# A key source area and constraints on entrainment for basin-scale sediment transport by Arctic sea ice

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**Abstract.** Combining field measurements, remote sensing data and numerical modelling, a key site for entrainment and dispersal of sediments throughout the Arctic has been identified near the New Siberian Islands. At this location, the relevant boundary conditions are shown to be highly conducive to sediment entrainment and export. The total ice-bound sediment export of 18.5 x $10^6$ t for an entrainment event documented in 1994/95 is of the same order of magnitude as annual sediment supply to the deep sea sector of the Eurasian Arctic and the Greenland Sea. Satellite imagery from different years and ancillary data indicate that ice advection from this source may play an important role in sedimentation downstream in the Transpolar Drift.

## Introduction

Rafting of sediments by Arctic sea ice is surmised to be a major mode of particulate transport in the Arctic Ocean at present [*Pfirman et al.*, 1990, *Hebbeln and Wefer*, 1991, *Reimnitz et al.*, 1992] and during the past 5 Ma [*Clark and Hanson*, 1983, *Bischof and Darby*, 1995], with potential importance also for the dispersal of pollutants [*Pfirman et al.*, 1995]. Given the sparsity of mostly opportunistic shipboard observations [*Nürnberg et al.*, 1994, *Eicken et al.*, 1997] and problems in inferring source areas from sedimentological data [ *Bischof and Darby*, 1997, *Pfirman et al.*, 1997], there is a need for comprehensive, quantitative assessments of entrainment and transport to help interpret Arctic sediment records and delimit the geological and climatological impact of sea-ice rafting of particulates. The present study focusses on entrainment and export of sediments by sea ice in the East Siberian Arctic. A combination of field measurements, analysis of remote sensing data and numerical modelling has been employed to estimate the quantitative importance of individual entrainment events, elucidate constraints on sediment entrainment and assess the importance of sea-ice rafting of particulates in a wider context.

## Highly sediment-laden sea ice in the East Siberian Arctic

The Laptev Sea has been identified as a region of high ice production and potential source of sediment-laden sea ice. During two expeditions in July to October 1995, field measurements based on tentative identification of heavily sediment-laden sea ice in Advanced Very High Resolution Radiometer (AVHRR) satellite imagery were carried out in this sector of the Siberian Arctic (Fig. 1, Fig. 2). Aerial surveys and ground-truth data revealed high sediment concentrations (geometric mean core-averaged concentration of suspended particulate matter, SPM, in 11 cores of 191.6 g $m^{-3}$, median 141.6 g $m^{-3}$, Table 1) throughout a highly deformed first-year ice cover. The assessment of ice age (<1 year) is supported by the sediment distribution, ice morphology as well as ice salinity measurements and stratigraphic analysis (for methods see *Eicken* [1998]). The latter also indicates that sediment entrainment was associated with frazil ice formation, with the high mean ice thickness of 3.23 ± 1.79 m (8 profiles between 50 and 200 m long) as a result of rafting and ridging of decimeter-thick floes.

The highly sediment-laden ice is significantly depleted in oxygen-18 ($\delta^{18}O$ mode of –3.5 ‰, 10 cores, Fig. 1) compared to sediment-laden ice further to the West (Fig. 2, central region with mode 0.5 ‰, 11 cores, with a median SPM of 23.8 g $m^{-3}$, 10 cores, and sediment composition similar to that of the westernmost region), indicating a substantial contribution by river discharge [*Bauch et al*., 1995, *Eicken et al*., 1997]. Parent water-mass salinities have been derived for individual sediment-laden ice segments from a mixing model. The composition of Atlantic and zero-salinity Lena water is based on coastal ice and water samples (Fig. 1) and data by *Bauch et al*. [1995] (Fig. 3), with a growth-rate dependent fractionation coefficient estimated as 1.5 ‰ [*Eicken*, 1998]. The stable-isotope data and the clay-mineral composition of sediments obtained from ice floes at the locations shown in Fig. 1 suggest a source area in the illite-rich eastern Laptev Sea or near the New Siberian Islands [*Silverberg*, 1972, *Lindemann*, 1999]. While clay minerals do not allow us to exclude the East Siberian shelf as a source area, the surface hydrography of the southern Laptev Sea in September 1994 and the comparatively small discharge by eastern Siberian rivers, support ice formation in fresher waters that extended northeast from the Lena Delta towards the New Siberian Islands (Fig. 2).

## Reconstructing sediment entrainment and subsequent dispersal by sea ice

To help constrain the estimate of ice origin, backtrajectories were obtained from a large-scale dynamic/thermodynamic sea-ice model [*Kreyscher et al*., 1997] for the period April to July 1995, when the sediment-laden ice drifted in deeper waters at greater distance from the coast (Fig. 2). Since interaction with the coastline limits model predictions, the October-March trajectories have been derived from 85 GHz SSM/I passive microwave satellite data (National Snow and Ice Data Center, Boulder) through tracking of features such as leads, large ice floes and deformed ice distinguished by emissivity contrasts (*Kolatschek* [1999]; see also *Alexandrov* *et al.* [in press]; the total displacement error based on monthly motion vectors is estimated as 90 to 180 km at maximum). The reconstructed trajectories indicate ice formation and sediment entrainment to have occurred in the vicinity of the New Siberian Islands in less than 30 m water depth (<17 m south of the islands) during September/October 1994 (Fig. 2), which is in good agreement with the interpretation of the field data. Ice formation and export were promoted by winds averaging 7.1 ± 3.0 m $s^{-1}$ (Kotelnyy weather station data, September 15 to October 31 1994, with 10 % of all observations >10 m $s^{-1}$ and 74 % from the southerly sector). Model simulations by *Lyard* [1997] indicate that tidal current velocities at this location, peaking at >0.1 to >0.2 m $s^{-1}$, rank among the highest in potential source areas of Arctic sediment-laden ice, thereby enhancing resuspension and entrainment of sediments. Along with autumn freeze-up storms and storm surges [*Ashik and Vanda*, 1995], tidal forcing also explains the dynamic thickening [*Kowalik and Proshutinsky*, 1994] and removal of ice observed in ice-core stratigraphies and remote-sensing data. Ice-floe trajectories and SSM/I scenes for fall freeze-up indicate that this new ice was advected offshore east of New Siberian Island and in part extruded through Blagoveshchenskiy Strait (Fig. 2). The latter is also supported by ice stratigraphic and thickness data, indicative of dynamic thickening through multiple rafting events.

A further factor maximizing ice formation and sediment resuspension are the surface water salinities close to the point of coincident density maximum and freezing point at 24.7 psu (Fig. 3). Thus, substantial nighttime ice formation during early freeze-up as a result of radiative cooling (also observed in AVHRR and Okean Radar imagery in fall of 1995 in the study area) is promoted up to the point where salt rejection raises salinities above 24.7 psu, with convective overturning allowing for resuspension of bottom sediments. Convective instabilities at the margin of the plume may contribute further to sediment entrainment [*Dmitrenko et al*., 1999]. Export of sediment-laden ice formed later in the season is limited, since circulation stagnates once the ice becomes landlocked [*Rigor and Colony*, 1997].

**Assessing the importance of ice rafting events**

Previous attempts at estimating transport by ice rafting were hampered by the patchy occurrence of sediment-laden ice. In order to overcome these limitations, the extent of sediment-laden ice has been mapped with a multispectral classification technique based on AVHRR data covering the entire study area [*Kolatschek*, 1999]. From coincident ground measurements of spectral albedo, SPM data, aerial photography and SPOT satellite imagery, spectral endmembers for different ice classes have been derived for the AVHRR visible-range frequency bands (channels 1 and 2). Sensitivity studies with a radiative-transfer model [*Light et al*., 1998] lend further support to this approach. Based on the classification of AVHRR data and ground measurements of sea-ice SPM, the total sediment load has been derived as $18.5 \times 10^6$ t (Fig. 2, Table 1).

To put this assessment into perspective, it has been compared with estimates of the current sedimentation rates in the Eurasian Arctic Basin and the Greenland Sea, where mass fluxes range between 2 and 10 g $m^{-2}$ $yr^{-1}$ [*Bischof and Darby*, 1997, *Nørgaard-Pedersen et al*., 1998] and around 20 g $m^{-2}$ $yr^{-1}$ [*Eisenhauer et al*., 1990], respectively. Distributing between 65 and 80 % of the total sediment load ($18.5 \times 10^6$ t) throughout $3 \times 10^6$ $km^2$ in the Transpolar Drift (based on estimates of sediment loss from sea ice during summer melt by *Freitag* [1999]) and depositing the remaining 20 to 35 % over $0.5x10^6$ $km^2$ in the ice-covered Greenland Sea, results in mass fluxes for a single year of 4 to 5 g $m^{-2}$ $yr^{-1}$ and 7 to 13 g $m^{-2}$ $yr^{-1}$, respectively. Owing to significant uncertainties in the derived sediment loads and Arctic Basin sedimentation rates, these numbers can merely provide a first, rough estimate of the potential importance of single export events and their role in the sediment budget of the Arctic Ocean.

While longer time series are required to improve this assessment, the combination of field measurements, remote-sensing data and modelling clearly indicates the waters surrounding the New Siberian Islands to be a unique site, potentially of basin-wide importance, for present-day sediment entrainment and export. Sediment supply from coastal erosion, supplemented by long-range transport from the Lena Delta, is at a maximum in this part of the Laptev Sea and amounts to at least $20\text{-}40x10^6$ t $yr^{-1}$ [*Gordeev et al*., 1996, *Are*, 1999]. Shallow water depths, wind and tidal forcing, and lowered surface salinities promote sediment entrainment as well as ice production and export in early fall. Analysis of satellite imagery for 1965 and 1994-1997 and field observations in 1992 [*Dethleff et al*., 1993] and 1994 [*Anderson*, pers. comm., 1998] northeast and south of the New Siberian Islands indicate that comparable events have occurred frequently. Less definite indications of the importance of this region have also been provided by sedimentological and drifting buoy data [*Pfirman et al*., 1997]. The high illite content in the clay fraction of surface sediments downstream in the Transpolar Drift matches those found in the source area; it contrasts with lower illite fractions in sediments from the Kara and western/central Laptev Seas [*Pfirman et al*., 1997, *Berner and Wefer*, 1994].

## Conclusions

Based on this analysis, we hypothesize that present-day lithogenic sedimentation in the Eurasian Arctic is significantly influenced by sea-ice rafting of particulates originating in the vicinity of the New Siberian Islands. However, placing events such as the one portrayed in this study in the larger context of Arctic Ocean sedimentation requires a more comprehensive approach integrating process studies, modelling and sedimentological analysis. Attributing basin-wide importance to sediment entrainment at few key sites such as the New Siberian Islands is commensurate with the patchy distribution of sediment-laden ice [*Pfirman et al*., 1990, *Nürnberg et al*., 1994], corresponding to the temporal and regional limitation of ice production, entrainment and export. While such patchiness may restrict generalizations based on individual studies (including this one), the present work also demonstrates that a combination of field measurements, remote sensing and modelling can help resolve this dilemma by improving and extending the scant database of present-day sea-ice transport of particulates.

The massive release of particulates over a comparatively small area during summer ice melt results in a high sedimentation-rate variability on short time scales and explains the order-of-magnitude differences in ice-derived lithogenic fluxes observed in sediment traps from the Greenland Sea [*Hebbeln and Wefer*, 1991, *Berner and Wefer*, 1994]. The trajectory shown in Fig. 1 demonstrates such far-field transport linkages between the eastern Siberian Arctic and the Nordic Seas. Domination of ice-derived sedimentation by a small number of source areas of disproportionate importance greatly increases its variability on geologic time scales. Hence, intermittent changes in the sedimentation regime of the Arctic Basin, apparent in sediments from the central Arctic Ocean [*Spielhagen et al*., 1997, *Nørgaard-Pedersen et al*., 1998], may well be due to changes in the balance of processes controlling entrainment and export at confined sites such as the New Siberian Islands. Recent studies have shown changes in atmospheric circulation in this region and a corresponding decrease in ice extent [*Maslanik et al*, 1996]; future work will have to elucidate whether the sedimentation history in the Arctic Basin provides information on past variability of land-ocean-atmosphere interaction in such a key location.

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**Table 1: Areal extent and sediment load of ice classes derived from remote-sensing and ice-core SPM data**

| *Ice type* | *Area, km²* | *Sed. load, $10^6$ t* Minimum[a] | Best estim.[b] | Maximum[c] |
|---|---|---|---|---|
| Open water, melt puddles | 230,000 | 0 | 0 | 0.4 |
| Clean ice or low sediment load | 309,000 | 0 | 0 | 0.5 |
| Medium sed. load | 63,000 | 8.8 | 5.5 | 11.2 |
| High sed. load | 21,000 | 3.0 | 13.0 | 20.4 |
| Total | | 11.8 | 18.5 | 32.5 |

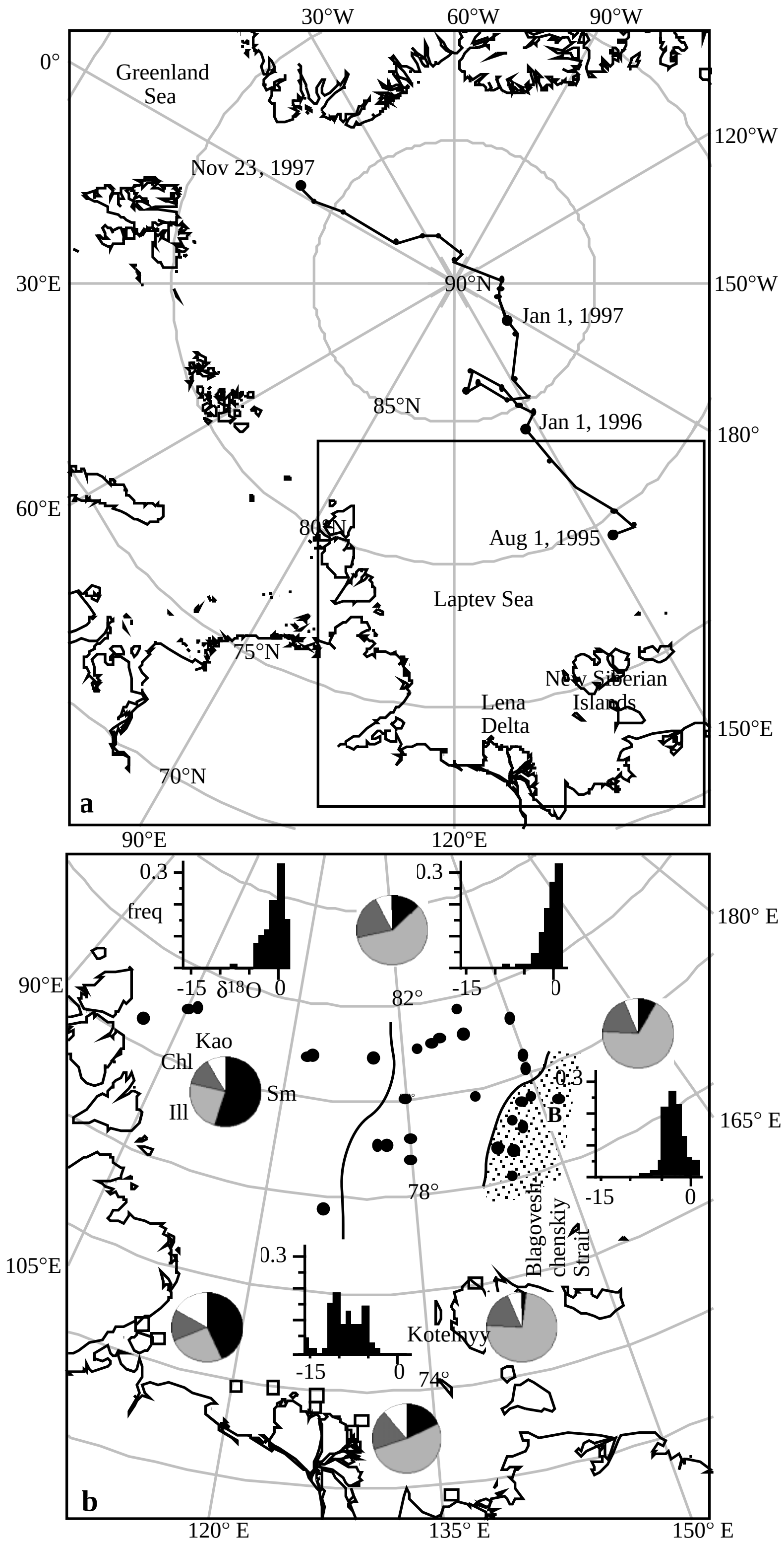
a: Based on geometric mean sediment concentration of 111 core segments (89.2 g $m^{-3}$) of upper 1.57 m of ice for medium and high sediment load areas
b: Based on geometric mean sediment load of bottom 50% of all cores for medium sedi ment load (87.3 g $m^{-2}$) and top 50% for high load (616.9 g $m^{-2}$)
c: Based on geometric mean sediment load of bottom 75% of all cores for medium sedi ment load (178.6 g $m^{-2}$) and top 25% for high load (972.5 g $m^{-2}$), i.e. assuming same frequency distribution of high/medium load as determined by satellite data (note that these numbers are the same, if bottom/top cores are defined by the sediment concentration in the upper 0.2 m of ice, i.e. the layer visible in satellite imagery)

## Figure captions

Fig. 1: Study area in the Laptev Sea and trajectory of buoy deployed in sediment-laden ice (a, buoy transmission ceased in November 1997, based on interpolated ice motion, sediment-laden ice field most likely passed Fram Strait in January 1998). Sampling locations in the Laptev Sea (b, dots: July-September 1995, squares: October 1995, buoy deployment at location "B" in sediment-laden ice shown in stippled outlines; solid lines separate three distinct ice fields of different origins and characteristics). Histograms show frequency distribution of $\delta^{18}O$ (‰) of ice samples, pie charts indicate average clay mineral composition (Kaolinite, Smectite, Illite, Chlorite) of samples obtained from sea-ice floes (the chart for Kotelnyy has been supplemented by surface sediment data from *Silverberg* [1972]).

Fig. 2: Distribution of sediment-laden ice, based on classification of AVHRR data (inset, corresponding to orange box, shows result of classification; brown: high sediment concentrations, orange: intermediate sediment concentrations, white: low or zero sediment concentration, blue: open water, grey: clouds), with reconstructed trajectories to point of origin derived from passive microwave data (each arrow corresponding to monthly displacement) and model simulations (trajectory based on daily integrations; red hatched areas show location of sediment-laden ice field for dates indicated). Surface water salinities are also shown for September 1994 (contours in psu). The light and dark grey lines delineate the 50 and 200 m waterdepth contour.

Fig. 3 a: $\delta^{18}O$ of coastal ice and water samples obtained in October 1995 (locations shown as squares in Fig. 1b). The solid line is a regression fit to all water samples, the dashed line connects Atlantic and Lena water composition based on *Bauch et al.* [1995]. b: Frequency distribution of parent water mass salinities for sediment-laden ice layers, derived from mixing model for Atlantic and Lena water endmembers. The dashed line corresponds to the salinity of coincident freezing point and density maximum.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60°W
90°W
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Greenland
Sea
120°W
Nov 23, 1997
30°E
90°N
150°W
Jan 1, 1997
85°N
Jan 1, 1996
180°
60°E
80°N
Aug 1, 1995
Laptev Sea
75°N
New Siberian
Islands
Lena
Delta
150°E
70°N
a
90°E
120°E
0.3
freq
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82°
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0.3
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165° E
78°
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0
Blagovesh-
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Figure 1

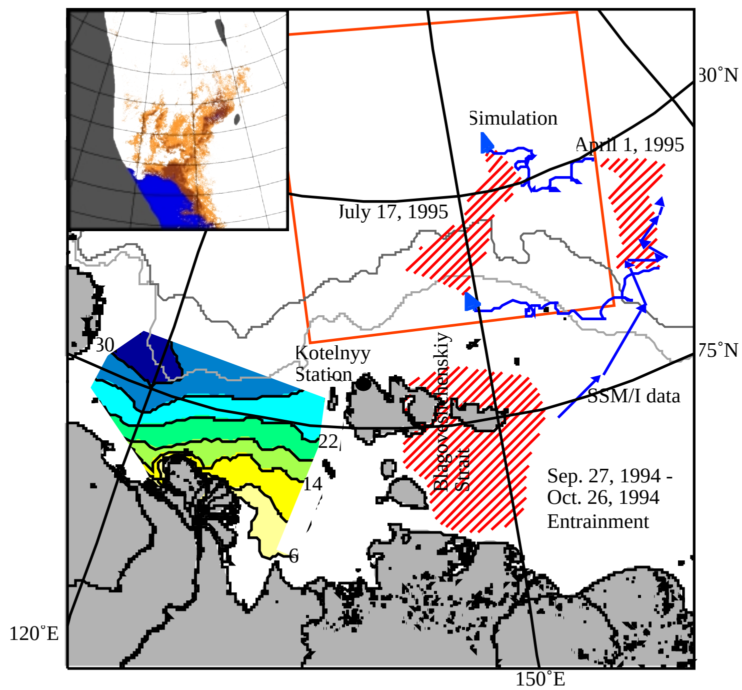


Figure 2

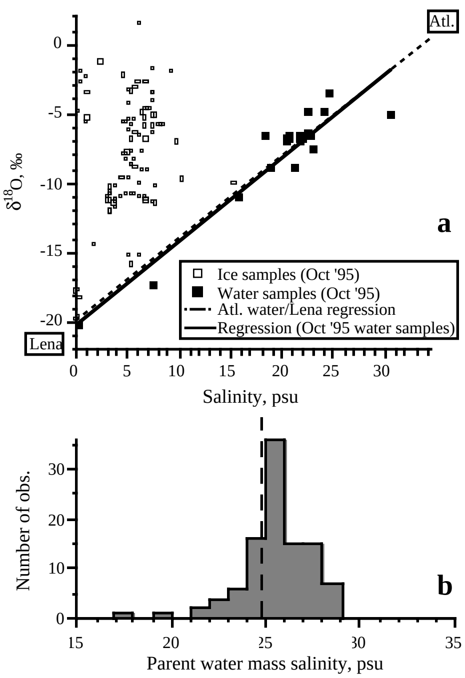


Figure 3