College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, OR 97331

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2.1 ABSTRACT

Surface sediments from the Chukchi, East Siberian, and Laptev sea shelves were examined for biogenic silica, total organic carbon, total nitrogen, C/N ratios, and carbonate (Fig. 2). Shelf sediments contain predominantly biogenic silica (up to 14.3 %), secondary organic carbon (0.2-2.3 %), and minor amounts of carbonate (<0.2 %). Spatial distributions of biogenic silica and total organic carbon show strong east-west gradients across the shelf. The highest concentrations of biogenic silica and total organic carbon were present in sediments from the western Chukchi Sea and east of the Lena delta in the Laptev Sea. In contrast, East Siberian Sea sediments show the lowest concentrations of all biogenic phases measured. In general, total organic carbon concentrations and C/N ratios decrease away from river deltas in the East Siberian and Laptev seas, suggesting a terrigenous source of organic carbon proximal to rivers.

A linear mixing model for C/N ratios was used to determine the relative contributions of marine and terrigenous organic carbon to shelf sediments. In western Chukchi Sea sediments, organic carbon is predominantly marine in origin (>98 %), reflecting high surface productivity in the overlying water column and reduced input of terrigenous organic carbon. The contribution of terrigenous organic carbon to Chukchi shelf sediments increases (up to 10 %) to the east. Local rivers supply organic matter to East Siberian and Laptev shelf sediments, particularly east of the Lena delta where up to 32 % of organic carbon is terrigenous in origin. Spatial patterns of biogenic matter on the Siberian shelf are controlled largely by source, ice distribution, and hydrography. Therefore, variations in biogenic silica and total organic carbon in shelf sediments may be a valuable tool for interpreting changes in source and hydrographic conditions driven by climate fluctuations.

2.2 INTRODUCTION

The broad (500-800 km), anomalously shallow (<60 m) shelves of the Siberian Arctic comprise an extensive area (Fig. 1) that is important to biological productivity, and related carbon deposition and export (Schubert and Stein, 1997; Wheeler et al., 1996). The Siberian shelves form about 36 % of all Arctic shelves and represent approximately 25 % of total world shelves (Coachman and Aagaard, 1974). Water column and sediment investigations show that some of the highest levels of primary and secondary production occur on these extensive shelves (Walsh et al., 1989; Grebmeier et al., 1995). Due to seasonally high surface-water productivity and delivery of large quantities of terrigenous organic carbon by rivers, the Siberian shelves may be a significant source and sink for organic carbon in the Arctic. Export from and sequestering of organic carbon on these shelves may thus have important implications for the global carbon budget and climate changes on long timescales.

The export of particulate organic material from the Siberian shelves is dependent on primary production, riverine inputs, and transport mechanisms, including sea ice, current patterns, and changes in water column structure. The relative contribution of marine versus terrigenous organic matter in East Siberian and Laptev sea sediments is unknown. Studies of shelf sediment C/N ratios and carbon isotopes suggest a terrigenous source of organic matter in the east, shifting to predominantly marine sources to the west (Naidu et al., 1993). The identification of sources and sinks of marine versus terrigenous biogenic matter to the Siberian shelves is essential to understanding the role of the Arctic shelves in the sequestering and export of carbon.

In this study we examine the composition, source, and spatial distribution of biogenic matter on the Chukchi, East Siberian, and Laptev shelves (Fig. 2). Measurements of total organic carbon, biogenic silica, carbonate, and C/N ratios of 85 surface sediment samples from these shelves were analyzed in order to identify sources and sinks of biogenic matter on the shelf. Spatial distributions of biogenic phases and C/N ratios were also used to help delineate between terrigenous and marine sources in order to infer sediment transport pathways and source regions.

2.3 BACKGROUND

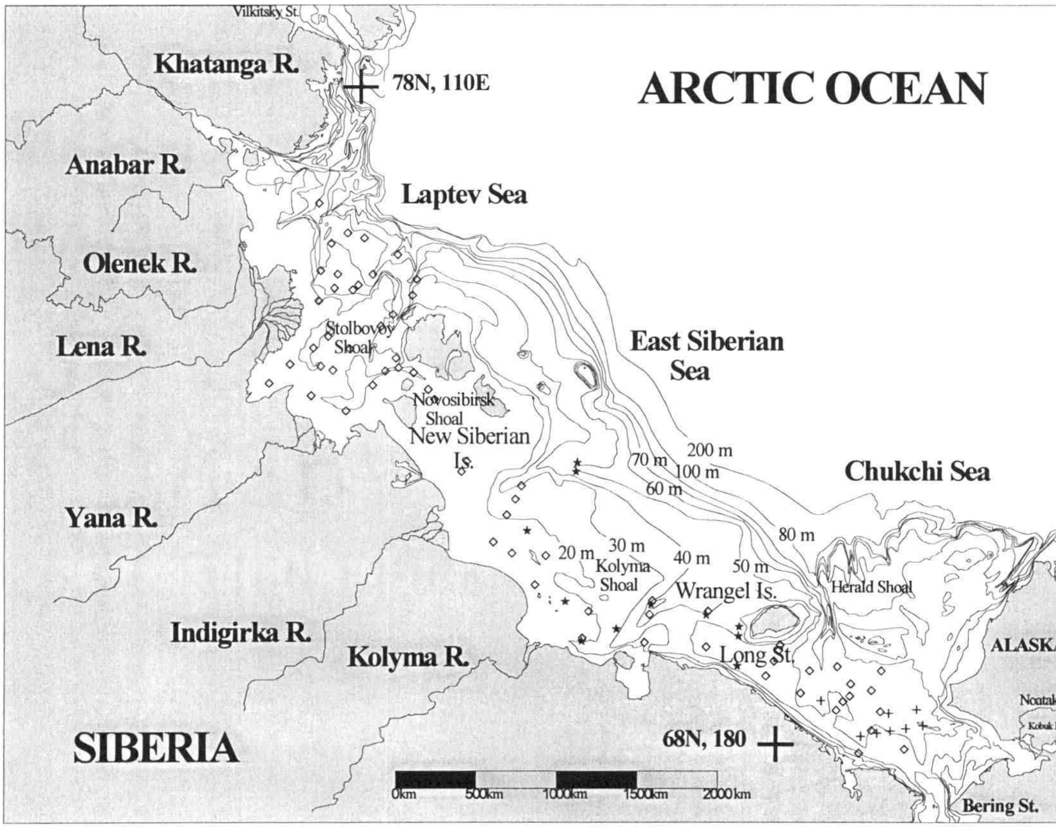
2.3.1 *Physical Oceanography*

Rivers draining Siberia contribute a significant inflow of freshwater seasonally from May until September. These Siberian shelves receive approximately 0.1 Sv (1 Sv = $10^6 m^3 s^{-1}$) annually of freshwater from riverine sources (Lunberg and Haugan, 1996). Submarine canyons cutting across these shelves represent offshore extensions of the large rivers draining into the Siberian Arctic shelf (Coachman and Aagaard, 1974) (Fig. 3). Ice covers the majority of the shelf year-round with open areas localized to polynyas. Ice thickness in the winter is from 3-3.5 m thick and decreases in the summer to about 1 m thick with open areas proximal to river mouths (Naugler et al., 1974).

In spite of large variability in atmospheric and hydrographic conditions on the Siberian shelf, it is possible to identify generally easterly-flowing currents across these shelves (McManus et al., 1969; Timokhov, 1994; Pavlov, 1996; Pavlov et al., 1996) (Fig. 4). In summer, three distinct water masses flow in through the Bering Strait to the Chukchi Sea: the Alaskan coastal-Yukon River water (ACW) in the east and Bering shelf (BSW) and Anadyr waters (AW) in the west (Fig 4). The mean annual transport through the Bering Strait is about 0.8 Sv, with maximum values occurring in June (Coachman and Aagaard, 1988; Lunberg and Haugan, 1996).

A sharp vertical hydrographic front extending north-south delineates the Bering shelf and Anadyr waters from the Alaskan coastal water. Cold, saline (S = 32.5 ‰, T = 1.5 °C) water upwelled in the Gulf of Anadyr (AW) continuously supplies nutrients to the western Chukchi Sea. Warmer, less saline Alaskan coastal water (S = 31.8 ‰, T = 4 °C), generally depleted in nutrients, flows northward along the coast and enters the central Arctic Ocean circulation near Point Barrow (Coachman and Aagaard, 1974) (Fig. 4). East Siberian Coastal water (SCW) enters through the Long Strait at intermediate depths (McManus et al., 1969; Coachman and Shigaev, 1992; Pavlov, 1996; Pavlov et al. 1996).

Surface circulation in the East Siberian Sea consists of a sluggish cyclonic circulation with a stable eastward-flowing coastal transport (Fig. 4). Surface waters move



R/V Northwind 1962 +
R/V Northwind 1963 ◇
R/V Burton Island 1964 ★

Figure 3. Bathymetric map of the Siberian Arctic Shelf.

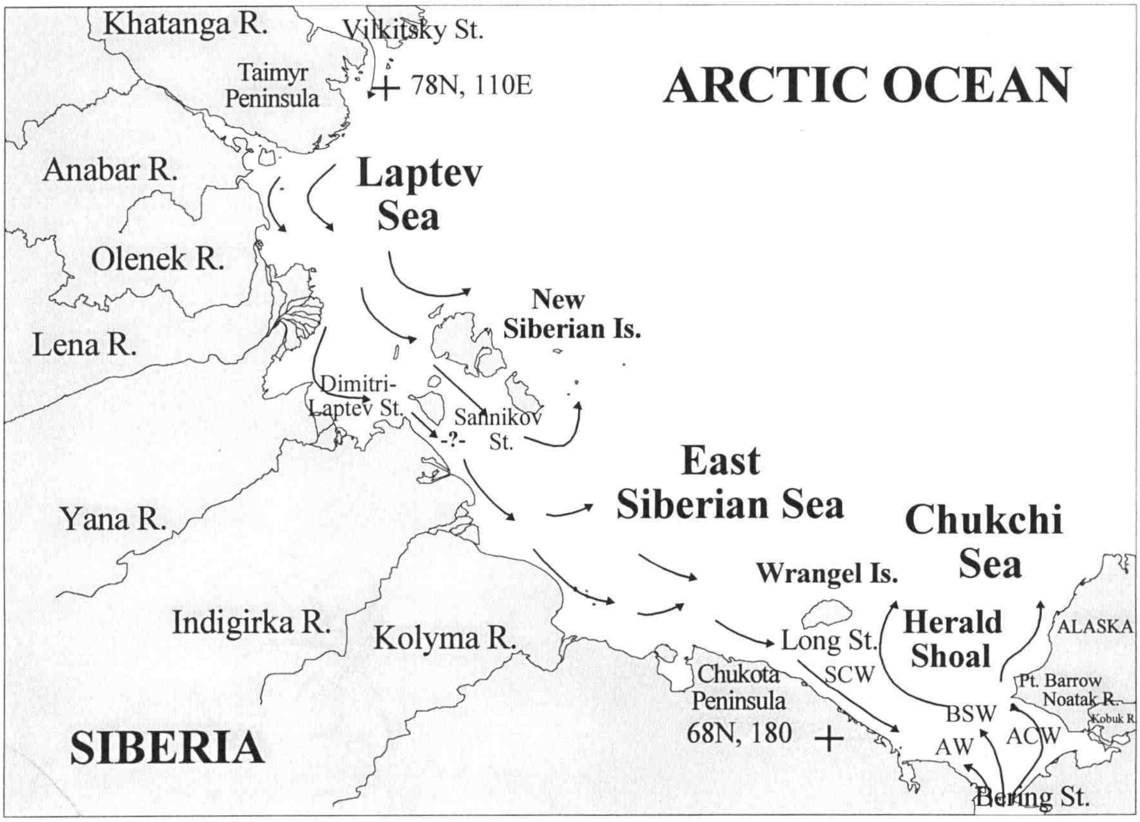


Figure 4. Surface currents on the Siberian shelf (compiled from Coachman and Aagaard, 1974; Grebmeier, 1993; Timokhov, 1994; Grebmeier et al., 1995; Hass et al., 1995; Pavlov, 1996; and Pavlov et al., 1996). ACW=Alaskan Coastal Water; BSW=Bering Shelf water; AW=Anadyr Water; SCW=Siberian Coastal Water.

offshore adjacent to the New Siberian Islands and in submarine canyons (Coachman and Aagaard, 1974; Timokhov, 1994).

The Laptev Sea is characterized by eastward-flowing surface adjacent to the coastline with an offshore component in the east (Fig. 4). Entering through the Vilkitsky Strait, the Kara Sea supplies approximately 0.35 Sv annually of seawater to the Laptev Sea (Pavlov and Pfirman, 1995; Pavlov, 1996; Pavlov et al., 1996). This water flows eastward along the coastline to the Lena delta (Timokhov, 1994; Hass et al., 1995), where surface currents diverge (Pavlov, 1996; Pavlov et al., 1996). One branch continues eastward along the Siberian coast flowing through the Sannikov and possibly the Dimitri-Laptev Straits into the East Siberian Sea (Timokhov, 1994; Hass et al., 1995; Pavlov, 1996; Pavlov et al., 1996). A second, larger branch heads north-northwest and combines with the Transpolar Drift (Pavlov, 1996; Pavlov et al., 1996).

2.3.2 *Sedimentary Processes*

The two primary sources of sediment and organic matter to these shelves are detritus delivered by local rivers, sea ice, coastal erosion, and biogenic material produced *in situ* (Fig. 5). Combined, the Lena, Yana, Indigirka, and Kolyma rivers account for 45 % (50.1 x 10^6 t) of the total suspended matter delivered annually to the Arctic Ocean from the Siberian continent (Gordeev et al., 1997). The Lena and Yana contribute >86 % of TOC discharged from rivers to the Laptev Sea, delivering 5.5 10^6 t/yr (Gordeev et al., 1997). The Indigirka and Kolyma Rivers also account for >86 % (1.5 10^6 t/yr) of TOC delivered by rivers to the East Siberian Sea (Gordeev et al., 1997). In contrast, rivers draining directly into the Chukchi Sea, Kobuk and Noatak, have limited annual sediment and TOC discharges (Gordeev et al., 1997). Yukon River water which flows through the Bering Strait may carry large quantities of particulate and organic matter into the southern Chukchi Sea (McManus et al., 1969). River water makes up approximately 10 % of the water flowing through the Bering (Gordeev et al., 1997).

High primary productivity in the western Chukchi Sea, fueled by nutrient-rich Anadyr water, is the major source of biogenic matter to the sea floor (Sambrotto et al.,

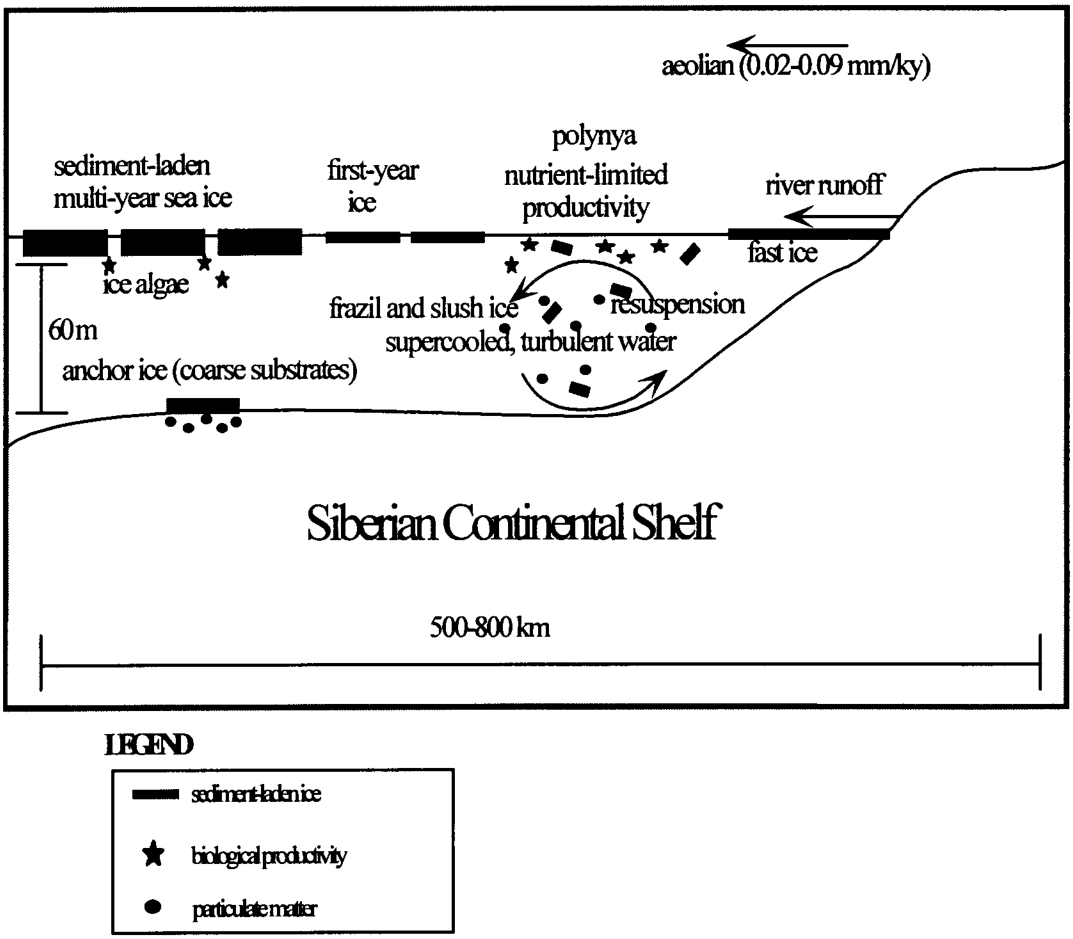


Figure 5. Diagram of sediment sources and transport pathways on the Siberian Arctic shelves.

1984). Elsewhere on the shelf, primary productivity is patchy and depends upon the amount of ice cover and nutrient supply (Grebmeier et al., 1995; Stein and Nürnberg, 1995).

Sea ice plays a direct, potentially dominant, role in surface productivity and sedimentation on these shelves (Fig. 5). Locally, elevated productivity has been observed where ice cover is low, such as proximal to the ice edge in a polynya and at river mouths (Stein and Nürnberg, 1995). Also, large volumes of sediment may be entrained from these shallow continental shelves into frazil and anchor ice during strong storms at the time of freeze-up (Barnes et al., 1982; Reimnitz and Kempema, 1987). Sediment may also be entrained in ice by frazil ice filtration, entrainment of upward floating sediment-laden anchor ice, or discharge of sediment-rich waters over coastal ice canopies. This sediment-laden sea ice may then travel long distances (>400 km) from the site of entrainment before congealing into fast ice (Reimnitz and Kempema, 1987). The amount of sediment carried in this ice may be several times the annual input by rivers (Barnes et al., 1982; Reimnitz and Kempema, 1987). This ice can be a source of ice algae and nutrients, as well as a source of sediment to the Siberian shelves.

A prominent perennial polynya seaward of winter fast ice forms on the Laptev Sea shelf. Here, rapidly-forming new ice is continuously advected offshore (Reimnitz et al., 1994). Generally, the annual freeze-up at the onset of winter does not incorporate old, deep draft ice. On the shelf as much as 1000 km of fetch may develop along with waves up to 6 m at this time (Reimnitz et al., 1995; Timokhov, 1994). The result is intense, wind-induced turbulence of super-cooled water favorable to sediment resuspension and entrainment by frazil ice.

2.3.3 *Deep Ocean Sources of Organic Carbon*

Dissolved and particulate sources of biogenic material to the Arctic Basin are terrigenous detritus supplied by rivers, *in situ* biological production, and ice production and melting (Fig. 5). The largest riverine sources of organic matter are the Mackenzie and Yukon rivers to the Canada Basin and the Lena, Ob, and Yenisey rivers to the Eurasian

Basin. The Canada Basin exhibits relatively high ratios of dissolved organic matter to particulate organic matter (Wheeler et al., 1996). Walsh (1995) suggests that organic carbon and nitrogen are exported from the Bering and Chukchi seas to halocline waters into the Canada Basin. In contrast, organic carbon in Chukchi shelf water has high concentrations of particulate organic carbon (POC) with low dissolved (DOC) and total organic carbon (TOC) relative to slope and basin waters, suggesting that the export of organic material from the Chukchi shelf to the halocline is unlikely or is not the only source of TOC to the Canada Basin (Wheeler et al., 1996).

Organic matter found in Eurasian Basin sediments is predominantly terrigenous in origin, as reflected by low hydrogen indices, high C/N ratios, and high lignin contents (Schubert and Stein, 1997). The organic matter is entrained in sea ice on the Siberian shelves and then released in the basin during melting. Salinity, $\delta^{18}O$, and mass balance considerations indicate that a major pathway of Siberian river water is along the Lomonosov Ridge to the Arctic basin (Bauch et al., 1995. Wheeler et al. (1996) also observed high concentrations of DOC with C/N ratios indicative of terrigenous sources along the Lomonosov Ridge and Makarov flank. They suggest that the Siberian rivers are the source of this terrigenous organic carbon. Clay mineralogical and provenance studies also point to the Siberian shelves as a source of sediment to the central Arctic basins (Pfirman et al., 1990; Nürnberg et al., 1994; Stein and Korolev, 1994; Stein et al., 1994).

2.4 METHODS

Eighty-five core-tops from gravity cores collected during 1962-1964 from the Chukchi (25), East Siberian (29), and Laptev (31) sea shelves were analyzed for total carbon, total nitrogen, carbonate, and biogenic silica (Fig. 2; Table 1). Samples were taken from the top 9 cm for all but two cores, the deepest samples at a 10-12 cm depth. Modern sedimentation rates across the shelf range from 0.2-0.7 cm/yr (Huh, per comm.).

Table 1. Total organic carbon, total nitrogen, C/N ratio, carbonate, and biogenic silica contents of sediment-core samples.

Sample	Depth (cm)	Latitude (North)	Longitude (East)	TOC*	Total Nitrogen*	C/N Ratio	CaCO3*	Biogenic Silica*
BI64-10	2-6	74.62	160.00	1.040	0.142	7.319	0.0008	2.47
BI64-11	0-2	74.35	160.00	1.072	0.150	7.151	0.0070	1.94
BI64-17	2-5	72.40	157.50	0.551	0.072	7.649	0.0013	1.28
BI64-31	0-3	70.63	167.50	0.786	0.108	7.269	0.0000	3.56
BI64-34	1-4	70.05	165.00	0.808	0.118	6.823	0.0027	2.30
BI64-38	0-2	71.27	170.00	1.422	0.196	7.250	0.0055	7.76
BI64-48	0-4	70.92	175.00	1.234	0.160	7.706	0.0000	8.44
BI64-52	1-4	71.12	177.50	0.917	0.117	7.842	0.0083	5.61
BI64-53	0-3	70.77	177.50	0.614	0.086	7.130	0.0021	4.02
BI64-55	2-5	70.00	177.50	1.092	0.153	7.154	0.0007	7.21
BI64-59	0-4	70.78	163.50	0.494	0.071	6.979	0.0003	1.66
NW362-62	0-2	69.00	-176.00	2.136	0.278	7.675	0.0216	14.26
NW362-70	0-2	68.50	-170.98	1.619	0.208	7.779	0.1303	8.17
NW362-72	0-2	68.48	-169.02	1.204	0.151	7.997	0.2126	6.58
NW362-77	0-2	68.02	-169.03	1.510	0.208	7.254	0.0531	9.00
NW362-78	0-4	68.03	-170.00	1.255	0.166	7.572	0.0857	7.50
NW362-79	0-2	68.03	-171.00	1.782	0.268	6.659	0.0310	9.80
NW362-80	0-2	68.03	-172.00	2.110	0.294	7.183	0.0196	10.60
NW362-82	0-2	68.02	-174.08	0.977	0.129	7.546	0.0005	5.06
NW63-14	6-8	67.47	-170.37	1.458	0.279	5.228	0.0935	8.60
NW63-18	5-7	68.60	-171.60	1.746	0.257	6.792	0.1083	9.70
NW63-19	4-6	68.13	-172.40	2.049	0.297	6.911	0.0541	9.34
NW63-21	2-4	67.58	-173.41	0.581	0.091	6.411	0.0296	3.42
NW63-25	3-6	68.72	-174.83	2.100	0.288	7.299	0.0539	11.07
NW63-26	2-4	68.93	-174.25	2.167	0.310	6.979	0.0220	10.77
NW63-27	5-7	69.15	-173.78	1.838	0.259	7.094	0.0304	10.76
NW63-28	6-8	69.42	-173.25	1.622	0.218	7.433	0.0632	9.16
NW63-29	2-4	69.89	-174.44	1.686	0.240	7.017	0.0510	10.88
NW63-32	7-9	69.80	-176.65	1.638	0.232	7.062	0.0374	12.23
NW63-34	0-2	69.32	-177.58	0.869	0.122	7.152	0.0088	5.67
NW63-37	10-12	69.75	179.80	1.060	0.143	7.422	0.0196	6.66
NW63-39	4-6	70.18	-179.57	0.755	0.107	7.085	0.0178	5.17
NW63-40	3-6	70.43	-179.25	0.892	0.123	7.255	0.0192	6.13
NW63-41	5-7	70.63	-179.00	0.589	0.083	7.140	0.0199	3.31
NW63-42	9-11	69.63	-171.00	1.255	0.159	7.881	0.0786	7.60
NW63-44	2-5	69.20	-172.00	1.661	0.230	7.227	0.0475	9.10
NW63-46	0-3	70.45	175.00	1.141	0.161	7.108	0.0231	7.25
NW63-50	4-7	71.42	174.95	1.304	0.181	7.216	0.0149	10.00
NW63-51	0-3	71.57	170.00	1.249	0.150	8.342	0.0074	3.53
NW63-52	2-6	71.38	169.99	0.511	0.072	7.097	0.0002	1.75
NW63-54	0-2	70.72	170.00	1.252	0.168	7.450	0.0054	4.00
NW63-57	0-4	70.09	165.00	0.819	0.107	7.634	0.0065	2.28
NW63-60	0-4	70.83	165.07	0.468	0.070	6.689	0.0066	1.48

Table 1, Continued

NW63-64	4-7	71.17	159.95	0.847	0.108	7.828	0.0006	1.54
NW63-67	0-1	71.92	160.03	1.150	0.118	9.735	0.0099	0.97
NW63-74	0-4	71.75	155.03	0.823	0.096	8.602	0.0045	1.39
NW63-77	0-2	72.40	155.23	0.851	0.100	8.491	0.0077	1.11
NW63-78	0-3	72.63	155.30	1.007	0.121	8.338	0.0036	1.10
NW63-80	0-2	73.07	155.37	0.997	0.146	6.843	0.0345	1.13
NW63-82	0-4	73.47	155.40	0.758	0.131	5.808	0.1976	1.29
NW63-87	0-2	73.33	149.67	0.492	0.059	8.296	0.0127	0.90
NW63-88	0-2	73.03	149.63	0.584	0.062	9.401	0.0157	0.89
NW63-94	0-2	74.33	143.73	0.954	0.087	10.995	0.0099	0.88
NW63-95	0-1	74.44	142.72	0.546	0.066	8.326	0.0087	0.81
NW63-97	0-3	74.50	140.43	0.944	0.103	9.174	0.0254	1.01
NW63-98	6-7	74.32	138.97	0.711	0.075	9.438	0.0224	1.21
NW63-99	0-1	74.50	138.00	0.599	0.074	8.140	0.0302	0.95
NW63-101	0-1	74.00	138.03	1.198	0.127	9.463	0.0303	1.13
NW63-103	0-1	73.50	138.00	1.372	0.137	9.985	0.0280	1.16
NW63-107	0-1	72.50	137.67	1.559	0.151	10.346	0.0214	1.31
NW63-112	10-11.5	72.25	134.42	1.110	0.097	11.429	0.0006	1.21
NW63-115	1-2	73.00	134.17	0.533	0.057	9.301	0.0316	0.90
NW63-118	0-2	73.75	133.88	1.366	0.123	11.115	0.0897	0.95
NW63-119	4.5-5.5	72.80	133.00	2.041	0.204	10.000	0.0408	1.26
NW63-122	5.5-6.5	71.50	130.92	1.849	0.181	10.222	0.0373	1.33
NW63-125	4-5	72.25	131.00	1.632	0.151	10.790	0.0864	1.24
NW63-128	0-2	73.03	131.17	1.944	0.198	9.822	0.0608	1.35
NW63-130	2-3	73.57	131.42	1.276	0.138	9.240	0.0362	1.28
NW63-134	4-5	74.77	134.48	0.566	0.070	8.141	0.0552	0.90
NW63-136	0-2	75.25	134.50	0.766	0.095	8.097	0.0458	1.04
NW63-139	3-4	76.02	134.55	1.173	0.141	8.302	0.0363	1.36
NW63-141	0-1	76.42	133.50	1.195	0.134	8.897	0.0548	1.30
NW63-143	2-4	76.43	129.88	0.821	0.116	7.106	0.0700	1.10
NW63-146	3-4	75.57	129.82	1.334	0.163	8.180	0.0507	1.33
NW63-148	2-3	75.08	129.78	1.483	0.166	8.935	0.0958	1.39
NW63-149	5-6	74.79	129.77	1.497	0.164	9.141	0.0964	1.26
NW63-151	3-4	74.53	128.38	1.423	0.154	9.257	0.1144	1.33
NW63-153	0-1	74.53	125.93	0.694	0.072	9.584	0.0302	1.09
NW63-157	2-3	75.18	124.33	1.107	0.138	8.048	0.0150	1.29
NW63-160	6-7	75.72	124.37	1.002	0.107	9.330	0.0562	1.27
NW63-161	3-4	76.03	125.97	0.810	0.101	8.007	0.0378	1.15
NW63-166	1-2	75.50	120.00	0.833	0.097	8.604	0.0582	1.12
NW63-188	3.5-4.5	74.93	127.30	1.142	0.133	8.607	0.0554	1.22
NW63-193	2-3	73.93	128.28	1.870	0.194	9.616	0.1086	1.57
NW63-197	0-2	71.65	157.00	0.907	0.114	7.980	0.0035	1.27

* Measurement in weight percent

The maximum age of these sediments is, therefore, 60 years (relative to 1662-1964), with most being <35 years. Because intense bioturbation occurs down to a depth of 10-15 cm (Grebmeier, per comm.), small-scale variability within the top 15 cm sampled is negligible. Using a mean sedimentation rate of 0.45 cm/yr for shelf sediments, suggests an integrated record of approximately 30 years for the top 15 cm.

A 400-500 mg sample of each sediment core was pulverized with an agate mortar and pestle, dried in a 100 °C oven for 1 hour, and then cooled to room temperature in a dessicator. Splits were taken from this homogenized sample to measure carbonate, total carbon, total nitrogen, and biogenic silica contents. These samples were also used to determine total carbon and nitrogen of individual size fractions.

A 20-30 mg split of the pulverized sample was analyzed for carbonate using a Coulometrics titrator. The instrument was calibrated using a standard of 12 % carbonate. Sample carbonate concentrations were determined by subtracting a mean blank measurement made on pure phosphoric acid and multiplying by the calculated correction factor determined from standard measurements. Blank measurements ranged from 1.0-2.9 counts, while samples ranged from 0.9-37.5 counts. Replicate samples (n=10) showed precision to be better than 2.0 %. Accuracy of the Coulometrics titrator determined from standard measurements was within 1.5 %.

Total carbon and nitrogen weight percentages were determined for bulk sediments and individual size fractions. Analyses were measured in duplicate using a high-temperature combustion Carlo Erba NA-1500 CNS Analyzer. Calibration curves were determined from 8-10 anactelide standards containing 29.99 % carbon and 11.66 % nitrogen by weight. Standard curves had an r^2 greater than 0.9991. Precision of total carbon and nitrogen analyses were <5 % and <7 %, respectively. Organic carbon weight percentages were then calculated from each duplicate by difference (organic carbon = total carbon - carbonate). Averaged weight percentages of organic carbon and total nitrogen values show a mean deviation of <5 % and pooled (n=85) standard deviations from duplicate runs of 0.090 and 0.005 %, respectively.

Total carbon, total nitrogen, carbonate, and organic carbon were also determined for individual size fractions of representative samples for each region. Bulk samples were disaggregated, dispersed with 10 ml stock solution of Na-hexametaphosphate (2.0 g/L), and then wet and dry sieved through a series of sieves to obtain the sand (>63 μm), silt (2-62 μm), and clay (<2 μm) fractions. Samples with high sand contents were then dry-sieved to obtain the >500, 250-500, 125-250, and 63-125 μm fractions. Individual size fractions were pulverized, dried, and placed in a dessicator until analysis. Total organic carbon and C/N ratios were then calculated for each size fractions. Precision for the size fraction analyses were <5 % for both total carbon and nitrogen analyses.

Biogenic silica analyses were measured in duplicate using the method of Mortlock and Froelich (1989). Analytical precision as an averaged standard deviation of 85 duplicates was 0.22 %. Total organic carbon, total nitrogen, carbonate ($CaCO_3$), and biogenic silica abundances, as well as C/N ratios for all bulk samples are listed in Table 1.

2.5 RESULTS

Biogenic matter along the shelf is predominantly organic carbon and biogenic silica, with minor amounts of carbonate. Highest concentrations of biogenic silica, total organic carbon, and carbonate are present in Chukchi shelf sediments (Fig. 6 and 7). Concentrations of total organic carbon are also elevated in the eastern Laptev Sea east of the Lena River delta.

Carbonate weight percentages ranged from 0.0 to 0.21 %. East-west variability along the shelf shows elevated values in the Chukchi and Laptev seas with values close to zero in the East Siberian Sea. Highest values are present in sediments adjacent to Alaska on the Chukchi Sea shelf. Values up to 0.11 % were observed in the Laptev Sea east of the Lena delta. Elsewhere in the Laptev Sea, carbonate values were <0.07 %. All samples

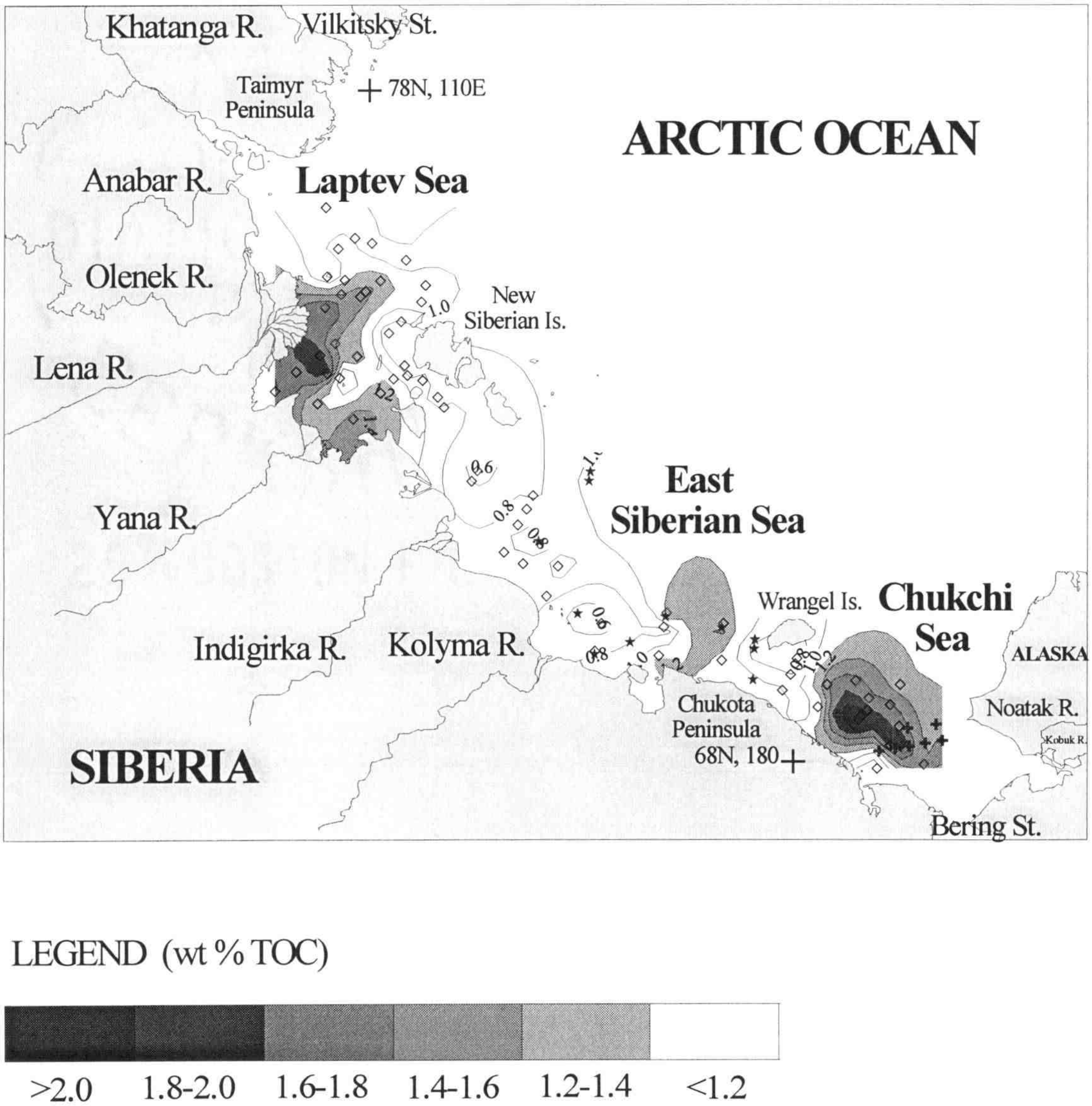


Figure 6. Spatial distribution of total organic carbon present in shelf sediments.

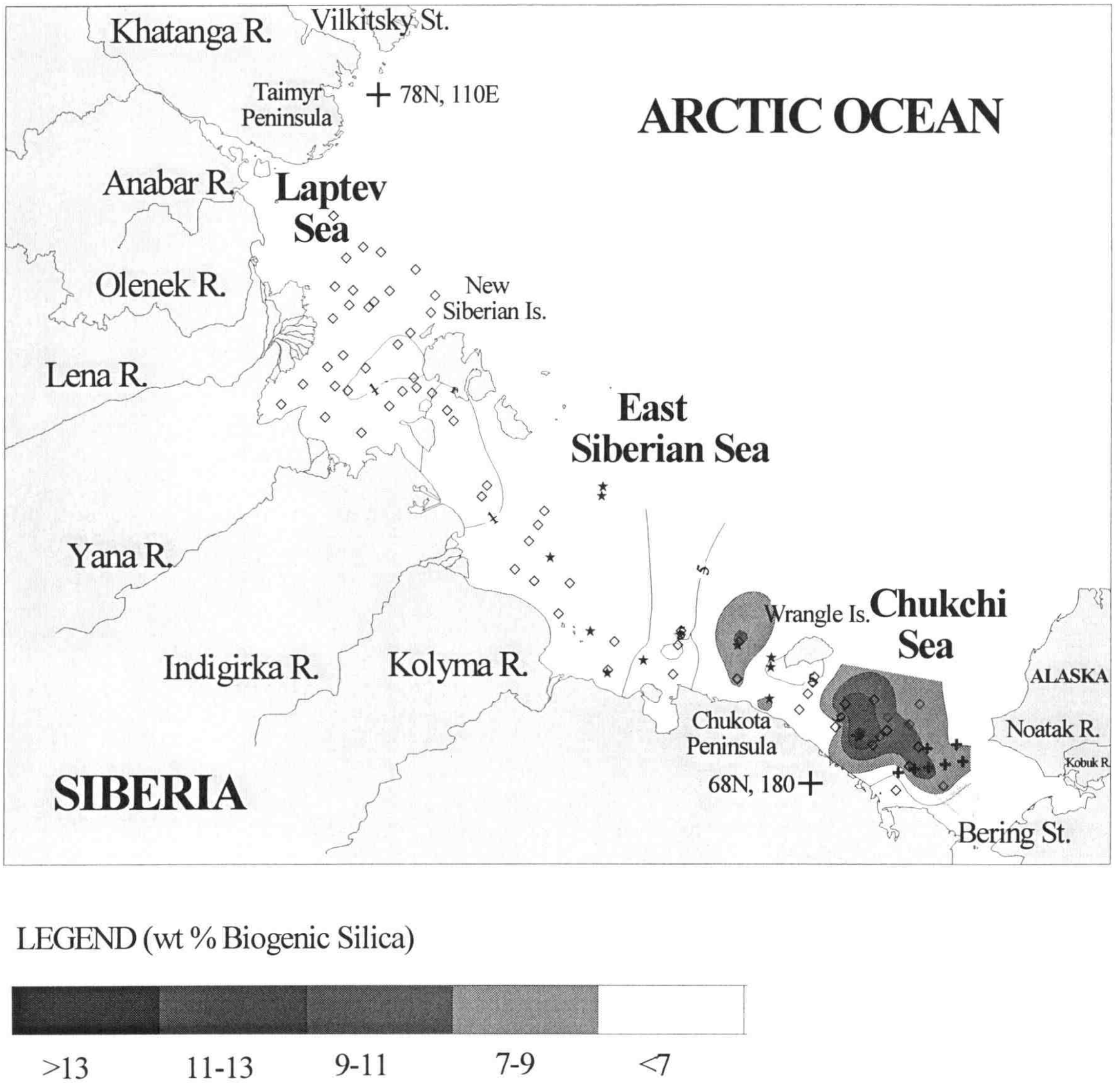


Figure 7. Spatial distribution of biogenic silica present in shelf sediments.

measured from East Siberian shelf sediments show weight percentages <0.04 %, with most values close to 0.01 %.

The range of total nitrogen present in shelf surface sediments is 0.06-0.31 %. East-west trends of total nitrogen show elevated values in the western Chukchi Sea and east of the Lena delta in the Laptev Sea. Values <0.20 % are present in East Siberian Sea shelf sediments.

Total organic carbon ranged from 0.42 to 2.17 % along the shelf. Highest concentrations (>2 %) are present in sediments on the western Chukchi shelf and east of the Lena delta (Fig. 6). In East Siberian Sea shelf sediments, total organic carbon values up to 1.30 % were observed east of the Kolyma submarine valley, with all other samples in the region having values <1.0 %.

C/N ratios range from 4.91-11.42 for bulk sediments and 6.84-98.88 for individual size fractions. Lowest bulk sediment C/N ratios are present on the western Chukchi Sea shelf (6.38-7.12), increasing eastward up to 7.97. The coarse fraction samples from the eastern Chukchi Sea have C/N ratios up to 11.10, whereas in the western Chukchi Sea all samples and size fractions measured have C/N ratios ≤8.06. East Siberian Sea sediments show a large range of C/N ratios (6.70-9.75). C/N ratios of individual size fractions show elevated values to the southwest of Wrangel Island (≤13.70) and off the Kolyma (≤10.83) and Indigirka (≤18.77) rivers. Bulk sediments from the Laptev Sea have the highest C/N ratios seen along the shelf (>8.0), particularly east of the Lena delta (9.2-11.44). Individual size fraction analyses from western Laptev shelf sediments have C/N ratios up to 98.88. C/N ratios in the Laptev Sea show a strong negative correlation with distance (latitude) from the Lena delta (Fig. 8).

Biogenic silica, the dominant biogenic component on the shelf, exhibits the strongest east-west gradient (Fig. 7). Values are highest (14.3 %) in the Chukchi Sea, southeast of Wrangel Island, and decrease to the west to <2.0 %. A plot of biogenic silica versus total organic carbon shows two distinct sedimentary regimes (Fig. 9). On the Chukchi shelf, biogenic silica and total organic carbon concentrations are high and positively correlated.

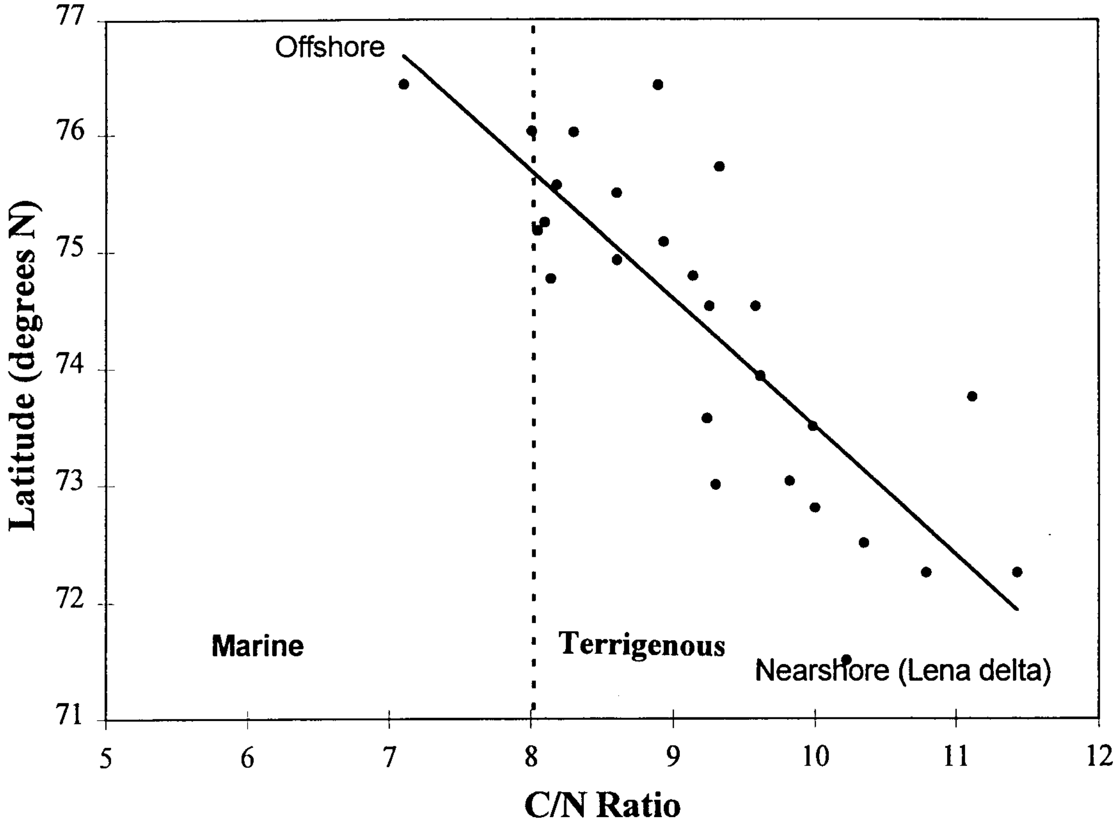


Figure 8. C/N ratios of bulk samples versus distance (latitude) from the Lena River delta.

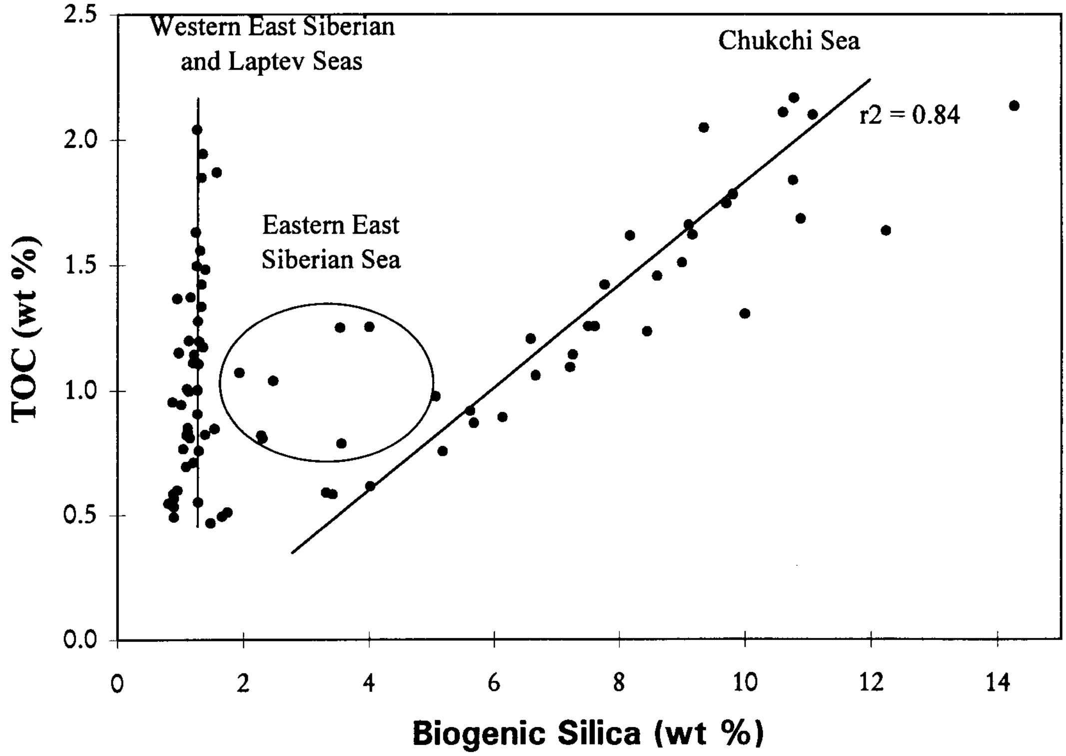


Figure 9. Plot of biogenic silica versus total organic carbon.

Laptev and East Siberian sea shelf sediments west of the Kolyma submarine valley have a large range of total organic carbon concentrations with low biogenic silica contents. East Siberian Sea sediments east of the Kolyma submarine valley to Wrangel Island fall in a field somewhere between the other two distinct end-members. Samples in this group all have similar total organic carbon with biogenic silica concentrations intermediate between the low values observed west of the Kolyma submarine valley and the high values present to the east in Chukchi shelf sediments.

2.6 DISCUSSION

2.6.1 *Carbonate Distribution*

Variations in carbonate contents in Siberian shelf sediments are controlled primarily by terrigenous detritus delivered by rivers and *in situ* productivity. Similar to previous sediment studies (Naugler, 1967; Creager and McManus, 1966; Stein et al., 1994), samples examined in this study indicate that carbonate does not contribute significantly (<0.21 %) to the Siberian shelf. Sediments adjacent to Alaska have the highest carbonate contents observed in this study. Creager and McManus (1966) found that surface sediments proximal to the Alaskan coast may contain large amounts (up to 14 %) of carbonate due to mollusk shells, carbonate clasts proximal to Cape Lisburne, and locally abundant foraminifera. Mollusk shell material observed in samples adjacent to Alaska are responsible for the elevated carbonate contents measured in this study.

Carbonate values are somewhat elevated off the Lena River, possibly as a result of detrital carbonate delivered by the Lena River. The Lena River contributes >77 % of the dissolved carbonate entering the East Siberian and Laptev seas (Anderson and Olsson, 1996). Possibly the Lena also supplies particulate carbonate to this region from Paleozoic and Mesozoic clastic sequences. Some of the dissolved carbonate may precipitate out as the fresh water mixes with seawater, resulting in the observed trends. Stein et al. (1994) measured values between 0.10 and 0.84 % carbonate in Laptev Sea surface sediments, so even the highest values measured in this study are on the low end of their values for the same region.

Although the Siberian shelves, in particular the Laptev Sea, are thought to be a large source of sediment to the deep Arctic basin, low concentrations of carbonate indicate that it is not a source of carbonate (Darby et al., 1989; Pfirman et al., 1990; Nürnberg et al., 1994; Stein et al., 1994; Dethleff, 1995; Schubert and Stein, 1997). High carbonate concentrations (>30 %) are found in sediments from the Canada Basin (Darby et al., 1989) and in surface sediments near Spitsbergen and Greenland (Stein et al., 1994). The most probable sources of carbonate to these regions are ice transport and turbidite deposition from Paleozoic limestone present in the Canadian territories and Greenland (Darby et al., 1989; Stein et al., 1994).

2.6.2 *Distribution of Biogenic Silica*

Biogenic silica distributions on the Chukchi and East Siberian shelves seems to be largely controlled by bathymetry, large-scale circulation, sea-ice distribution, and the productivity patterns of surface water. The highest values are present in the open-water, nutrient-rich western Chukchi Sea and decreases dramatically eastward (Fig. 7). A distinct maximum (>14 %) is observed in western Chukchi Sea sediments, similar to that observed by Ogorodnikov and Rusanov (1978) and Logvinenko and Ogorodnikov (1980). Absolute abundances of diatom assemblages also show a pronounced peak in this region (Polyakova, 1989). Sambrotto et al. (1994) concluded that the source of biogenic material to the southwestern Chukchi may be a combination of surface productivity and influx and deposition of biogenic detritus from the Bering Sea. This maximum in biogenic silica and diatoms in surface sediments coincides with a marked increase in water depth and decrease in current velocities (Coachman and Aagaard, 1974). Nutrient-rich Bering and Anadyr waters flushed through the Bering Strait not only fuel siliceous productivity, but may also supply fine biogenic detritus to the low-energy central Chukchi shelf.

Biogenic silica percentages are positively correlated (r^2=0.83) with clay (r^2=0.83) and total organic carbon (r^2=0.84) contents measured in Chukchi shelf sediments (Fig. 9 and 10). Transmission electron microscope (TEM) images of fine particles (<1.0 μm) separated according to Stoke's law show two distinct size groups. Relatively light, large (0.5-0.8 μm) broken diatom frustules are associated with denser, smaller (<0.1-0.3 μm) clay particles (Fig. 11). X-ray diffraction of the <1.0 μm fraction, shows the mineralogy to be predominantly illite, chlorite, and smectite with lesser amounts of kaolinite, quartz, and feldspar. The diatom frustules and clay platelets, although differentiated by density and size, settle together under similar hydrographic conditions.

Biogenic silica is also elevated east of the Kolyma submarine valley in East Siberian Sea sediments. A localized polynya has been observed in East Siberian Sea adjacent to Wrangel Island (USCG, 1965; Codispoti and Richards, 1968). The high values of biogenic silica, as well are total organic carbon, observed east of the Kolyma submarine valley correlate to this local open-water region. It appears that bottom sediments may reflect surface productivity patterns associated with recurring polynyas.

Biogenic silica percentages in the Laptev Sea are <1.4 %, reflecting low productivity, preservation, and/or dilution in this region. Values are somewhat elevated off the eastern Lena delta, possibly due to nutrient-driven productivity from the Lena River. A distinct biogenic silica minimum is observed in sediments blanketing the floor of the Sannikov Strait. Stein and Nürnberg (1995) observed a maximum (>3 %) in biogenic silica concentrations in this region. Ice-edge algal blooms associated with polynyas observed repeatedly in this region, result in sea-floor sediments high in biogenic material. Inter- and intra-annual variability of hydographic conditions result in large spatial and temporal changes in the ice-edge and related high surface productivity. This variability may be able to account for the low values observed in this region in this study (1962-1964) compared to values observed in 1992 by Stein and Nürnberg (1995). This observation suggests that

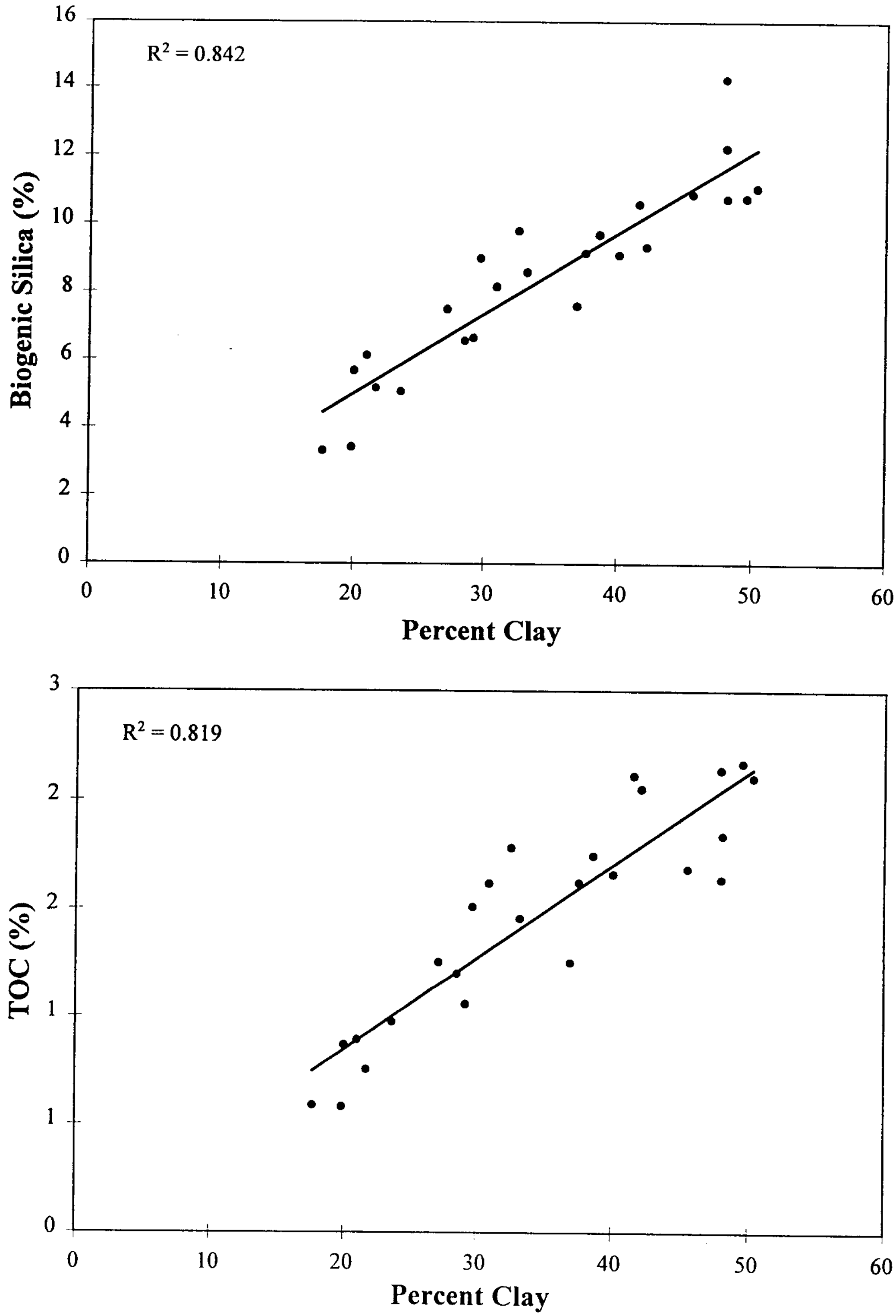
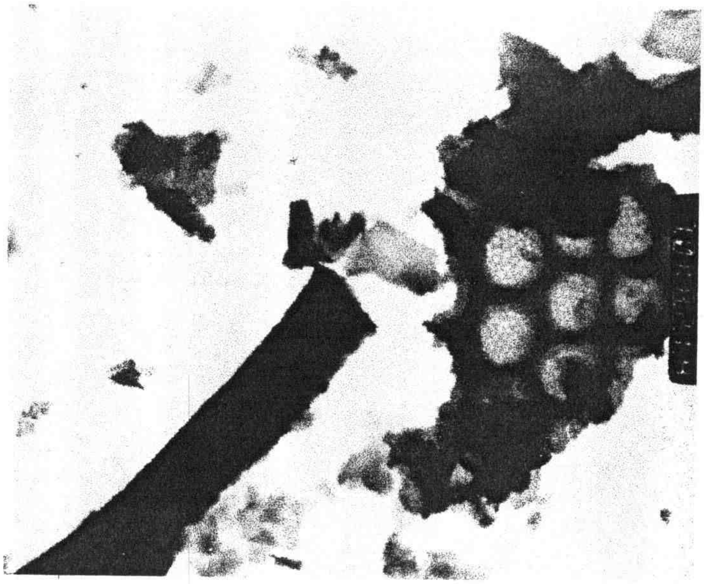


Figure 10. Correlation of percent clay with biogenic silica and total organic carbon contents measured in Chukchi Sea shelf sediments.

17 mm = 1 μm



5 mm = 1 μm

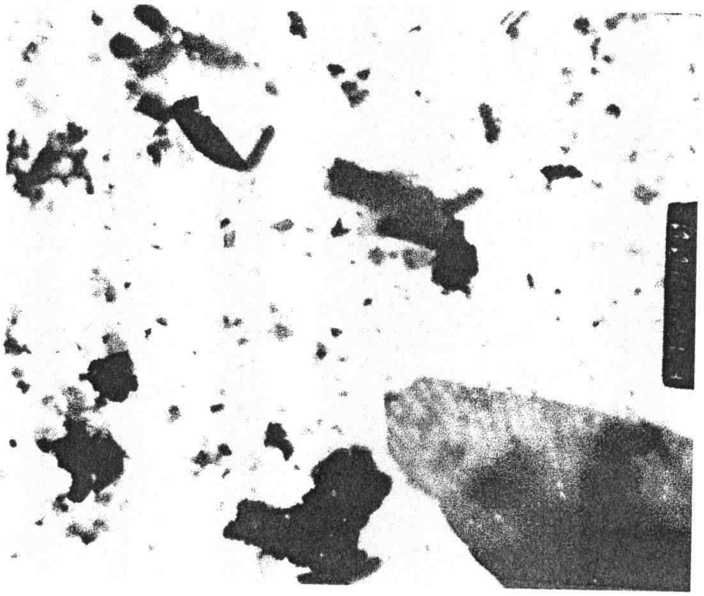


Figure 11. Transmission electron microscope photographs of fine-grained sediments (<1.0 μm) from the Chukchi Sea shelf.

biogenic silica and other productivity proxies may serve as a tool for reconstructing hydrographic and resulting ice-edge position changes.

2.6.3 *Distribution and Sources of Organic Carbon*

The distribution and composition (marine vs. terrigenous) of organic carbon may contain important information about source, transport pathways, and surface-water productivity. East-west variability of total organic carbon along the shelf exhibits relatively high concentrations in Chukchi and Laptev shelf sediments with lowest concentrations in sediments from the East Siberian Sea (Fig. 6). The two regions with highest organic carbon contents are the western Chukchi Sea southeast of Wrangel Island and east of the Lena delta in the Laptev Sea. In the East Siberian Sea, concentrations of organic carbon are <1.0 % with locally elevated values (up to 1.3 %) east of the Kolyma submarine valley at shallow water depths.

Accumulation of total organic carbon in the western Chukchi seems to be a function of particle size and productivity patterns of overlying surface waters. The region of highest total organic carbon contents corresponds to the region of highest biogenic opal and surface productivity measurements in the western Chukchi Sea (Walsh et al., 1989; Coachman and Shigaev, 1992; Grebmeier, 1993; Grebmeier et al., 1995). Total organic carbon contents of surface sediments also show a strong positive correlation (r^2=0.82) with clay contents (Fig. 10). Increased preservation of organic carbon has been shown to occur in fine-grained sediments in shelf regions of the world, including the Bering, Beaufort, and Chukchi seas (Tanoue and Handa, 1979; Keil et al., 1994; Mayer, 1994; Hedges and Keil, 1995). Adsorption of organic carbon on the large surfaces of clay particles may be partly responsible for the correlation of clay and organic carbon contents observed in the Chukchi Sea sediments. Dilution by silt- and sand-rich sediments closer to shore, a reduced current regime north of the Bering Strait, and source of organic carbon from Bering shelf and surface waters may also play a large role in the association of total organic carbon with fine-grained sediments. Also, low-density biogenic detritus tends to settle with fine-grained particles as observed by TEM images in this study (Fig. 11).

Surface sediments of the East Siberian shelf show low values of total organic carbon, reflecting lower productivity, preservation, and possibly dilution by inorganic particulates supplied by the Kolyma and Indigirka rivers. Elevated values (≤1.3 %) occur on either side of the Kolyma submarine valley. Similar to biogenic silica distributions, sediments elevated in organic carbon correspond to a reoccurring seasonal polynya. C/N ratios (<7.5) of sediments in this region are indicative of marine sources, implying higher rates of productivity associated with the perennial polynya or dilution of terrigenous sources by marine sources offshore. In contrast, samples with high total organic carbon contents west of the Kolyma submarine valley have C/N ratios up to 9.7. The Kolyma River seems to be a source of terrigenous organic carbon to this shallow, near-shore region.

East of the Lena River, total organic carbon contents of surface sediments reach values up to 2.04 %, approaching the high values seen in sediments of the western Chukchi shelf. In contrast to mean C/N ratios observed in the western Chukchi (7.16±0.55), the mean C/N ratio for Laptev Sea sediments is 9.16±1.06, reflecting different sources of organic matter to each region. Examination of C/N ratios versus distance (latitude) from the Lena River shows a distinct trend (Fig. 8). C/N ratios close to the Lena delta have high C/N ratios, indicative of terrigenous-derived organic carbon, while offshore low C/N ratios suggest a marine source of organic carbon. Elevated total organic carbon contents associated with high C/N ratios in surface sediments proximal to the Yana delta indicate that the Yana River is also a source of organic detritus to shelf sediments. The highest C/N ratio, observed in the 125-250 μm fraction (98.88), present on the shelf is in the Olenek river valley, suggesting that the Olenek may also be a source of organic matter to Laptev shelf sediments.

A source of organic carbon independent of diatom (marine) productivity contributes to Laptev and East Siberian shelf sediments. The regional differences in the distribution of organic matter is exemplified in a plot of biogenic silica versus organic carbon (Fig. 9).

Although sediments from the Chukchi and Laptev seas both exhibit high organic carbon contents, they plot as distinct biological regimes. In the Chukchi Sea, biogenic silica and organic carbon show a strong positive correlation (r^2=0.84.) In contrast, shelf sediments west of the Kolyma submarine valley exhibit a range of organic carbon concentrations with minor amounts of biogenic silica.

A plot of biogenic silica percentages versus C/N ratios of shelf sediments also identifies two major biologic depositional regimes (Fig. 12). Chukchi Sea surface sediments, with high biogenic silica, have C/N ratios indicative of marine sources. The Laptev and East Siberian seas, in contrast, have a large range of C/N ratios associated with low biogenic silica contents. The elevated C/N ratios seen in the East Siberian and Laptev seas suggest a terrigenous source of organic matter supplied by local rivers.

Biogenic silica, total organic carbon, and C/N ratio spatial distributions suggest marine productivity dominates east of the Kolyma submarine valley, where open waters and high nutrients fuel productivity. In shallow coastal sediments of the western East Siberian and eastern Laptev seas, the Kolyma, Lena, and Yana rivers supply up to 32 % of the total organic carbon.

2.6.4 *Sources of Organic Carbon Determined from C/N Ratios*

To further identify the sources and sinks of organic material on the Siberian shelf, a mixing model similar to the isotopic mixing equation (shown below) developed by Calder and Parker (1968) and Shultz and Calder (1969) was used.

$$\text{Terrigenous Fraction} = F_{terr} = (C/N_{bulk} - C/N_{marine}) / (C/N_{terr} - C/N_{marine})$$

$$\text{Marine Fraction} = F_{marine} = 100 - F_{terr}$$

The mixing model has two end-member, terrigenous and marine, sources of organic material, each with distinct C/N ratios. Mean C/N ratios for marine phytoplankton and

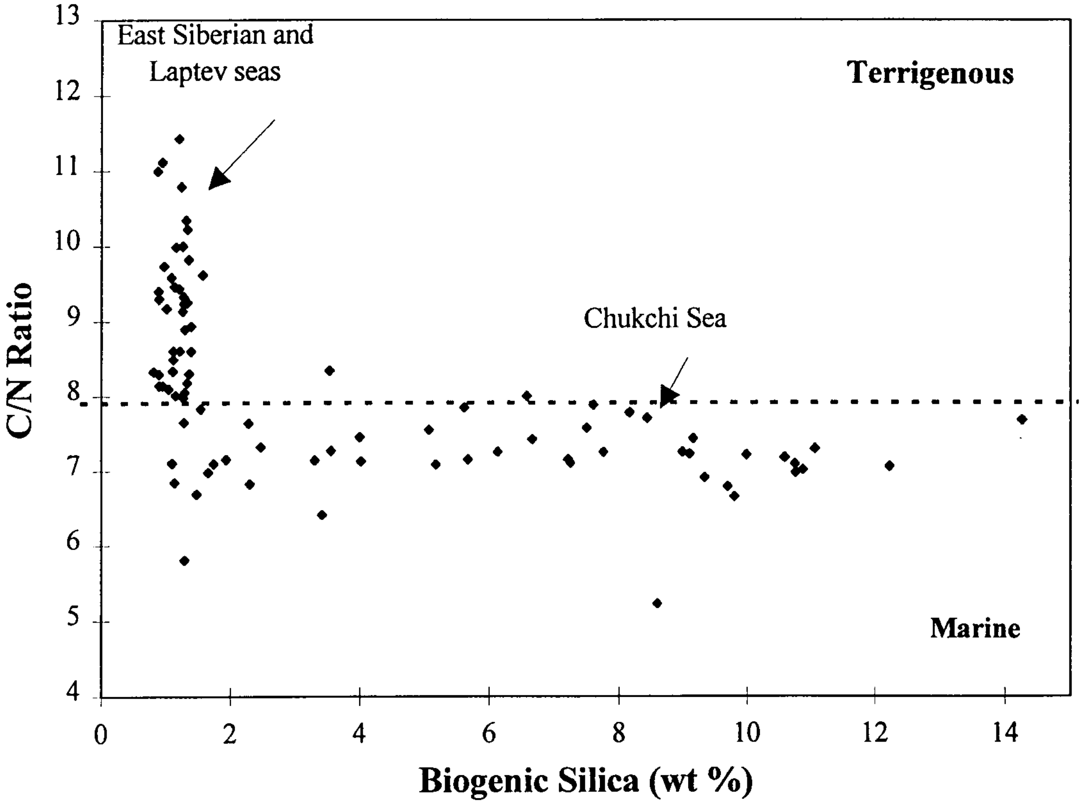


Figure 12. Plot of percent biogenic silica versus C/N ratio.

zooplankton is 6.0, whereas land plants are characterized by C/N ratios >15 and soils have C/N ratios in the range of 10.0-15.0 (Stein, 1991).

The major assumptions are that there are only two end-members of organic carbon, that the two end-members are distinct and can be determined accurately, and that variations in C/N ratios are only the result of changes in source material. C/N ratios and $\delta^{13}C$ spatial patterns show similar trends in Chukchi shelf sediments, suggesting C/N ratios can be used to quantify the relative contribution of marine and terrigenous organic carbon to surface sediments (Scalan et al., 1992; Naidu et al., 1993).

Arctic sediments are rich in illite and smectite which readily fix ammonium in interlayers. Measurements of total nitrogen, thus, may lead to a high estimation of marine organic matter. Comparison of illite and smectite clay contents of these sediments with total nitrogen and C/N ratios show no correlation, suggesting ammonium fixation does not play an important role in controlling changes in C/N ratios (Mammone et al., 1997b).

In the Chukchi Sea it was assumed that the marine end-member of the particulate organic carbon (POC) to shelf sediments consists mainly of phytoplankton from the water column. Sources of marine POC on the Chukchi shelf are a combination of phytoplankton produced in the Chukchi Sea as well as the north Bering Sea (Walsh et al., 1989; Sambrotto et al., 1994). In the mixing model a mean value of 7.21 ± 0.22 based on values measured in seven sediment trap samples from the south Chukchi Sea was used to determine the marine end-member (Naidu et al., 1993). The biogenic component of water-column samples from the western Chukchi Sea is >92 % diatoms (Walsh et al., 1989). The range of C/N ratios of diatoms is 6.5-7.5 (Stein, 1991), supporting the 7.21 C/N ratio as a reasonable estimate for the marine end-member.

The sources of terrigenous organic carbon to shelf sediments on the Chukchi shelf are local rivers, the Kobuk and Noatak, Yukon sediments coming through the Bering Strait, and erosion of coastal headlands. A mean C/N ratio (15.22 ±2.53) was calculated from six Noatak and Kobuk bedload C/N ratios (Naidu et al., 1993) for the terrigenous end-member. Erosion of Alaskan coastal bluffs, although significantly large (2-10 m/yr)

(Naidu et al., 1993; Reimnitz and Barnes, 1987), have not been included in the calculation of the terrigenous end-member due to the lack of available C/N data.

In the absence of C/N ratio data for phytoplankton in the East Siberian and Laptev seas, a median C/N ratio for diatoms (7.0) was used as an estimate (Stein, 1991). Local rivers are the dominant source of terrigenous organic carbon to these shelves. C/N ratios of suspended particulate matter of rivers draining into the East Siberian and Laptev seas have been measured. Studies off the continental shelf of Washington show that dissolved and particulate C/N ratios for rivers are similar (Wheeler, per comm.). Assuming this holds true for the Siberian rivers, the terrigenous end-member for the Laptev and East Siberian seas was calculated using the dissolved C/N ratios of rivers draining into each sea (Gordeev et al., 1997). For the East Siberian Sea the mean C/N ratio for the Kolyma and Indigirka rivers of 20.4±0.71 was used. Mean C/N ratios of the Khatanga, Lena, Yana, Olenek, and Anabar rives yield a value of 20.6±3.14 for the Laptev Sea terrigenous end-member.

Results of the mixing model show a strong east-west shift in source of organic carbon, with increased terrigenous input to the west where local rivers supply large quantities of sediment (Fig. 13). Chukchi shelf sediments contain less than 10 % terrigenous organic carbon, whereas sediments from the Laptev shelf may include up to 32 % terrigenous-derived organic carbon.

On the Chukchi shelf, sediments with the highest contribution of terrigenous organic carbon are found adjacent to Alaska where the Noatak and Kobuk rivers locally supply organic carbon (Fig. 6 and 13). Sediments removed from direct influence by rivers in the western Chukchi Sea contain <2 % terrigenous organic carbon. As suggested by the high biogenic silica contents and the mixing model, the western Chukchi Sea is an important biologically productive region. These findings are consistent with carbon isotopic data used in a mixing model (Naidu et al., 1993).

Generally, contributions of terrigenous organic carbon in the East Siberian Sea are <12 %, with two regions, proximal to the Kolyma and Indigirka rivers exceeding

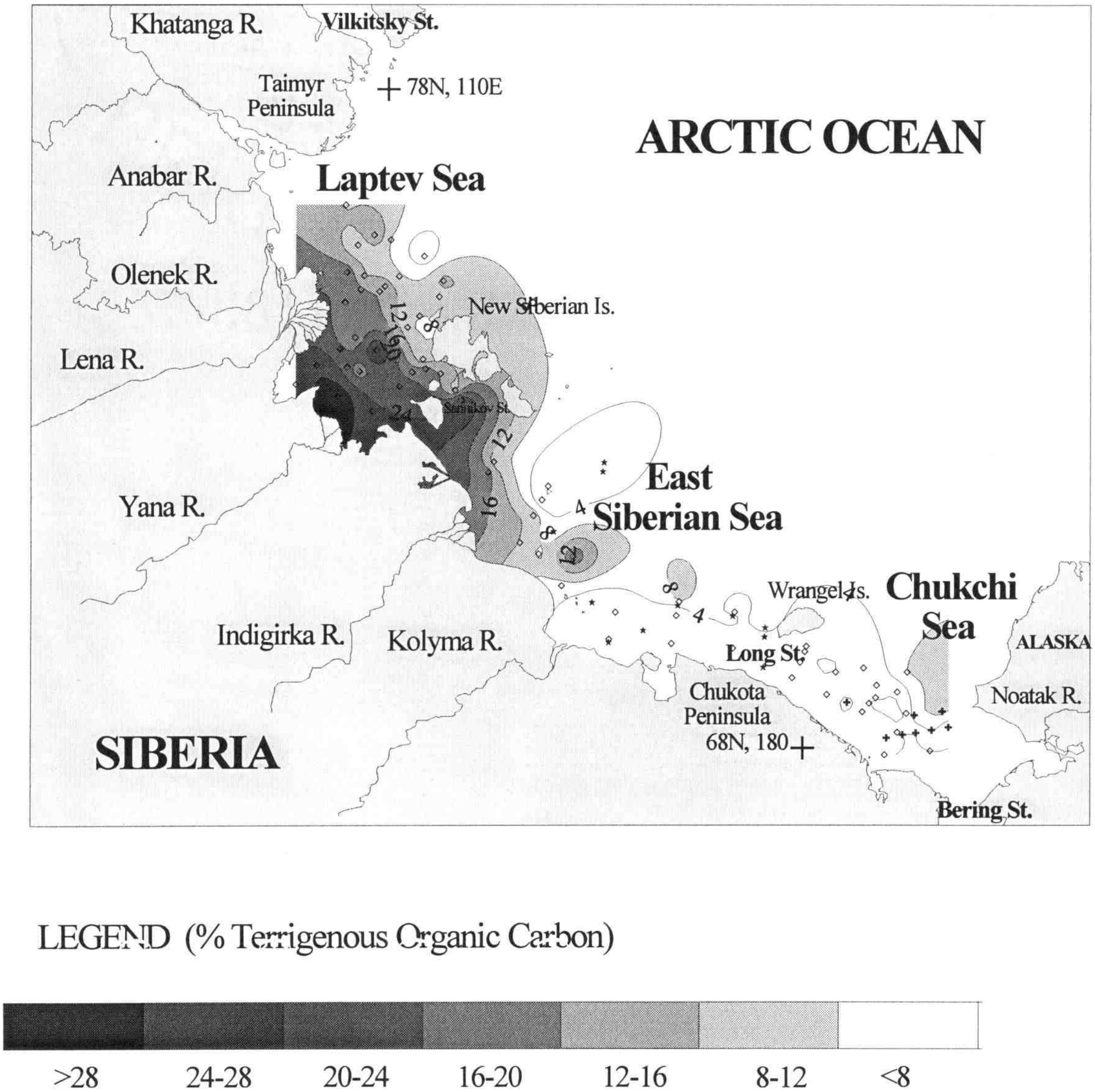


Figure 13. Percentage of terrigenous organic carbon contributing to shelf sediments determined from a mixing model of C/N ratios.

20 % terrigenous organic carbon. The source of terrigenous organic carbon on Central Bank between the Indigirka and Kolyma submarine valleys is most likely delivered by the rivers. The elevated concentrations of terrigenous carbon (>20 %) in the western East Siberian Sea may be from the New Siberian Islands and/or transport of Laptev Sea organic matter through the Sannikov Strait. In both the East Siberian and Laptev seas, marine sources of organic matter becomes increasingly important offshore.

The largest sink of terrigenous organic matter is east of the Lena delta in the Laptev Sea, where the Lena River supplies large amounts of organic carbon (17.6 x 10^6 t/yr) to the shelf (Gordeev et al., 1997). Near-shore marine organic carbon contributes between 70-80 %, whereas marine sources form >90 % of the sediment organic carbon offshore. A mixing model using isotope data measured on inorganic carbon from the Laptev Sea shows similar trends (Erlenkeuser et al., 1995).

Based on these findings, it seems that C/N ratios with supporting carbon isotope data may be a useful tool for determining sources and sinks of organic matter on the Siberian shelf. Variations in these C/N ratios may have long-term implications for studying changes in river supply in the Laptev and East Siberian seas and Bering Strait inflow into the Chukchi Sea caused by changes in sea-level and climate. In order to apply C/N ratios to the sediment record, supporting data should be used and the following assumptions should be made: variations in C/N ratios are only caused by changes in source, and marine and terrigenous end-members are distinct and can be accurately determined.

2.7 CONCLUSIONS

The dominant biogenic component of Siberian shelf surface sediments is biogenic silica, with secondary organic carbon, and minor carbonate. Sediment biogenic silica contents show a strong east-west gradient with highest values in the western Chukchi Sea. Here, nutrient-rich waters from the Gulf of Anadyr enter through the Bering Strait and fuel diatom productivity. Concentrations of biogenic silica remain elevated through the Long Strait and into the East Siberian Sea where a polynya supports high productivity locally. West of the Kolyma submarine valley in the East Siberian Sea and all of the Laptev Sea, shelf sediments contain <2 % biogenic silica. The spatial distribution of biogenic silica reflects surface productivity, hydrographic, and ice conditions. Biogenic silica may serve as tool for reconstructing ice-edge positions.

Examination of the spatial distributions of biogenic silica, total organic carbon, and C/N ratios of surface sediments indicates distinct biologic depositional regimes along the shelf. In the Chukchi, biogenic silica and organic carbon show a strong positive correlation. Laptev and East Siberian sediments west of the Kolyma submarine valley exhibit a range of organic carbon concentrations, yet contain little biogenic silica. A source of organic carbon independent of diatom productivity contributes to Laptev and East Siberian shelf sediments. Regional differences in the distribution of organic matter is the result of two distinct sources, marine and terrigenous.

A mixing model using C/N ratios was used to quantify the relative contribution of marine and terrigenous organic carbon to surface sediments. Results of the mixing model show a strong east-west shift in source and sink of organic carbon, with increased refractory organic carbon delivered by local rivers to the west. Chukchi shelf sediments contain less than 10 % terrigenous carbon, whereas sediments from the Laptev shelf may contain up to 32 % terrigenous organic carbon. Distance from terrigenous sources and surface productivity largely control variations in marine and terrigenous contributions of organic matter. Variations in shelf sediment C/N ratios, supported by isotopic data, may have implications for studying changes in river supply and Bering Strait inflow resulting from sea-level and climate fluctuations.

CHAPTER 3: GRAIN SIZE AND CLAY MINERALOGY OF SIBERIAN SHELF SEDIMENTS

K. A. Mammone[1], C. Viscosi-Shirley[2], P. U. Clark[1], and N. G. Pisias[2]
[1]Department of Geosciences, Oregon State University, Corvallis, OR 97331
[2]College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, OR 97331

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3.1 ABSTRACT

Grain size frequency distributions and semi-quantitative clay mineral abundances were determined for surface sediments from the Chukchi, East Siberian, and Laptev sea shelves. Factor analysis of the grain-size data identifies four end-member grain-size frequency distributions that account for >94 % of the variability in shelf sediments. Silt- and clay-rich (factor 1 and 2) sediments are dominant, with fine sand (factor 3 and 4) generally confined to shoals often close to island and coastline sources. Fine sand is also present offshore at depth (>50 m) in the western Laptev Sea. Clay and silt fine offshore and contain clay mineral assemblages similar to the Kolyma and Indigirka river systems, suggesting that these rivers draining Siberia are the dominant source of fine sediment to the East Siberian shelf. These river sediments are then dispersed offshore in a northeasterly direction roughly following surface currents and bathymetry. Similar to the East Siberian Sea, local rivers draining Siberia supply most of the fine sediment to the Laptev shelf. Laptev shelf sediments exhibit strong east-west gradients in both grain size and clay mineral assemblages. In the west, rivers draining a flood-basalt complex in Siberia result in smectite-rich clays. Sediments in the Laptev Sea coarsen from silty-clay and clayey-silt in the east to fine sands with secondary clay and minor silt in the west. Sea-ice appears to play an important role in the dispersal, reworking, and mixing of these Laptev shelf sediments. In contrast to the Laptev and East Siberian shelves, local rivers draining Siberian and Alaska do not contribute significantly to Chukchi shelf sediments. Northward-flowing currents entering through the Bering Strait supply clay and silt to the Chukchi shelf. These sediments shift from clayey-silts to silty clays as the current energy of water flushing through the Bering Strait decreases. Texturally varied sediments proximal to island and coastline sources are the result of multiple sources and reworking of sediments by currents, sea-ice, and bioturbation.

3.2 INTRODUCTION

A crucial problem of international concern is the potential for extensive radionuclide contamination on the Siberian Arctic shelf from activities of the former Soviet Union.

Although radioactive fallout has declined drastically in the last few decades, dumping of nuclear waste on the Siberian shelf, as well as discharge of contaminants into Arctic rivers, raise serious questions about the extent of pollution in the Arctic environment.

Rivers draining Siberia account for nearly 90 % of the total annual runoff into the Arctic Ocean, and are important pathways for radionuclides to the Arctic Ocean. These rivers drain into shallow (<60 m) and anomalously broad (500-800 km) continental shelves bordering Siberia (Fig. 3). Radionuclides (in particular ^{137}Cs, $^{239,240}Pu$) have an affinity for fine-grained sediments. Sediments supplied by rivers and found on the Siberian shelves are predominantly clay- and silt-size particles (Naugler, 1967; Silverberg, 1972; Naugler et al., 1974; Nürnberg et al., 1994). Because recent studies point to the Siberian shelves as large source regions for predominantly fine-grained sediments to the Arctic Ocean (Pfirman et al., 1990; Ablemann, 1992; Nürnberg et al., 1994, Stein and Korolev, 1994; Stein et al., 1994; Dethleff, 1995; Schubert and Stein, 1997; Eicken et al., 1997), identifying sedimentary processes on these shelves is critical for examining the linkage between particle-reactive pollutants delivered from the former Soviet Union to the Siberian shelves and central Arctic Basin (Fig. 1).

We examined 78 surface sediment samples collected from the Chukchi, East Siberian, and Laptev sea shelves during 1962-1964 in order to assess sediment transport sources and pathways on the shelf (Fig. 2). In particular, factor analysis of grain-size data and semi-quantitative estimates of clay mineral abundances were used to identify the spatial patterns on these shelves. A better understanding of modern sedimentary processes may also be a useful tool for evaluating past changes in source and transport pathways driven by climate and hydrographic fluctuations.

3.3 BACKGROUND

3.3.1 *Physical Oceanography*

River discharge, surface currents, and sea-ice are important mechanisms whereby sediment is introduced and is redistributed on the shallow Siberian shelves. Riverine fluxes are highest from April through September (~90 %), peaking in June (Coachman and Aagaard, 1974; Gordeev et al., 1997). Despite large variability in winds and surface currents, the general direction of flow is easterly across the Siberian shelves (McManus et al., 1969; Timokhov, 1994; Pavlov, 1996; Pavlov et al., 1996). The Arctic Ocean ultimately receives water from three sources: Pacific water flowing through the Bering Strait (0.8 Sv annually; 1 Sv = 10^6 m^3 s^{-1}), Atlantic water flowing though the Barents Sea, and 0.1 Sv annually of freshwater from riverine sources (Lunberg and Haugan, 1996).

Three distinct northerly-flowing water masses enter the Chukchi Sea through the Bering Strait: Bering shelf (BS) and Anadyr waters (AW) in the west and Alaskan coastal-Yukon River water (ACW) in the east (Fig. 4) (Grebmeier et al., 1995). Bering shelf water diverges in the Chukchi Sea to flow northeast and northwest around Herald Shoal (Fig. 4). Anadyr water, upwelled in the Gulf of Anadyr, flows through the Bering Strait and continuously supplies cold, nutrient-rich water to the western Chukchi Sea. The relatively warm, fresh Alaskan coastal water continues northward along the Alaskan coastline. Alaskan coastal water enters the central Arctic Ocean circulation near Point Barrow through Barrow Canyon (Coachman and Aagaard, 1974, 1981; Weingartner et al., 1996). East Siberian coastal water enters the Chukchi Sea through the Long Strait at intermediate depths (McManus et al., 1969; Coachman and Shigaev, 1992; Pavlov, 1996; Pavlov et al., 1996). Current velocities in the Bering Strait and Barrow Canyon have been observed in excess of 1 m/s (Weingartner et al., 1997). Elsewhere on the Chukchi shelf, surface currents are weaker and generally do not exceed 0.4 m/s (mean <0.1 m/s). (Look into; Grebmeier, McManus et al., 1969).

Surface circulation in the East Siberian Sea consists of a sluggish cyclonic circulation with a stable west to east coastal transport and secondary offshore component adjacent to the New Siberian Islands and in submarine canyons (Coachman and Aagaard, 1974; Timokhov, 1994). Surface currents are generally 0.03-0.05 m/s, but may reach up to 0.07-0.1 m/s in the Long Strait (Pavlov, 1996).

The Laptev Sea is characterized by surface currents moving from west to east along the coastline with an offshore component in the east (Fig. 4). Entering through the Vilkitsky Strait, the Kara Sea supplies approximately 0.35 Sv annually of seawater to the Laptev Sea (Pavlov and Pfirman, 1995; Pavlov, 1996; Pavlov et al., 1996). This water flows eastward along the coastline to the Lena delta (Timokhov, 1994; Hass et al., 1995), where surface currents diverge (Pavlov, 1996; Pavlov et al., 1996). One branch continues eastward along the Siberian coast flowing through the Sannikov and possibly the Dimitri-Laptev Straits into the East Siberian Sea (Timokhov, 1994; Hass et al., 1995; Pavlov, 1996; Pavlov et al., 1996). A second, larger branch heads north-northwest and combines with the Transpolar Drift (Pavlov, 1996; Pavlov et al., 1996). Mean summer surface currents in the Laptev Sea are 0.02 m/s, increasing eastward up to maximum velocities of 0.05 m/s (Hass et al., 1995; Pavlov, 1996).

Ice covers the majority of the shelf year-round with open areas localized to polynyas near shore (Fig. 5). Ice cover in the winter is 3-3.5 m thick and decreases in the summer to about 1 m with open areas along the coast near river mouths (Naugler et al., 1974). Formation of ice on the Siberian shelf is dominated by three processes: freeze-up of vast ice-free regions in autumn, winter ice production in extensive coastal polynyas seaward of fast ice, and melting of ice in the spring.

3.3.2 *Sedimentary Processes*

The two primary sources of sediment on these Arctic shelves are terrigenous detritus delivered by local rivers, sea ice, and coastal erosion (2-10 m/yr along Alaskan coast), and biogenic material produced *in situ* (Fig. 5) (Naidu et al., 1993; Reimnitz and Barnes, 1987). During the summer, several large rivers that drain into the shallow Arctic seas contribute a significant inflow of freshwater and sediment. The Lena River accounts for more than 70 % of the overall inflow of the riverine waters to the Laptev Sea (Dehn et al., 1995), delivering 17.6 x 10^6 tons of suspended sediment annually (Gordeev and Sidorov, 1993; Gordeev et al., 1997). Combined, the Lena, Yana, Indigirka, and Kolyma rivers account for 45 % (50.1 x 10^6 t) of the total suspended particulate matter delivered annually to the Arctic Ocean from the Siberian continent (Gordeev et al., 1997). In contrast, sediment and organic matter delivered to the Chukchi Sea by rivers is low.

High primary productivity in the western Chukchi Sea, fueled by nutrient-rich Pacific water entering through the Bering Strait, is the major source of biogenic matter to the sea floor (Sambrotto et al., 1984). Elsewhere on the Siberian shelves, primary productivity is patchy and depends upon the amount of ice cover and nutrient supply (Grebmeier et al., 1995; Stein and Nürnberg, 1995; Mammone et al., 1997a). Highest concentrations of biogenic silica (≤14.3 %), total organic carbon (≤2.3 %), and carbonate (≤0.1 %) on these shelves are present in Chukchi shelf sediments (Mammone et al., 1997a). Although total organic carbon is also high (2.0 %) east of the Lena delta in the Laptev Sea, up to 32 % is terrigenous-derived organic carbon from the Lena and Yana rivers (Mammone et al., 1997a). In contrast, East Siberian Sea sediments show the lowest concentration of all biogenic phases measured.

Sea ice plays a direct, potentially dominant, role in productivity and sedimentation on these shelves (Fig. 5). Locally, elevated productivity has been observed where ice cover is low, such as proximal to the ice-edge, in a polynya, and at river mouths (Stein and Nürnberg, 1995). Large volumes of sediment may be entrained from these shallow continental shelves into frazil and anchor ice during strong storms at the time of freeze-up (Barnes et al., 1982; Reimnitz and Kempema, 1987; Reimnitz et al., 1995). Sediment may also be entrained in sea-ice by frazil ice filtration, entrainment of upward floating sediment-laden anchor ice, or discharge of sediment-rich waters over coastal ice canopies. This sediment-laden sea ice may then travel long distances (>400 km) from the site of entrainment before congealing into fast ice (Reimnitz and Kempema, 1987). The amount of sediment carried in this ice may be several times the annual input by rivers (Barnes et al., 1982; Reimnitz and Kempema, 1987). Sediments delivered by rivers and entrained in sea-ice tend to be fine-grained (silt and clay), but may contain up to 28 % sand and gravel

(Pfirman et al., 1990; Reimnitz et al., 1987; Reimnitz, et al., 1993; Nürnberg et al., 1994; Dethleff, 1995).

Siberian shelf processes are not favorable for large-scale gouging of shelf sediments by sea ice (Nürnberg et al., 1994; Reimnitz, 1994; Reimnitz et al., 1994). In these shelves, a perennial polynya seaward of winter fast ice (10-20 m water depth) forms on Siberian shelves, rapidly forming new ice which is continuously advected offshore (Reimnitz, 1994; Reimnitz et al., 1994). The annual freeze-up at the onset of winter generally does not incorporate old, deep draft ice (Reimnitz, 1994; Reimnitz et al., 1994; Timokhov, 1994), again limiting potential gouging by sea-ice.

Although, ice gouging does not seem to be the dominant process in reworking bottom sediments on the Siberian shelves (Nürnberg et al., 1994; Reimnitz, 1994; Reimnitz et al., 1994), gouges have been observed locally by side-scan sonar on the Laptev shelf (23-42 m) in the vicinity of the New Siberian Islands and at the mouth of the Anabar River (Reimnitz et al., 1978; Lindermann et al., 1995; Kassens et al., 1995). The gouges observed on shoals off the west coast of the New Siberian Islands were interpreted to be relict from lowered sea level at 8700-7900 years B. P.. Reimnitz et al. (1978) also observed occasional grounding of sea ice seaward of the 20 m isobath on East Siberian Sea shoals. Gouging relief may not be preserved on these shelves due to large waves and turbulence observed adjacent to fast-ice flaw leads (Timokhov, 1994; Reimnitz et al., 1994).

3.4 METHODS

We analyzed 78 core-tops from gravity cores collected during 1962-1964 from the Chukchi (25), East Siberian (29), and Laptev (31) seas (Table 2) for their grain size frequency distributions (Fig. 2). Samples were taken from the top 5 cm for most cores, with the deepest samples at a 10-12 cm depth. Modern sedimentation rates across the shelf range from 0.2-0.7 cm/yr (Huh, personal comm., 1995), thus, the maximum age of these sediments is approximately 50 years, with most representing less than 30 years.

Table 2. Grain-size characteristics of sediment samples.

Sample I.D.	Sample Interval (cm)	Latitude (North)	Longitude (East)	Water Depth (m)	Gravel (wt %)	Sand (wt %)	Silt (wt %)	Clay (wt %)	>12 phi (wt %)
BI64-11	0-2	74.35	160.00	42	0.00	0.97	39.96	59.06	29.78
BI64-17	2-5	72.40	157.50	22	0.00	6.50	66.35	27.16	12.71
BI64-31	0-3	70.63	167.50	27	0.00	16.98	49.43	33.59	15.06
BI64-34	1-4	70.05	165.00	22	0.00	3.81	55.59	40.59	16.08
BI64-38	0-2	71.27	170.00	48	0.00	1.82	35.90	62.28	27.96
BI64-52	1-4	71.12	177.50	35	0.00	24.47	48.33	27.20	12.51
BI64-53	0-3	70.77	177.50	42	0.48	47.12	30.87	21.52	9.47
BI64-55	2-5	70.00	177.50	49	0.00	28.03	37.71	34.26	17.23
NW362-62	0-2	69.00	-176.00	51	0.00	8.72	43.34	47.93	19.59
NW362-70	0-2	68.50	-170.98	54	0.00	5.29	63.81	30.90	13.03
NW362-72	0-2	68.48	-169.02	56	0.00	7.98	63.52	28.51	12.05
NW362-77	0-2	68.02	-169.03	54	0.00	7.34	62.98	29.68	12.17
NW362-78	0-4	68.03	-170.00	53	0.00	9.41	63.45	27.14	12.42
NW362-79	0-2	68.03	-171.00	50	0.00	3.30	64.17	32.53	11.67
NW362-80	0-2	68.03	-172.00	40	0.00	0.84	57.62	41.54	18.10
NW362-82	0-2	68.02	-174.08	17	0.00	52.24	24.12	23.64	8.32
NW63-14	6-8	67.47	-170.37	48	0.00	3.93	62.89	33.18	15.52
NW63-18	5-7	68.60	-171.60	55	0.00	0.72	60.69	38.60	19.49
NW63-19	4-6	68.13	-172.40	51	0.00	1.16	56.74	42.11	19.49
NW63-21	2-4	67.58	-173.41	49	0.00	58.18	21.94	19.89	9.02
NW63-25	3-6	68.72	-174.83	51	0.00	2.79	46.93	50.28	22.66
NW63-26	2-4	68.93	-174.25	51	0.00	0.70	49.79	49.51	22.65
NW63-27	5-7	69.15	-173.78	52	0.00	1.94	49.99	48.08	22.23
NW63-28	6-8	69.42	-173.25	53	0.00	4.81	57.63	37.56	15.04
NW63-29	2-4	69.89	-174.44	52	0.00	3.17	51.31	45.52	18.92
NW63-32	7-9	69.80	-176.65	53	0.00	4.30	47.71	48.00	19.73
NW63-34	0-2	69.32	-177.58	48	0.00	61.35	18.60	20.05	8.48
NW63-37	10-12	69.75	179.80	50	0.81	34.55	35.49	29.15	10.04
NW63-39	4-6	70.18	-179.57	44	0.00	47.23	31.04	21.73	8.88
NW63-40	3-6	70.43	-179.25	40	0.00	47.49	31.49	21.02	8.36
NW63-41	5-7	70.63	-179.00	38	0.50	43.39	38.41	17.71	6.84
NW63-44	2-5	69.20	-172.00	53	0.00	4.33	55.59	40.07	16.56
NW63-46	0-3	70.45	175.00	45	0.00	13.23	45.42	41.36	15.63
NW63-50	4-7	71.42	174.95	41	0.00	3.11	47.81	49.07	21.06
NW63-51	0-3	71.57	170.00	46	0.00	2.41	45.34	52.25	24.85
NW63-52	2-6	71.38	169.99	51	0.00	1.48	36.45	62.07	26.49
NW63-54	0-2	70.72	170.00	30	0.00	3.19	47.98	48.83	21.66
NW63-57	0-4	70.09	165.00	24	0.00	2.99	54.53	42.47	18.81
NW63-60	0-4	70.83	165.07	24	0.00	38.15	41.93	19.92	8.63
NW63-64	4-7	71.17	159.95	10	0.00	2.68	59.73	37.59	14.69
NW63-67	0-1	71.92	160.03	23	0.00	2.58	65.72	31.70	13.13
NW63-77	0-2	72.40	155.23	21	0.00	0.37	58.65	40.98	18.30
NW63-80	0-2	73.07	155.37	34	0.00	0.60	50.40	49.00	11.24
NW63-82	0-4	73.47	155.40	37	0.00	2.36	47.32	50.33	11.11
NW63-87	0-2	73.33	149.67	16	0.00	7.88	65.92	26.20	14.35
NW63-88	0-2	73.03	149.63	15	0.00	12.46	66.19	21.35	10.05
NW63-94	0-2	74.33	143.73	17	0.00	39.58	43.92	16.51	7.55
NW63-95	0-1	74.44	142.72	16	0.00	48.61	36.78	14.61	5.17
NW63-97	0-3	74.50	140.43	28	0.00	4.85	60.98	34.17	13.34
NW63-99	0-1	74.50	138.00	20	0.00	18.55	56.39	25.06	7.29
NW63-101	0-1	74.00	138.03	21	0.00	1.04	59.79	39.17	13.92
NW63-103	0-1	73.50	138.00	22	0.00	1.42	56.76	41.82	16.91
NW63-107	0-1	72.50	137.67	24	0.00	2.83	51.17	46.00	16.97
NW63-115	1-2	73.00	134.17	17	0.00	27.74	43.81	28.45	11.53

Table 2, Continued

NW63-118	0-2	73.75	133.88	16	0.00	7.49	64.51	27.99	10.52
NW63-119	4.5-5.5	72.80	133.00	16	0.00	0.26	50.61	49.14	16.58
NW63-122	5.5-6.5	71.50	130.92	15	0.00	0.59	64.43	34.98	8.97
NW63-125	4-5	72.25	131.00	17	0.00	3.15	59.37	37.47	11.06
NW63-128	0-2	73.03	131.17	24	0.00	0.36	47.09	52.55	16.03
NW63-130	2-3	73.57	131.42	25	0.00	1.50	41.03	57.46	19.45
NW63-134	4-5	74.77	134.48	22	0.00	15.37	57.73	26.89	12.48
NW63-136	0-2	75.25	134.50	29	0.00	21.25	49.98	28.77	9.38
NW63-139	3-4	76.02	134.55	36	0.00	3.85	40.27	55.89	35.63
NW63-141	0-1	76.42	133.50	37	0.00	4.32	42.85	52.83	26.37
NW63-143	2-4	76.43	129.88	56	0.00	23.26	32.82	43.93	24.87
NW63-146	3-4	75.57	129.82	44	0.00	12.10	22.55	65.35	45.53
NW63-149	5-6	74.79	129.77	34	0.00	2.79	47.42	49.79	24.61
NW63-151	3-4	74.53	128.38	34	0.00	5.85	47.50	46.64	24.13
NW63-153	0-1	74.53	125.93	33	0.00	57.84	17.73	24.43	8.23
NW63-157	2-3	75.18	124.33	41	0.00	59.47	10.98	29.55	14.62
NW63-160	6-7	75.72	124.37	50	0.00	30.83	27.53	41.64	24.11
NW63-161	3-4	76.03	125.97	47	0.00	52.66	14.82	32.52	17.20
NW63-166	1-2	75.50	120.00	45	0.00	53.58	18.56	27.86	14.04
NW63-188	3.5-4.5	74.93	127.30	38	0.00	11.18	44.27	44.55	23.04
NW63-193	2-3	73.93	128.28	25	0.00	4.46	47.71	47.83	18.79
NW63-197	0-2	71.65	157.00	13	0.00	3.26	55.48	41.25	19.58

Because of extreme bioturbation down to a depth of 10-15 cm (Grebmeier, personal comm., 1995), small-scale variability within the top 15 cm sampled is negligible.

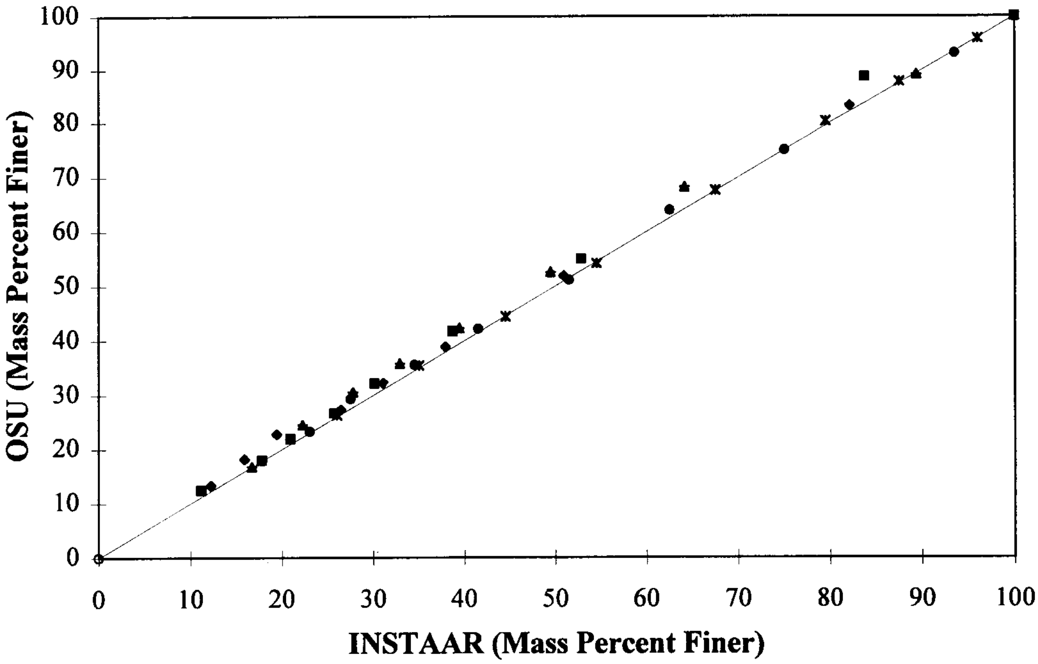
High-resolution particle-size analysis was completed using a combination of standard wet and dry sieving techniques and a Micromeritics Sedigraph 5100. A 3-4 gram split of each sample was disaggregated, sonicated, and dispersed with a stock solution (2 g/L) of Na-hexametaphosphate after removal of salts and organics via 30 % H_2O_2 and washing. The <4.5 ϕ fraction was removed by wet-sieving, then dried and sieved at half phi intervals from -1 to 4.5 ϕ. A suspension of 0.05-0.07 g/ml of the 4.5-12 ϕ fraction was rapidly and automatically measured by a Sedigraph 5100 in terms of equivalent spherical sedimentation diameter (ESSD).

Results from rerunning of 19 samples gave a precision for the Sedigraph of ±5 % difference in the medians of the <4.5 ϕ fraction. Twelve replicate analyses gave a precision of ±6.9 %. Coates and Hulse (1985) also observed lowered precision between duplicate samples due to the difficulty in keeping the sample homogenized down to 2-3 grams.

The Sedigraph was calibrated using a narrow-ranged garnet standard and by interlaboratory comparison with a Sedigraph 5000D at INSTAAR (Boulder, CO) and a Sedigraph 5100 at the Micromeritics Laboratory (Norcross, Georgia). Comparison of 6 samples with INSTAAR and 2 samples with Micromeritics gave a correlation coefficient >0.991 (Fig. 14).

Standard sieving techniques were used to characterize the 4.5 ϕ sizes at 0.5 ϕ intervals (Folk, 1974). Replicate sieving of 10 samples gave a precision of ±5 %, comparable to precision of the Sedigraph 5100 data. Sieving and Sedigraph data were then combined to define grain size frequency distributions for each sample. Statistics (mean, skewness, kurtosis, median, and standard deviation) were calculated for each sample using data from the cumulative curve and standard moment equations after Folk (1974).

Q-mode factor analysis of the grain size frequency distribution of the 78 surface sediment samples was used to extract information about provenance and transport



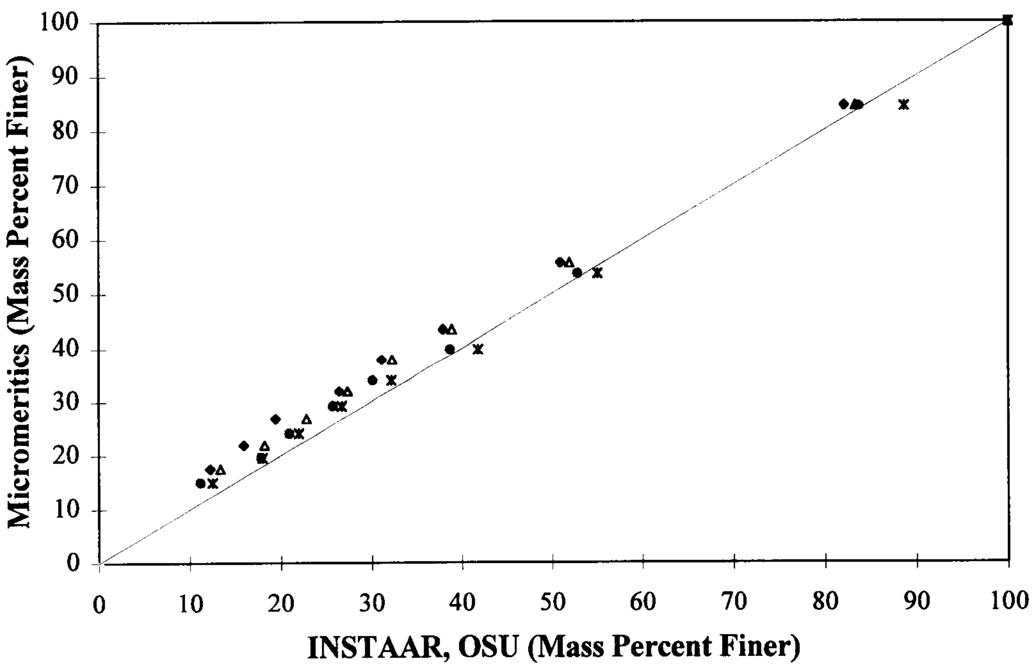


Figure 14. Interlab comparison: mass percent finer for individual size classes are plotted for each lab. The line indicates a 1:1 correlation. Data symbols are used to distinguish different samples.

pathways. Each sample is considered to be completely described in terms of its size frequency distribution by weight percent of sediment contained in each 0.5 ϕ class from -1.0 to 12.0 ϕ. The Q-mode analysis focuses on the central portion of the curve and effectively classifies samples on the basis of mean and standard deviation (Syvitski, 1991). Q-mode factor analysis examines the size frequency data and groups samples with similar distributions so that each group (factor) describes a unique source or transport mechanism. This multivariate statistical method attempts to find the most unique samples and expresses all other samples as mixtures of these end-member distributions. The factor loading of each sample indicates the degree of similarity of each sample with each end-member on a scale from zero (no similarity) to one (100% similarity).

Approximately 3.0 grams of 65 of the 78 core tops were examined for clay mineralogy using a Scintag X-ray diffractometer. All samples were treated with H_2O_2 to remove organics, washed with deionized water to remove salts and organic residue, and dispersed with Na-hexametaphosphate. The <9 ϕ and 9-5.6 ϕ fractions, as well as the <12 ϕ fraction for several samples, were then separated by centrifugation. The size separates were Mg-saturated with 0.5*M* $MgCl_2$, and then smeared on glass slides to make oriented clay films. The <9 ϕ size fraction was solvated with ethylene-glycol vapor for 4-6 hours preceding analysis on a Scintag XRD. Slides were scanned at a rate of 1° 2θ per minute from 2° to 34° 2θ at increments of 0.02 steps/degree (54 % relative humidity).

Semi-quantitative estimates of clay mineral abundances were made by measuring the peak areas of smectite (17 Å), illite (10 Å), chlorite (7.2 Å) and kaolinite (7.1 Å) from the ethylene-glycolated diffraction pattern of the <12 ϕ and <9 ϕ fraction using the Biscaye (1965) method. Estimation of the relative abundances of chlorite and kaolinite were based on resolution of the 3.5 Å region doublet and applied to the 7.1/7.2 Å peak (Biscaye, 1964). Weighting factors were applied to smectite (1), illite (4), chlorite (2), and kaolinite (2) peak areas to account for differences in diffracting abilities of various minerals, as well as differences caused by changes in 2θ. These four clay mineral abundances were then normalized to 100 % (Biscaye, 1965), although small quantities of quartz and feldspar were observed in the <9 ϕ fraction.

3.5 RESULTS

3.5.1 *Grain Size*

Using Shepard's (1954) grain-size classification, Siberian shelf can be described as predominantly clayey-silts (46 %), with secondary sand-silt-clay mixtures (31 %) and silty-clays (23 %) (Fig 15). Notably absent are pure sands, silts, and clays, as well as mixtures of sand and silt and sand and clay. A strong concentration of samples lies on the silt-clay axis with a diffuse array extending toward the sand apex. Gravel was observed in four sediment samples, all off the west and southwest coast of Wrangel Island.

Surface sediment grain size distributions show very little correlation with water depth (Fig. 16). Spatial distributions of surface sediment show that clayey-silts blanket the deep (>45 m) central Chukchi Sea, shallow and intermediate regions (<30 m) west of the Indigirka submarine valley in the East Siberian Sea, and both the western Lena submarine valley and shelf east of the Lena delta at water depths <25 m in the Laptev Sea (Fig. 17). Silty-clays are present east of the Indigirka submarine valley in the East Siberian Sea, as well as on the shoal between the east and west Lena submarine valleys in the Laptev Sea. Sand-silt-clay mixtures are present proximal to islands on the shelf and off the Chukota Peninsula in the Chukchi Sea. Mixed sand-silt-clays are also important in the western Laptev Sea. The sand-silt and clay-sand surface sediment samples are adjacent to the New Siberian Islands and in the western Chukchi Sea, respectively.

Because sediment samples are often skewed and bimodal with a high percentage of >12 ϕ material (Fig. 18), describing sediments in terms of median, mean, and standard deviation (sorting) is not a useful tool for sample comparison and determing spatial trends. Sediments on the shelf are very poorly sorted to extremely poorly sorted according to Folk's (1974) classification.

Q-mode factor analysis was undertaken in order to help delineate spatial trends and relate samples to each other statistically. Q-mode factor analysis accounts for >94.3 % of the variability in the data set with four factors having eigenvalues >10 %.

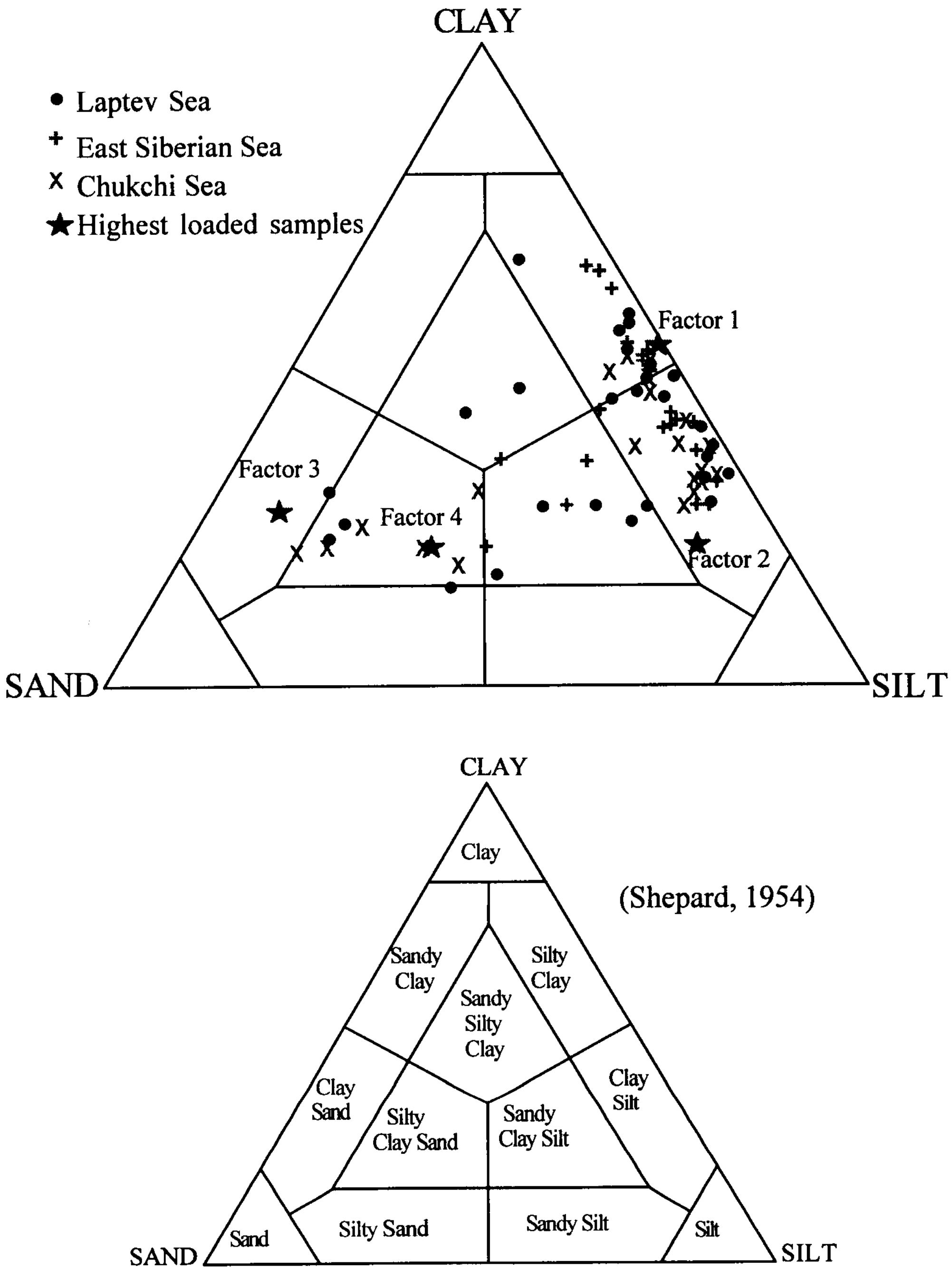


Figure 15. Ternary diagram showing sand, silt, and clay fractions of sediment samples from the Chukchi (x), East Siberian (+), and Laptev seas (•). Stars (★) indicate the highest loaded sample for each factor.

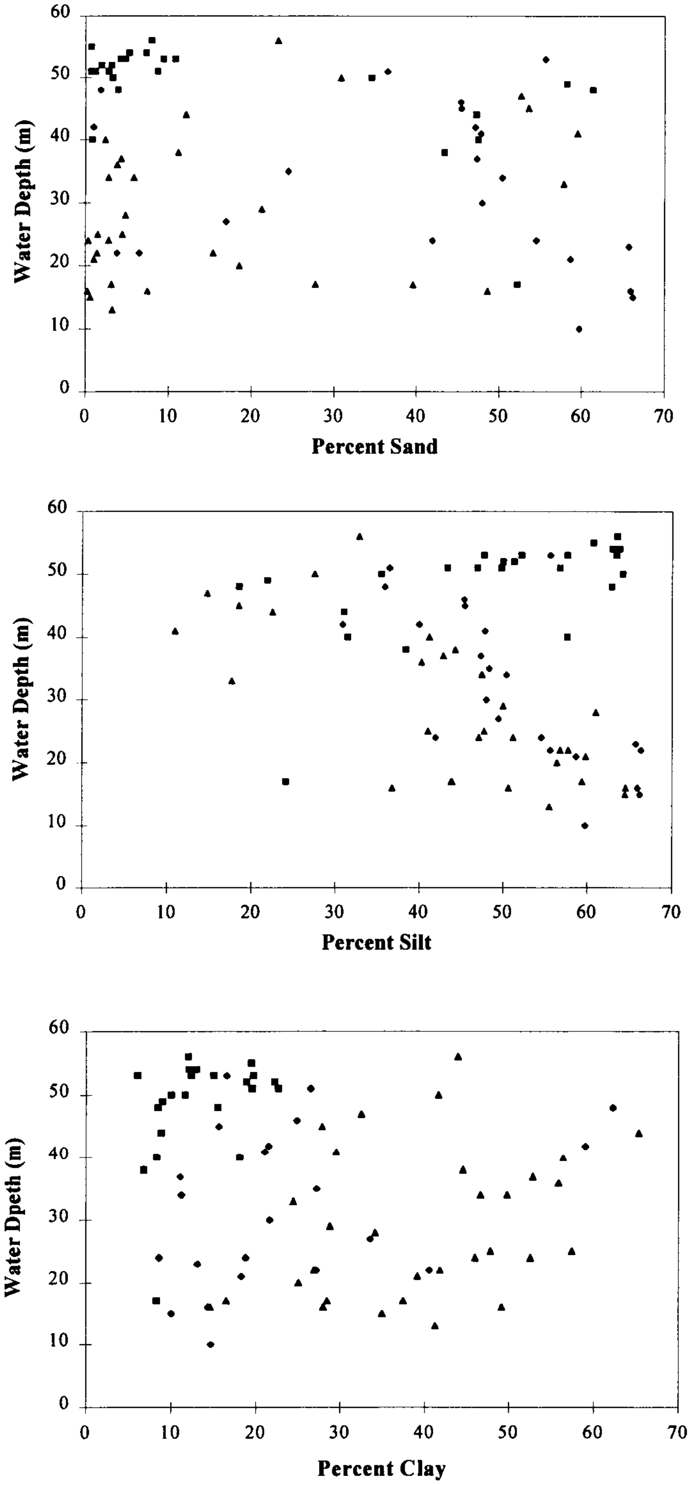


Figure 16. Correlation of grain size and water depth for surface sediments from the Chukchi (■), East Siberian (◆), and Laptev seas (▲).

Figure 17. Spatial distribution of sediment textures based on Shepard's (1954) classification.

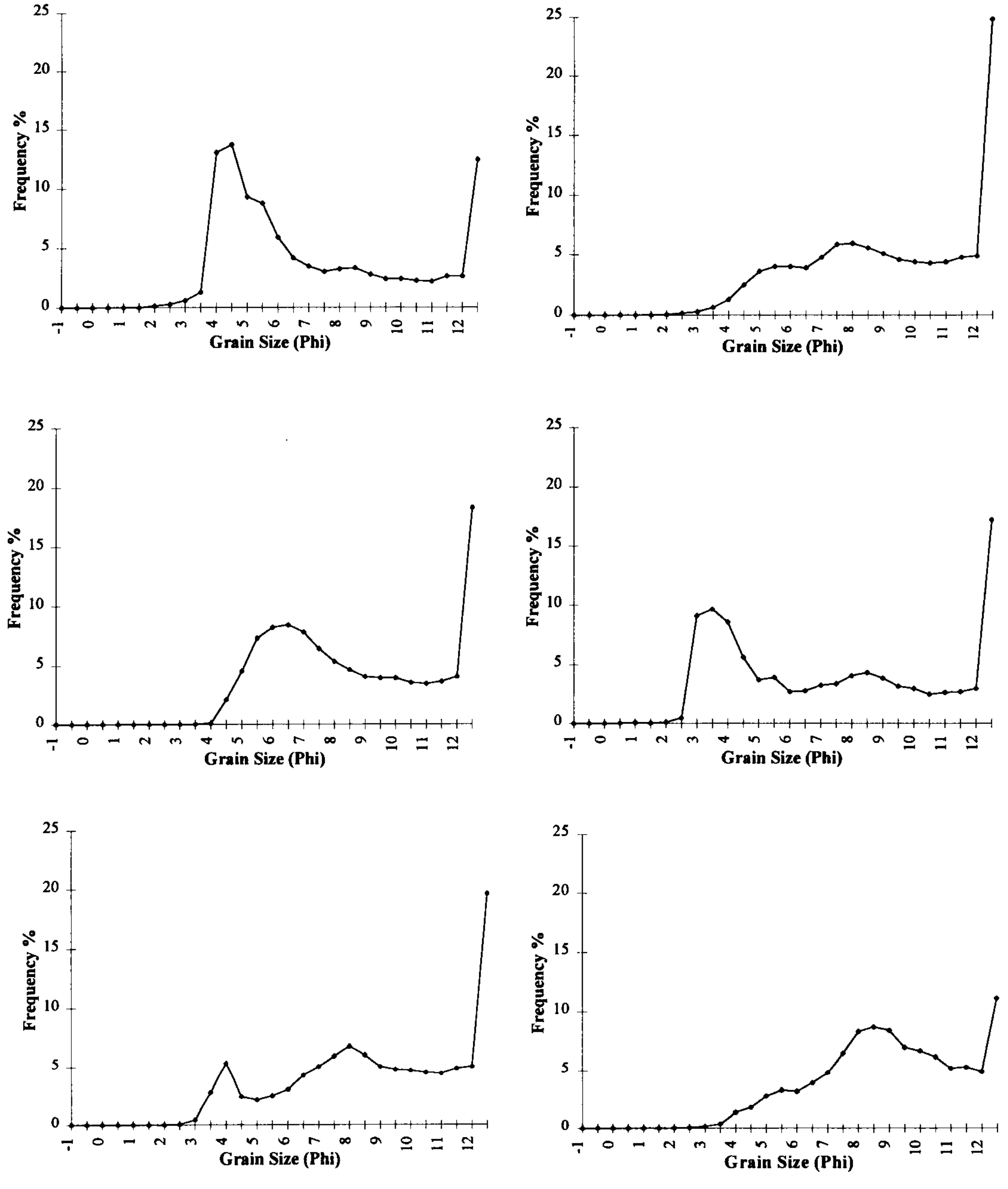


Figure 18. Examples of individual frequency curves of surface sediments that are highly skewed, bimodal, and poorly-sorted. The high percentage of >12 ϕ material measured in most samples contribute to the poor sorting of these sediments.

Eigenvalues beyond the fourth factor account for less than 2.5 % of the variability contained within the data set, so were not considered significant. The composition of each factor can be described by representative samples, samples with highest loading for each factor (Fig. 19; Table 3).

Factor 1: Factor 1 is the dominant factor accounting for 41 % of the variability among the samples. An examination of the highest loaded samples show this factor to be composed of predominantly fine silt (≥35 %) and clay (≥49 %), with minor amounts of sand (<3 %) and >12 ϕ fraction contributing between 11-26 % (Table 3). Samples of this factor have a primary mode at 8.5 ϕ with a minor secondary mode at 6.0 ϕ (Fig. 19). Representative samples occur at water depths ranging from 16-51 m (Table 3). Generally this fine-sediment (factor 1) is present at mid-depth waters in the East Siberian and Laptev seas (Fig. 20).

Factor 2: Factor 2 accounts for 27 % of the variability in the grain-size data. Representative samples for this factor all have one mode in the medium silt range at 5.5 ϕ (Fig. 19). These sediments are composed predominantly of silt (>63 %) with minor sand and a tail of fine silt and clay. These samples have <15 % >12 ϕ material and are present at depth in the central Chukchi Sea and in shallow regions of the East Siberian Sea (Fig. 20).

Factor 3: Samples rich in fine sand (>52 %) comprise this factor. Clay is the secondary component (20-33 %) and silt is the least important component (8-17 %) (Table 3). This sediment possesses a primary mode at 3.0 ϕ with 8-14 % in the >12 ϕ fraction (Fig. 19). These sediments occur in a range of water depths (17-48 m) (Fig. 21, Table 3).The highest loaded samples are present west of the Lena submarine valley offshore and at depths >40 m. This sand-rich sediment is also locally abundant at depths <20 m off the Chukota coast in the western Chukchi Sea.

Factor 4: Representative samples for factor 4 are bimodal with a primary mode at 4.0 ϕ and a secondary mode at 5.5 ϕ (Fig. 19). Sand (>47 %) is the dominant grain size of this sediment, followed by silt (30-40 %) and clay (20-30 %) (Table 3). Similar to factor 3, >12 ϕ material comprises <14 % of this sediment. Sediments of this factor are present

Table 3. Factor compositions as defined by grain size and clay mineral abundances of the five highest loaded samples for each factor.

Sample	Water Depth (m)	Loading	% Gravel	% Sand	% Silt	% Clay	% >12 phi	Illite	Chlorite	Kaolinite	Smectite
FACTOR 1	Eigenvalue = 40.6										
NW63-128	24	0.910	0.00	0.36	47.09	52.55	16.03	53	20	17	10
NW63-52	51	0.902	0.00	1.48	36.45	62.07	26.49	61	24	12	3
NW63-80	34	0.893	0.00	0.60	50.40	49.00	11.24	64	21	10	5
NW63-119	16	0.872	0.00	0.26	50.61	49.14	16.58	56	21	14	9
NW63-25	51	0.859	0.00	2.79	46.93	50.28	22.66	54	28	12	6
FACTOR 2	Eigenvalue = 27.2										
NW63-88	15	0.884	0.00	12.46	66.19	21.35	10.05	63	24	8	6
NW63-87	16	0.873	0.00	7.88	65.92	26.20	14.35	62	22	9	7
BI64-17	22	0.833	0.00	6.50	66.35	27.16	12.71	65	19	12	4
NW362-78	53	0.821	0.00	9.41	63.45	27.14	12.42	-	-	-	-
NW362-72	56	0.789	0.00	7.98	63.52	28.51	12.05	-	-	-	-
FACTOR 3	Eigenvalue = 11.7										
NW63-157	41	0.903	0.00	59.47	10.98	29.55	14.62	45	15	32	9
NW63-161	47	0.860	0.00	52.66	14.82	32.52	17.20	41	15	34	10
NW362-82	17	0.759	0.00	52.24	24.12	23.64	8.32	-	-	-	-
NW63-153	33	0.752	0.00	57.84	17.73	24.43	8.23	47	17	27	7
NW63-34	48	0.692	0.81	61.35	18.60	20.05	8.48	44	24	24	7
FACTOR 4	Eigenvalue = 14.8										
NW63-39	44	0.778	0.00	47.23	31.04	21.73	8.88	52	20	23	6
NW63-40	40	0.749	0.00	47.49	31.49	21.02	8.36	55	22	19	4
NW63-41	38	0.734	0.50	43.39	38.41	17.71	6.84	56	22	15	7
NW63-60	24	0.724	0.00	38.15	41.93	19.92	8.63	61	24	11	4
NW63-166	45	0.698	0.00	53.58	18.56	27.86	14.04	35	16	39	10

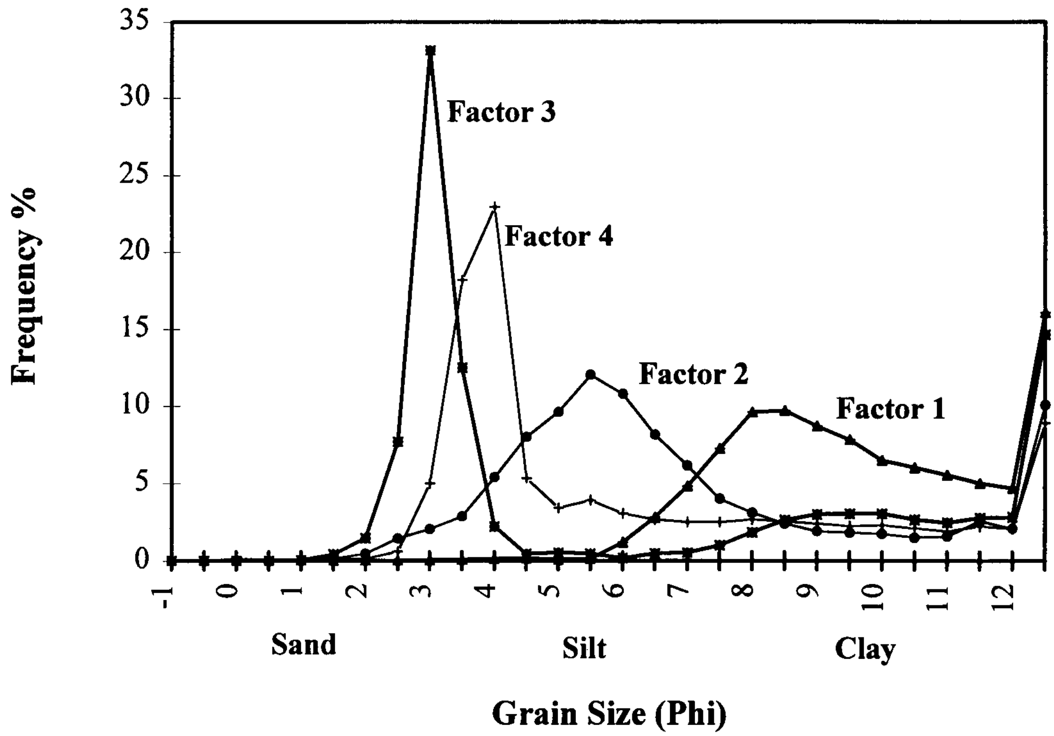


Figure 19. Grain-size frequency distributions of highest loaded samples for each factor.

Figure 20. Spatial distribution of factors 1 and 2. Shaded areas represent the regions of highest factor loadings (>0.65).

at shallow depths off the coast of Wrangel Island, at depth in the western Laptev Sea and Yana submarine valleys, as well as on Kolyma Shoal in the East Siberian Sea (Fig. 21).

3.5.2 *Clay Mineralogy*

Clay minerals on the Siberian shelf are illite, chlorite, smectite, and kaolinite. Illite, the dominant clay mineral (35-67 %) on the shelf, exhibits strong longitudinal variations (Fig. 22). Highest concentrations of illite are present throughout the East Siberian Sea (62 ±2 %), with extreme values present off the Kolyma River mouth (Table 4, Fig. 22). West of the Indigirka submarine valley into the Laptev Sea and to the east into the Chukchi Sea, mean illite concentrations decrease to 52 ±7 and 51 ±4, respectively. Illite concentrations in the Laptev Sea exhibit a strong east-west gradient, decreasing to the west from 63 % to 35 %.

In contrast, chlorite abundances in surface sediments show little east-west change across the shelf. Although chlorite varies from 14-28 % along the shelf, mean abundances of chlorite show no significant difference between the Chukchi (23 ±2), East Siberian (23 ±2), and Laptev (20 ±3) seas (Table 4). Chlorite is most abundant in the central Chukchi Sea, off the Kolyma River in the East Siberian Sea, and southeast of the New Siberian Islands (Fig. 22). Laptev Sea surface sediments show a strong decrease in chlorite abundances from east (>22 %) to west (<16 %).

Smectite concentrations range from 6-39 % and exhibit the largest spatial variability in shelf sediments (Fig. 22). Highest concentrations (up to 39 %) are found in the western Laptev Sea. Concentrations decrease sharply into the East Siberian Sea where <10 % of clay minerals in surface sediments consist of smectite. East of the Kolyma submarine valley smectite concentrations are slightly higher. Heading east into the Chukchi Sea, relative abundances of smectite increase (up to 28 %).

Kaolinite contributes between 2-11 % to shelf sediment clays (Table 4). Mean kaolinite concentrations in the Chukchi (6 ±1), the East Siberian (5 ±2), and the Laptev (9

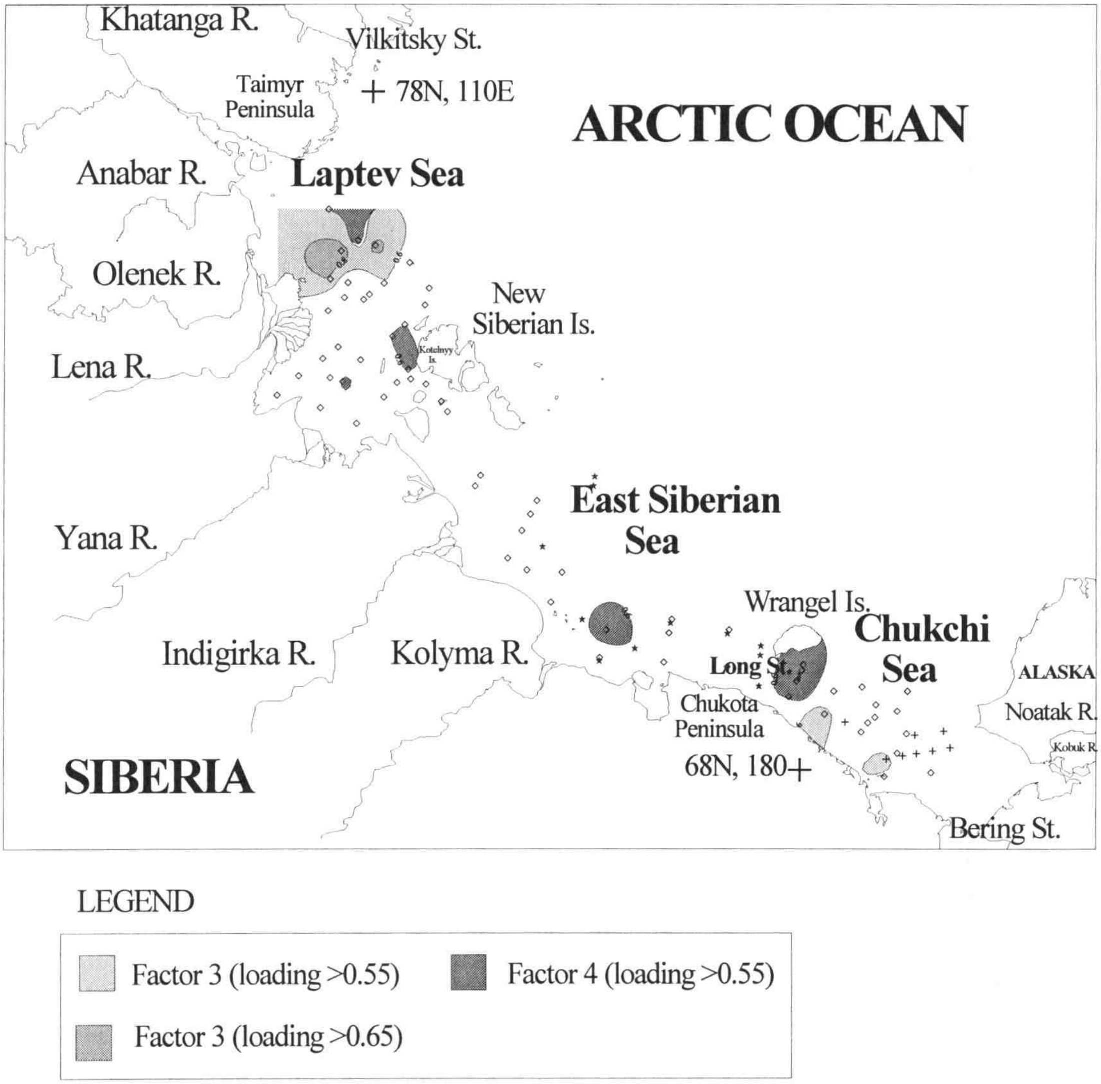


Figure 21. Spatial distribution of factors 3 and 4. Shaded areas represent the regions of highest factor loadings (>0.55).

Table 4. Range and mean clay mineral percentages of the of the clay fraction (<9 ϕ). Semi-quantitative clay abundances determined using the Biscaye method (1965).

	# Samples	Range (%)	Mean ± SD (%)
Chukchi Sea			
Illite		44-57	51 ±4
Chlorite	19	19-28	23 ±2
Smectitie		13-28	20 ±4
Kaolinite		2-7	6 ±1
East Siberian Sea			
Illite		56-67	62 ±2
Chlorite	18	19-28	23 ±2
Smectite		6-13	9 ±2
Kaolinite		3-8	5 ±2
Laptev Sea			
Illite		35-63	52 ±7
Chlorite	28	14-25	20 ±3
Smectite		7-39	20 ±9
Kaolinite		6-11	9 ±1

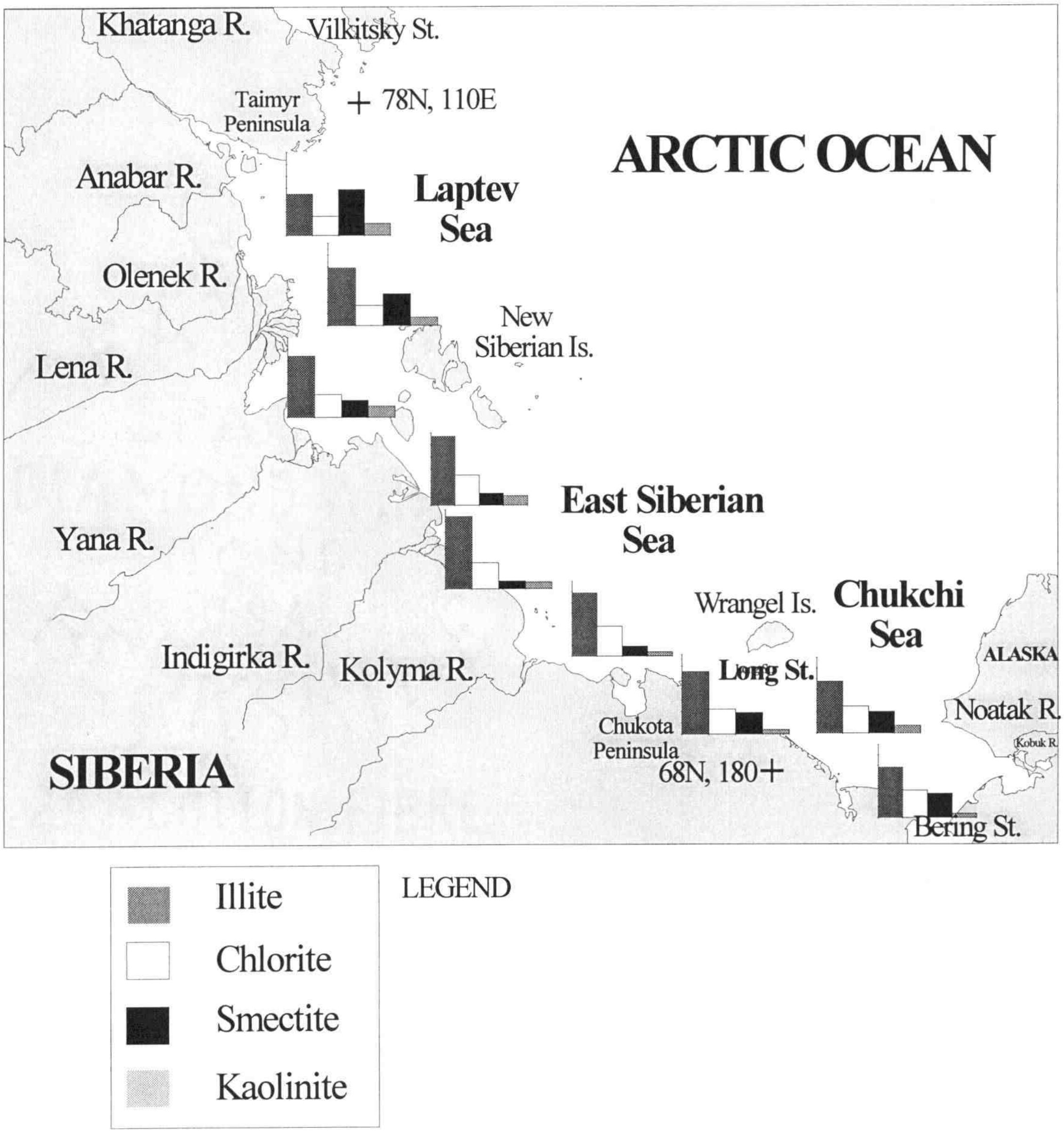


Figure 22. Histograms showing relative clay mineral abundances for representative samples calculated for the <9 ϕ size fractions using the method of Biscaye (1965).

±1) seas indicate that kaolinite is fairly constant across the shelf. Elevated (11 %) kaolinite concentrations are observed in the Laptev Sea, east of the Lena delta (Fig. 22).

X-ray diffraction of the >12 ϕ material from representative samples for each sea shows a marked increase in the relative abundance of smectite, the finest clay mineral. This increase in smectite in the East Siberian Sea is accompanied by a proportional decrease in chlorite and kaolinite. The overall composition of the >12 ϕ material is similar to the <9 ϕ fraction. Illite is the predominated clay in the East Siberian Sea, whereas increased smectite accompanied by decreased illite and chlorite dominate in the Laptev and Chukchi seas. Although reduced from the clay fraction, quartz and feldspar were observed in the >12 ϕ fraction diffractograms. TEM analysis of representative samples showed the East Siberian and Laptev sea fine fraction (<10 ϕ) to be composed entirely of clay minerals. In contrast, Chukchi shelf fine sediments are bimodal, composed of low-density, coarse diatom frustules and fine, dense clay particles (Mammone et al., 1997a).

3.6 DISCUSSION

3.6.1 *Chukchi Sea*

The grain size of surface sediments on the Chukchi Sea shelf is controlled by source, currents, and biological surface productivity. Chukchi Sea sediments can be divided into two sediment groups, silt- and clay-rich sediments (factors 1 and 2), in the central depression and fine sands (factor 3 and 4) adjacent to the Chukota Peninsula and Wrangel Island coastlines. Clayey-silts are present at depth in the east-central depression and become more clay-rich to the west. These sediments (factor 1) also contain high concentrations of >12 ϕ material (>20 %).

Sources of fine sediment to the Chukchi shelf are inflow of sediment through the Bering Strait, inflow of sediment through the Long Strait from the East Siberian Sea with currents, biological productivity, and erosion of coastal headlands. The most likely source of the wide-spread clay and silt in the central Chukchi Sea is inflow of fine sediment through the Bering Strait. Coarse sand and silt deposited on the Bering Strait seafloor by northward flowing currents through the Strait, fine to clayey-silts and silty-clays to the northwest (Creager, 1963; McManus et al., 1969; Logvinenko and Ogorodnikov, 1980). Surface and near-bottom currents decrease markedly in the central Chukchi region (McManus et al., 1969; Coachman and Aagaard, 1974), where medium-grained (5.5 ϕ mode) silt (factor 2) is mapped (Fig. 20). A strong relationship, therefore, exists between current velocity of Bering Strait water as it flows through the Chukchi Sea and grain size.

High smectite concentrations (up to 28 %) in the central Chukchi Sea also suggest a southern source to Chukchi shelf sediments (Naidu et al., 1982; Naidu and Mowatt, 1983; Darby et al., 1989) (Fig. 21). The Yukon River and Aleutian Islands supply significant amounts of smectite to the Bering Sea which is then flushed through the Bering Strait by currents and deposited in the central Chukchi Sea. Naidu et al. (1982) similarly observed high concentrations of smectite (20-30 %) in Chukchi Sea surface sediments derived from water and sediment flowing though the Bering Strait.

These fine sediments (factor 1 and 2) also correlate well with regions of high surface productivity fueled by nutrient-rich Bering and Anadyr waters entering through the Bering Strait (Sambrotto et al., 1984; Grebmeier, 1993; Grebmeier et al., 1995; Walsh, 1995), suggesting a fine biogenic component. High total organic carbon (>2 %) and biogenic silica (up to 14 %) concentrations in shelf sediments reflects this high surface productivity (Mammone et al., 1997a). Transmission electron microscope analysis of the <10 ϕ particles reveals the fine fraction to be a mixture of clay platelets and diatom frustules (Mammone et al., 1997a), supporting the conclusion that biogenic matter contributes a fine component to shelf sediments.

Local rivers draining Alaska into the eastern Chukchi Sea do not contribute significantly to shelf sediments in the central and western regions. Coarse sand and gravel supplied by local rivers (Noatak and Kobuk) are found close to the Alaskan shore, trapped by an extensive barrier island system (McManus et al., 1969; Phillips and

Coglan, 1987). C/N ratios indicative of terrigenous organic carbon sources suggest that Alaskan rivers may contribute small quantities of sediment to the deep central Chukchi Sea (Mammone et al., 1997a). Yukon River water entering through the Bering Strait is also a source of terrigenous organic matter to these regions (Naidu et al., 1989).

Fine sand (factor 3) is present along the Siberian coast at depths ranging from 17 to 48 m (Fig. 21). These sediments are comprised of >50 % sand with a primary, well-sorted mode at 3 ϕ (Fig. 21). Heavy mineral analysis of sediments in the region between Wrangel Island and the Siberian coast indicates multiple sediment sources to this region, although high concentrations of orthopyroxene grains indicate that the Siberian coast and Wrangel Island are the principal sources of coarse sediment (Silverberg, 1972; Naugler et al., 1974). Clinopyroxene concentrations likely reflect the influence of the Kolyma River (Naugler, 1967; Silverberg, 1972).

East Siberian coastal water (SCW) entering the Chukchi Sea through the Long Strait may supply clay-sized sediment to the western Chukchi. Increase illite accompanied by decreased smectite result from the influence of the Chukota Peninsula, Wrangel Island, and East Siberian Sea. East Siberian Sea sources contain abundant illite (59-67 %) and low amounts of smectite (<13 %).

Coarse silt (factor 4) is present off the southeast coast of Wrangel Island (Fig. 21). These sediments have a major mode at 4 ϕ and a secondary mode at 5.5 ϕ. Because East Siberian shelf sediments show a strong mode at 5.5 ϕ, possibly they may represent a western source of silt to the Wrangel Island region. Elevated concentrations of garnet and epidote indicate that Wrangel Island is an important source of coarse terrigenous detritus locally (Naugler, 1967; Naugler et al., 1974).

The entire western Chukchi Peninsula-Wrangel Island region is characterized by a mixture of sand, silt, and clay possibly resulting from multiple source regions (Fig. 17). Southeast of Wrangel Island is also the only region along the Siberian coast where gravel is present in small quantities (<1 %). An alternative mechanism that can explain this texturally varied sediments is the deposition of modern silt and clay on relict sand and gravel which is then mixed by strong current activity, ice gouging, or bioturbation. The well-sorted, rounded nature of the coarse fraction of these sediments suggest a mature source or intense deposition and reworking , possibly when sea-level was lower (Naugler et al., 1974). The presence of similar deposits along the entire Alaskan, Siberian, and Wrangel Island coastlines supports a relict source for these sediments when sea level was approximately 20-30 m lower (Creager, 1963; McManus et al., 1969; Logvinenko and Ogorodnikov, 1980).

3.6.2 *East Siberian Sea*

Silt- and clay-rich sediments (factor 1 and 2) supplied by the Kolyma and Indigirka rivers are generally dispersed offshore in a northeasterly direction roughly following the surface currents and bathymetry. Sediments fine offshore in the Kolyma and Indigirka submarine. This shift from silt-rich (factor 2) to clay-rich (factor 1) sediments offshore may be the result of distance from source (rivers) and possibly reduced current activity. The percentage of >12 ϕ also increase offshore at depth by a factor of 2, supporting a lowered energy regime. Coarsest sediments (factor 3) are present on Kolyma shoal (Fig. 21).

Clay-rich sediments (8.0 ϕ mode, >49 % clay, factor 1) are important in the Kolyma and Indigirka submarine valleys, as well as offshore at depth in the East Siberian Sea (Fig. 20). Similar to the Chukchi Sea, these fine-grained sediments have high concentrations (>24 %) of >12 ϕ material, a secondary silt component, and minor sand. Mean clay abundances indicate that illite (62 ±2) is the dominant clay mineral followed by Fe-rich chlorite (23 ±2). Mean clay abundances in shelf sediments are similar to mean abundances found in the Kolyma River (illite-59 %; chlorite-27 %) and the Kolyma-Indigirka delta (illite-71 %; chlorite-21 %), suggesting these rivers are an important source of fine-grained sediment to the East Siberian shelf (Silverberg, 1972).

Shallow regions close to shore are silt-rich (>65 %, factor 2) and are characterized by a primary mode at 5.5 ϕ, increased sand contents, and reduced clay percentages (<30 %), relative to offshore fine sediments (factor 1). A likely source for these sediments is the

'Ice-complex' or 'Edoma' which is permafrost composed of massive ground ice and frozen soil pillars formed in the late Pleistocene. The Ice-complex is present along major rivers of Siberia and along cliffs of the Siberian coast (Fukuda, 1994). Presently, the Ice-complex undergoes intense thawing (5 m/yr) during the summer (Saijo et al., 1994). Sediments from the Ice-complex show distinct modes at 3.0 and 5.5 ϕ (Nagaoka, 1994), suggesting that it may be a source of silt (factor 2; primary mode at 5.5 ϕ) on the East Siberian shelf.

Although the Kolyma Shoal is not well defined bathymetrically, texturally it is defined by fine sand (Fig. 21). Here grain-size frequencies still have a mode at 5.5 ϕ, but the grain size shifts to a primary mode at 4.0 ϕ and to >35 % fine sand. The occurrence of this coarse material at about 20 m water depth is difficult to explain, but may reflect the occurrence of ice-gouging observed on shoals in the East Siberian Sea (Reimnitz et al. , 1978) or increased current velocities.

High percentages of clinopyroxenes indicate that the Kolyma River is the dominant supplier of coarse sediment east of the Kolyma submarine valley, whereas to the west low concentrations of heavy minerals mixed with garnet-zircon assemblages indicate the Indigirka and New Siberian Sea region as sediment sources (Naugler et al., 1974).

3.6.3 *Laptev Sea*

Grain-size distributions show little correlation with water depth or distance from the coast in the Laptev Sea. The spatial distribution and composition of surface sediments are instead influenced primarily by sea-ice production, export, and melting. Intense bioturbation may also play an important role in mixing shelf sediments.

The Laptev Sea can be divided into three distinct regions according to texture and mineralogy (Fig. 12 and 20). Sediments around the New Siberian Islands on Novisibirsk and Stolbovoy shoals are a mixture of fine sand (factor 4) and silt (factor 2). High ilmenite and magnetite concentrations indicate that the New Siberian Islands are the source of the fine sand in this region (Stein and Korolev, 1994). Relatively low concentrations of lithics and plagioclase and rounding of grains suggest reworking, indicating a possible relict source for this fine sand (Naugler, 1967; Silverberg, 1972).

Although several sediment types exist in the eastern Laptev Sea, clayey-silts (factor 1) predominate at shallow depths nearshore and offshore at depth in the Lena and Yana submarine valleys (Fig 9). Sediments in this region have high concentrations of >12 ϕ material (>16 %) with less than 1 % sand. The Lena and Yana rivers supply most of the silt and clay to the region east of the Lena submarine valley (Hass et al., 1995?). The spatial distribution of these sediments closely parallels the distribution of terrigenous organic carbon supplied by the Lena river (Mammone et al., 1997a), suggesting that organic carbon adsorbed onto and transported by fine-grained particles supplied by the Lena and Yana rivers. Clay mineral assemblages resemble East Siberian shelf sediments with slightly elevated smectite and kaolinite abundances. Sources of smectite and kaolinite are rivers draining a flood-basalt complex to the marine sedimentary sequences present on the New Siberian Islands, respectively.

On the shoal between the Yana and eastern Lena submarine valleys, grain sizes shift to silty-clays with higher percentages of >12 ϕ material (>24 %) (Fig. 18 and Fig. 19). Dehn et al. (1995) attributed this shift to a lowered current regime away the eastern Lena River. The largest influx of river water and sediment (Timokhov, 1994; Alabyan et al., 1995), results in strengthened currents (up to 0.05 m/s) east of the Lena River relative to regions north of the Lena River (0.015-0.02 m/s) (Hass et al., 1995).

The western Laptev Sea is composed of a distinct mixture of well-sorted and rounded fine sands (factor 3 and 4), with secondary amounts of clay (>25 %) and silt (<15 %). In contrast, fine sands (factor 3 and 4) in the East Siberian and Chukchi seas are less rounded and contain nearly equal amounts of clay and silt. Scanning electron microscope analysis of the fine sands shows well-rounded quartz and feldspars and minor rock fragments, suggesting a mature source region or extensive reworking by wave or current activity.

Sea-ice processes may play an important role in explaining this distinct grain size distribution. The Laptev Sea produces and exports more ice than any other region in the

Arctic, thus ice processes may play an important role in sediment transport and distribution, particularly in the western Laptev Sea (Dethleff, 1995; Pavlov and Pfirman, 1995). Intense water-column turbulence and suspension freezing in perennial polynyas may redistribute large quantities of sediment within and out of this region (refs). Eicken et al. (1997) suggested that ice rafting of sediments during the melt season may be as important as transport of sediment by currents. Thus, the distribution and composition of modern surface sediments may be highly influenced by the release of sediment as ice melts over the Laptev shelf. Gouging by sea ice, observed by Kassens (1994) in the vicinity of the Anabar delta, may also play an important role by mixing older sand-rich sediments that occur 15-30 cm below the surface with modern mud (Silverberg, 1972).

Smectite (up to 39 %) is supplied to the Kara and western Laptev sea shelves by rivers (Ob, Yenisey, Khatanga) draining a large flood-basalt complex in western Siberia south of the Taimyr Peninsula. Washner (1995) attributed the high smectite concentrations in the western Laptev Sea to sediment delivered by the Khatanga River, as well as through the Vilkitsky Strait from the Kara Sea. Sediment may also enter the Laptev Sea in sea ice from the Kara Sea. The net flux of ice through the Vilkitsky Strait from the Kara to the Laptev sea is about 50 km^3/yr (Pavlov and Pfirman, 1995). Sediments on the entire Laptev shelf all contain elevated concentrations of smectite, reflecting western sources dispersed by eastward-flowing currents.

3.7 CONCLUSIONS

In general, surface sediments on the Siberian shelves are predominantly silty-clays and clayey-silts supplied by local rivers. Fine sands are generally confined to shallow regions proximal to island and coastline sources. In contrast, fine sand mixed with modern clay and silt is present at depth offshore in the western Laptev Sea. Sea-ice transport and ice-gouging may account for this texturally variable sediment.

Silt and clay dispersed by strong currents through the Bering Strait are deposited in the central Chukchi Sea. Clayey-silts fine to silty-clays as currents decrease in the western Chukchi Sea. The presence of high concentrations of smectite from Yukon and

Aleutian sources, accompanied by low illite, also indicates that sediment flushed through the Bering Strait is the source of sediments in the central Chukchi Sea. In contrast, clay and heavy minerals from the western Chukchi region suggest the Kolyma River, Chukota coast, and Wrangel Island. Deposition of modern silt and clay on relict gravel and sand result in texturally mixed, bimodal sediments. Biogenic components, biogenic silica and marine organic carbon, also contributes up to 16 % by weight to surface sediments in the central Chukchi Sea, reflecting surface productivity patterns.

Silt and clay (illite >59 %, chlorite >21 %) supplied by the Kolyma and Indigirka rivers to the East Siberian Sea are generally dispersed by currents offshore in a northeasterly direction roughly following the bathymetry. Fining offshore sediment distributions in this region exhibit dispersal patterns expected on shelves with large riverine input and no ice. River input is the dominant source of sediment to this region, indicated by clay mineral abundances in shelf sediments which resemble local river sources.

Laptev Sea sediments exhibit a strong east-west gradient both texturally and mineralogically. Grain-size distributions exhibit spatial distributions different than observed on river-dominated shelves in non-polar regions. Surface sediments are strongly influence by ice transport, particularly in the western Laptev Seas where intense production and export of sea ice occurs. Transport and release of particles by sea-ice melting, gouging, and turbulence, resuspension, and freezing of fine particles in coastal polynyas result in sediment distributions clearly independent of water depth, distance from source regions. Clay and heavy mineral analysis of Laptev shelf sediments indicate that the Khatanga River and other western sources contribute to the region west of the Khatanga submarine valley. In the eastern Laptev Sea, illite- and pyroxene-rich assemblages indicate that the Lena is the main source of sediment to this region. Eastward-flowing surface currents also supply fine-grained sediments from the west, indicated by elevated smectite concentrations derived from a flood-basalt complex on the Taimyr Peninsula.

Overall, clay mineral and grain-size analysis of surface sediments suggest varied depositional regimes controlled by sea ice, currents, surface productivity, source regions, as well as bathymetry. Sediments supplied by rivers in the East Siberian Sea and eastern Laptev Sea tend to fine offshore, suggesting that sediment tends to move offshore rather than along shore. Concentrations of smectite decreases rapidly away from source areas on the shelf, also supporting observations that large quantities of sediment tend not to disperse along the shelf, but are deposited and redistributed locally and transported offshore to the central Arctic Basin.

CHAPTER 4: CONCLUSIONS

The dominant biogenic component of Siberian shelf surface sediments is biogenic silica, with secondary organic carbon, and minor carbonate. Sediment biogenic silica contents show a strong east-west gradient with highest values in the western Chukchi Sea. Here, nutrient-rich waters from the Gulf of Anadyr enter through the Bering Strait and fuel diatom productivity. The spatial distribution of biogenic silica reflects surface productivity, hydrographic, and ice conditions. Biogenic silica may serve as tool for reconstructing ice-edge positions.

Regional differences in the distribution of organic matter is the result of two distinct sources, marine and terrigenous. A mixing model using C/N ratios was used to quantify the relative contribution of marine and terrigenous organic carbon to surface sediments. Results of the mixing model show a strong east-west shift in source and sink of organic carbon, with increased refractory organic carbon delivered by local rivers to the west. Chukchi shelf sediments contain less than 10 % terrigenous carbon, whereas sediments from the Laptev shelf may contain up to 32 % terrigenous organic carbon. Variations in shelf sediment C/N ratios, supported by isotopic data, may have implications for studying changes in river supply and Bering Strait inflow resulting from sea-level and climate fluctuations.

In general, surface sediments on the Siberian shelves are predominantly silty-clays and clayey-silts supplied by local rivers. Fine sands are generally confined to shallow regions proximal to island and coastline sources. In contrast, fine sand mixed with modern clay and silt is present at depth offshore in the western Laptev Sea. Sea-ice transport and ice-gouging may account for these texturally variable sediments.

The presence of high concentrations of smectite from Yukon and Aleutian sources, accompanied by low illite, indicates that sediment flushed through the Bering Strait is the source of silt and clay to the central Chukchi Sea. In contrast, local rivers that drain Siberia are the predominant source of fine sediment to the East Siberian and Laptev sea shelves. In the East Siberian Sea, sediments are generally dispersed by currents offshore in a northeasterly direction roughly following the bathymetry. Fining offshore sediment distributions in this region exhibit dispersal patterns expected on shelves with large riverine input and no ice.

Laptev Sea sediments exhibits a strong east-west gradient both texturally and mineralogically. Grain-size distributions exhibit spatial distributions different than observed on river-dominated shelves in non-polar regions. Surface sediments are strongly influence by ice transport, particularly in the western Laptev Seas where intense production and export of sea ice occurs. Transport and release of particles by sea-ice melting, gouging, and turbulence, resuspension, and freezing of fine particles in coastal polynyas result in sediment distributions clearly independent of water depth, distance from source regions

Overall, biogenic, clay mineral, and grain-size analysis of surface sediments suggest varied depositional regimes controlled by sea ice, currents, surface productivity, source regions, as well as bathymetry. Spatial patterns of grain size, clay mineralogy, and C/N ratios suggest that sediment disperse offshore rather than along shore in the East Siberian and Laptev seas. In contrast, the Chukchi Sea shelf is a repository for silt-rich sediment supplied by northward-flowing currents through the Bering Strait and clay-size biogenic matter from marine surface productivity.

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