Sediment source strength, transport pathways and accumulation patterns on the Siberian–Arctic’s Chukchi and Laptev shelves

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Abstract

In this study, we estimate sediment source strength and determine sediment transport/accumulation patterns on the Chukchi and Laptev shelves for lithogenic material from several key source regions. In the western Laptev Sea, sediments from the Siberian flood basalt province account for \( \leq 20\% \) of surface sediments, while detritus from the eastern Laptev’s Lena and Yana Rivers constitutes as much as \( 40\% \) of seafloor sediments. Eastern Laptev Sea sediments similarly reflect inputs from multiple sources; here, however, local inputs from the Lena and Yana Rivers are most prevalent. Chukchi Sea sediments are more homogeneous in composition, with sediments originating from the Okhotsk-Chukotsk volcanic belt and Bering Strait inflow comprising over \( 60\% \) of surface sediments except near Wrangel Island and along sections of the Siberian coast. In the Chukchi portion of our study area, the dominant sediment dispersal pathways are from the Bering Strait region to the north and from Long Strait to the east, into the central Chukchi Sea. There appears to be comparatively minimal sediment transport parallel to the Siberian coast at our sample sites (>40 m water depth). In contrast, at our Laptev Sea sites (typically >20 m water depth) sediments supplied by the Lena and Yana Rivers move primarily eastward/northeastward parallel to the coast, with relatively minimal transport to the west/northwest or north to the central shelf. Good correspondence between sediment accumulation patterns and currents on the Chukchi shelf indicates water circulation is an important sediment transport mechanism in this marginal sea. In the Laptev Sea, a combination of river outflow, cyclonic water circulation and the Siberian Coastal Current controls sediment distribution. We speculate that sediment ice rafting may also affect shelf sedimentation patterns through a combination of factors. Our findings have implications for the fate of particle reactive contaminants released to the Siberian continental margin.

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1. Introduction

Making up over one-third the total area of the Arctic continental shelf (Silverberg, 1972; Holmes, 1975; Macdonald et al., 1998), the Siberian shelf...
receives large amounts of sediment from river discharge (Gordeev et al., 1996; Lisitzin, 1996; Are, 1999) and coastal erosion (Timokhov, 1994; Are, 1999; Rachold et al., 2000). Recent studies indicate significant potential exists for polluting the shelf with various particle reactive substances including heavy metals, organochlorines and, to a lesser extent, radionuclides (Macdonald and Bewers, 1996; Pfirman et al., 1997; AMAP, 2002). Determining the dominant sediment transport directions and accumulation patterns of Siberian shelf sediments thus has important implications for identifying regions most threatened by particle reactive pollutants. On a more global scale, characterizing modern sedimentation patterns and the factors controlling them also provides a necessary baseline for interpreting the record of palaeoclimatic change preserved in Arctic sediments (Kassens and Thiede, 1994; Stein and Korolev, 1994). Such studies are critical in light of growing evidence that the Arctic is a key part of the global climate system, which will both respond sensitively to and amplify the effects of global climate change (Walsh, 1991).

Sediment dispersal and accumulation patterns reflect the net effect of spatial and temporal changes in sediment fluxes to the shelf and sediment transport processes. Since sediment transport agents such as currents and ice rafting are highly spatially and temporally variable on the Siberian shelf, we cannot predict sedimentation patterns in this region a priori on the basis of physical oceanographic data. A number of studies have characterized the clay and heavy mineral composition of various Siberian shelf sediment sources and, to a limited extent, their sediment chemistry (Naidu et al., 1982; Nürnberg et al., 1994; Behrendt et al., 1999; Eisenhauer et al., 1999; Rachold, 1999; Rossak et al., 1999; Wahsner et al., 1999; Schoster et al., 2000). These data provide direct evidence of sediment movement along various trajectories throughout the shelf and from there into the central Arctic basin. However, because the compositional data in these studies are expressed as abundances (e.g. ppm, %, etc.) rather than fluxes (e.g. mg/cm²/yr), the distribution of material from a particular source may be affected by dilution from other sources. This prevents comparing the magnitude of sediment transport along these trajectories and thus the accurate identification of dominant sediment dispersal pathways.

In this study, we determine fluxes to the Siberian shelf of sediment from key source regions based on measured surface sediment geochemistry and published sedimentation rates. Previously (Viscosi-Shirley et al., 2003), we described the major and minor element geochemistry of 81 surface sediment samples taken from Chukchi, East Siberian and Laptev sediment cores collected by the USCG in the 1960s (Figs. 1a and b). On the basis of these data we demonstrated that various geologic terrains supplying sediment to the Siberian shelf have distinct geochemical signatures. Here we estimate the percent abundance of these geochemical endmembers in the 81 surface sediment samples. We use these endmember percentages to assess the relative strength of individual sediment sources on various parts of the shelf. For the Laptev and Chukchi Seas, we compile published mass accumulation rate data and linear sedimentation rate data, which we convert to mass accumulation rates. Fluxes of the sedimentary geochemical endmembers are estimated based on the calculated endmember abundances and published sedimentation rate data. Dominant sediment transport pathways for sediments accumulating within our study area are inferred from spatial variability in endmember fluxes. Finally, to the extent possible given available physical oceanographic data, we evaluate controls on observed sediment accumulation patterns.

2. Background

2.1. Sedimentary geochemical endmembers

Sediment geochemistry can differentiate detritus from various sediment sources on the Siberian shelf. In Viscosi-Shirley et al. (2003), we characterized the multi-element chemistry (Si, Al, K, Mg, Sr, La, Ce, Nd) of 81 core top samples taken from sediment cores collected in the Laptev, East Siberian and Chukchi Seas by the USCG between 1962 and 1964 (Fig. 1b). In order to discern
compositional trends in the lithogenic fraction of shelf sediments, we expressed the bulk sedimentary chemical data on an organic (biogenic opal, carbonate and organic matter) free basis. A combination of Q-mode factor analysis and x–y scatter plots of these data indicated there are four distinct, endmember geochemical compositions evident in Siberian shelf sediments (Table 1). Each of these geochemical endmembers reflects sediment input from a different geologic terrain (Fig. 1b). (1) The shale endmember (Al, K and rare-earth element rich sediment) is eroded from fine-grained marine sedimentary rocks of the Verkhoyansk Mountains and Kolyma-Omolon superterrain, and discharged to the shelf by the Lena, Yana, Indigirka and Kolyma Rivers. (2) The basalt endmember (Mg rich) is supplied by NE Siberia’s Okhotsk-Chukotsk volcanic belt and Bering Strait inflow, and is prevalent in Chukchi Sea sediments. (3) The mature sandstone
endmember (Si rich) is present proximal to Wrangel Island and sections of the Chukchi Sea’s Siberian coast and is derived from the sedimentary Chukotka terrain found in these areas. (4) The immature sandstone endmember (Sr rich) is abundant in the New Siberian Island region and reflects inputs from sedimentary rocks that comprise the islands. The immature sandstone endmember is also prevalent in the western Laptev Sea, where it is eroded from sedimentary deposits blanketing the Siberian platform that are compositionally similar to those on the New Siberian Islands. Western Laptev can be distinguished from New Siberian Island region sediments by the presence of the basalt endmember, which indicates Siberian platform flood basalts are another source of western Laptev sediments. We also found evidence that the mature and immature sandstone endmembers, which consist of much coarser sediment than the other endmembers (Table 1), reflect erosional processes as well as provenance. In this study, we consequently focus on the distributions of shale and basalt endmember fluxes to evaluate sediment dispersal patterns.

2.2. Physical oceanography

On the Siberian shelf, sediment transport agents such as currents and sea ice exhibit high spatial and temporal variability. In the region of the Chukchi Sea spanned by our samples, currents at all water depths typically flow northward following bottom contours, although they can exhibit substantial short-term wind-driven fluctuations (Fig. 2) (Coachman et al., 1975; Coachman and Shigaev, 1992; Roach et al., 1995; Weingartner et al., 1998a). This cross-shelf flow passes around Herald Shoal to exit the region via Hope Sea Valley and Barrow Canyon. Laptev and East Siberian currents are believed to flow in cyclonic gyres both at the surface and at depth (Dmitrenko et al., 1995; Hass et al., 1995; Timokhov, 1994; Pavlov et al., 1996) and thus also have northerly, offshore components, strongest in the eastern part of each sea. The Siberian Coastal Current flows alongshore toward the east from the Laptev to the Chukchi Sea, where it turns north–northeast to join the cross-shelf flow (Coachman and Shigaev, 1992; Weingartner et al., 1998b). Studying the

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**Table 1**

<table>
<thead>
<tr>
<th>Endmember</th>
<th>Shale</th>
<th>Basalt</th>
<th>Mature sandstone</th>
<th>Immature sandstone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample IDa</td>
<td>NW63-119</td>
<td>NW63-29</td>
<td>NW63-34</td>
<td>NW63-153</td>
</tr>
<tr>
<td>Latitude</td>
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<td>69.89</td>
<td>69.32</td>
<td>74.53</td>
</tr>
<tr>
<td>Longitude</td>
<td>−174.44</td>
<td>−177.58</td>
<td>125.93</td>
<td></td>
</tr>
<tr>
<td>Si (wt%)</td>
<td>27</td>
<td>30</td>
<td>38</td>
<td>34</td>
</tr>
<tr>
<td>Al</td>
<td>9.5</td>
<td>7.5</td>
<td>4.6</td>
<td>6.5</td>
</tr>
<tr>
<td>K</td>
<td>2.9</td>
<td>2.1</td>
<td>1.8</td>
<td>2.5</td>
</tr>
<tr>
<td>Mg</td>
<td>1.7</td>
<td>1.7</td>
<td>0.6</td>
<td>0.7</td>
</tr>
<tr>
<td>Sr (ppm)</td>
<td>148</td>
<td>194</td>
<td>145</td>
<td>281</td>
</tr>
<tr>
<td>La</td>
<td>42</td>
<td>26</td>
<td>21</td>
<td>30</td>
</tr>
<tr>
<td>Ce</td>
<td>92</td>
<td>50</td>
<td>43</td>
<td>63</td>
</tr>
<tr>
<td>Nd</td>
<td>38</td>
<td>23</td>
<td>18</td>
<td>25</td>
</tr>
<tr>
<td>Sand (wt%)</td>
<td>&lt;1</td>
<td>3</td>
<td>61</td>
<td>58</td>
</tr>
<tr>
<td>Silt</td>
<td>51</td>
<td>51</td>
<td>19</td>
<td>18</td>
</tr>
<tr>
<td>Clay</td>
<td>49</td>
<td>45</td>
<td>20</td>
<td>24</td>
</tr>
</tbody>
</table>

*aCompositionally extreme samples from within the geochemical data set were selected to represent each endmember.*
The Siberian Coastal Current on the Chukchi shelf using fall measurements made between 1992 and 1995, Weingartner et al. (1998b) found that in fall of 1995 the easterly flowing Siberian Coastal Current failed to develop and coastal flow was to the west–northwest. According to Pavlov (1995) and Munchow et al. (1998), similar flow reversals have been observed in the Laptev and East Siberian Seas. Although it appears alongshore flow is generally to the east on the basis of Weingartner et al.'s work, we have yet to clearly establish the frequency and duration of these flow reversals, and the mechanisms that drive them.

While current velocity data are sparse, available information suggests the most vigorous current in our study area is the Chukchi’s mean offshore northerly flow, with velocities on the order of 25 cm/s in Bering Strait decreasing to ~10 cm/s in the central Chukchi (Weingartner et al., 1998a). Maximum flow velocities along this offshore gradient range from 100 cm/s in the strait to 40 cm/s in the central Chukchi. Current velocities in the Laptev and East Siberian gyres appear to be much slower, typically <10 cm/s, although speeds up to 25–50 cm/s have been observed (Holmes and Creager, 1974; Munchow et al., 1998). Alongshore, data from several sources (US Naval Oceanographic Office, 1958; Weingartner et al., 1998b) suggest easterly flow is generally 10–20 and 50 cm/s at a maximum. Westerly flow velocities appear to be similar in magnitude (Munchow et al., 1998; Weingartner et al., 1998b). Of importance for sediment dispersal is the observation that in the Laptev and East Siberian Seas the relative strength of offshore versus alongshore flow varies. However, this interplay between coastal and offshore flow is poorly characterized, as the amplitude of these oscillations in current strength is uncertain and their frequency unknown.

Ice rafting is another important sediment transport mechanism that occurs primarily during fall freeze-up. There are two main types of ice: fast ice, which is attached to shore and immobile in winter (Timokhov, 1994), and sea ice, drifting ice found seaward of the fast ice. While sea ice is typically compacted against the northern fast ice edge in the Chukchi and East Siberian Seas, it frequently moves offshore in the Laptev Sea creating a polynya in which new sea ice continuously forms and is advected seaward (Barnett, 1991). Conditions in the polynya, i.e. open, shallow and sometimes turbulent water, are primed for fine-grained bottom sediments to be resuspended, entrained by sea ice and exported from the shelf.
(Pfirman et al., 1990; Dethleff et al., 1993; Nürnberg et al., 1994; Reimnitz et al., 1994; Eicken et al., 1997). These ice rafted sediments may be transported to the central Arctic, Canadian shelf, or even North Atlantic before being re-deposited as the sea ice melts (Pfirman et al., 1990; Meese et al., 1997).

3. Methods

In a previous study (Viscosi-Shirley et al., 2003) we identified several geochemical endmembers in Siberian shelf surface sediments, each endmember representing lithogenic sediment input from a different source region. Here we determine the relative magnitude of sediment transport along various pathways on the Siberian shelf based on spatial gradients in sedimentary geochemical-endmember flux distributions. Using geochemical data generated in Viscosi-Shirley et al. (2003) for 81 surface sediment samples, we first quantify the percent abundance of each endmember in each surface sediment sample by constrained least-squares regression. (See Fig. 1b for a map of sample locations and approximate sample depths, and Viscosi-Shirley et al. (2003) Appendix B for sample latitudes/longitudes and geochemical results.) We then compile published data for the Chukchi and Laptev Seas characterizing mass accumulation rates and linear sedimentation rates, which we subsequently convert to mass accumulation rates. Endmember fluxes are calculated by combining our estimated endmember abundances with the published sediment accumulation rates. Note that sediment samples in the Chukchi Sea are generally from within the 0–4 cm depth interval, and those in the Laptev Sea are typically from within the top 0–3 cm. Given observed sedimentation rates (discussed below) and surface mixed layer depths, each sample consequently represents average sediment transport conditions over roughly the past century to millenium of sedimentation. The following sections specify the techniques and strategies used in the (1) surface-sediment sample partitioning; (2) sedimentation rate data compilation; and (3) sedimentary geochemical-endmember flux calculations.

3.1. Partitioning surface sediments according to their sources

We partition the chemical composition of the surface sediment samples to determine the contribution from each endmember, or sediment source, using constrained least-squares regression (Menke, 1984). This partitioning of surface sediment composition is based on eight chemical variables (Si, Al, K, Mg, Sr, La, Ce, Nd) and four endmember compositions (shale, basalt, mature sandstone and immature sandstone) (Table 1). As described in detail in Viscosi-Shirley et al. (2003), endmember compositions were defined by assuming compositionally extreme samples within the geochemical data set are representative of the endmembers. Thus, for each sample we have eight equations in four unknowns (unknowns in italics):

$$[\text{Si}]_{\text{sample}} = ([\text{Si}]_{\text{shale}} \times \%_{\text{shale}}) + ([\text{Si}]_{\text{basalt}} \times \%_{\text{basalt}}) + ([\text{Si}]_{\text{mature sandstone}} \times \%_{\text{mature sandstone}}) + ([\text{Si}]_{\text{immature sandstone}} \times \%_{\text{immature sandstone}}), \quad (1)$$

$$[\text{Al}]_{\text{sample}} = ([\text{Al}]_{\text{shale}} \times \%_{\text{shale}}) + \cdots. \quad (2)$$

We solve these equations with the constraints that (1) endmember percent contributions are greater than or equal to zero, and (2) the sum of squared residuals is minimized. Since this set of equations is solved for each of the 81 samples, if we let $n$ be the number of samples, $m$ the number of variables and $p$ the number of endmembers, we can write the full set of equations in matrix form as:

$$E_{n \times m} = A_{p \times m},$$

where $E$ is the data matrix, $D$ is the endmember composition matrix, and $A$ is the endmember contribution matrix that we are solving for. In determining a solution, if the data are unweighted, more abundant elements are fit more closely than less abundant elements. Thus, we weight the data such that the weights are inversely proportional to the variable values in each sample, as specified in Table 1. Note that while the raw data span over 50 orders of magnitude, the scaled values only vary by a factor of four.

(ARTICLE IN PRESS)
3.2. Compilation of sedimentation rate data

In developing a database characterizing modern Siberian-shelf mass accumulation rates, we use a combination of $^{210}$Pb and $^{14}$C based estimates of sedimentation rates. Because published mass accumulation rate data (mg/cm$^2$/yr) are scarce, we also employ published linear sedimentation rate data (cm/yr) in our calculations. The linear sedimentation rates are converted to mass accumulation rates as described in Appendix A. (This calculation was made for entries in Table 2 for which both linear sedimentation rates and mass accumulation rates are listed.) It is clearly applicable to include sedimentation rates determined by the $^{210}$Pb technique, which is used for estimating rates of deposition over the past 100 years (Faure, 1986). While $^{14}$C is used to establish sedimentation rates over longer timescales (45,000 years) (Bard, 1998), for our study carefully selected $^{14}$C based estimates can be employed in conjunction with the $^{210}$Pb based estimates. During the last

<table>
<thead>
<tr>
<th>Source</th>
<th>Core no.</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Linear sedimentation rate (cm/kyr)</th>
<th>Mass accumulation rate (mg/cm$^2$/yr)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chukchi Sea</td>
<td>Baskaran and Naidu (1995)</td>
<td>SU-5</td>
<td>67.03</td>
<td>169.00</td>
<td>159</td>
<td>$^{210}$Pb</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CH-40</td>
<td>70.28</td>
<td>167.91</td>
<td>119</td>
<td>$^{210}$Pb, Baskaran and Naidu determined</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CH-38</td>
<td>70.70</td>
<td>167.38</td>
<td>156</td>
<td>MARs in two additional cores, not</td>
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<tr>
<td></td>
<td></td>
<td>CH-21</td>
<td>71.20</td>
<td>164.20</td>
<td>115</td>
<td>included at left due to the evidence</td>
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<td></td>
<td></td>
<td>USGS84-12</td>
<td>71.48</td>
<td>165.12</td>
<td>324</td>
<td>of sediment mixing below the surface</td>
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<td></td>
<td></td>
<td>CH-25</td>
<td>72.63</td>
<td>167.08</td>
<td>83</td>
<td>mixed layer in the portion of the</td>
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<td></td>
<td>CH-13</td>
<td>72.52</td>
<td>164.13</td>
<td>167</td>
<td>$^{210}$Pb profile, used to estimate</td>
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<td>Huh p. comm.</td>
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<td>165.81</td>
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<td>26-38</td>
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<td>167.68</td>
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<td>USGS85</td>
<td>31-43</td>
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<td></td>
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<tr>
<td>Kulikov et al. (1970)</td>
<td></td>
<td>South of Wrangel Isl.</td>
<td>0–50</td>
<td>0–57</td>
<td>(29-see comment)</td>
<td></td>
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<tr>
<td>Laptev Sea</td>
<td>Bauch et al. (2001b)</td>
<td>PM9499</td>
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<td>75.00</td>
<td>128.50</td>
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<td>PM9462</td>
<td>74.50</td>
<td>136.00</td>
<td>52</td>
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<td>PS51/092-13</td>
<td>74.45</td>
<td>130.25</td>
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<td></td>
<td></td>
<td>PS51/092-12</td>
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<td>130.10</td>
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<td>PS51/080-13</td>
<td>73.50</td>
<td>131.50</td>
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<td>24</td>
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<tr>
<td>Johnson-Pyrtle (1999)</td>
<td>24</td>
<td>71.63</td>
<td>128.97</td>
<td>59</td>
<td>52</td>
<td>$^{210}$Pb and $^{137}$Cs</td>
</tr>
</tbody>
</table>

Note: Given linear sedimentation rate data, we estimate mass accumulation rates assuming an average grain density of 2650 mg/cm$^3$ and porosities of 57% and 67% in the Chukchi and Laptev Seas, respectively.
deglaciation, rising sea level flooded most of the Chukchi shelf by 12.8 calendar kyr B.P. (date originally from Elias et al., 1996; here has been converted from 14C to calendar years based on the polynomial equation given in Bard, 1998), central Laptev shelf by ~7 calendar kyr B.P. and outer Laptev shelf by ~9 calendar kyr B.P. (Bauch et al., 2001a,b). Bauch et al. find that in the Laptev Sea 14C-based sedimentation rates have been fairly constant since the transgression was complete, in particular over the past 4 kyr. In the Chukchi Sea, there is no evidence of lithologic changes in post transgressive sediments (Elias et al., 1996), suggesting that during this period Chukchi sedimentation rates have been relatively stable as well. Thus we limit ourselves to 14C based sedimentation rates derived for post transgressive sediments that will likely yield values reasonably comparable to those established by the 210Pb technique.

Several criteria were established for the selection of sedimentation rate data. We use only 14C-based sedimentation rates calculated from 14C ages that were corrected for fractionation and reservoir effects and converted to calendar years. In the publications chosen as sources of 210Pb-based sedimentation rates, the effects of sediment mixing on downcore 210Pb profiles have been constrained in order to accurately quantify sediment accumulation rates from the 210Pb data. Note that 210Pb based sedimentation rates are derived from the slope of the linear regression of downcore 210Pb excess data plotted versus cumulative dry mass, and for the cores used in our endmember flux estimations these regressions have R's > 0.816 (n = 4–11) in Baskaran and Naidu (1995) and an R of 0.941 (n = 5) in Huh's work (personal communication).

3.3. Estimating endmember fluxes

We determine the flux of material from each source, or endmember, to each sample location as: fluxshale (for example) = % abundance\textsubscript{shale} × MAR\textsubscript{biogenic-free},

where % abundance\textsubscript{shale} is the contribution the shale endmember makes to a given sample, as calculated in our partitioning model, and MAR\textsubscript{biogenic-free} is the biogenic-free mass accumulation rate at that sample location, estimated from published data. Modeled endmember percent abundances describe endmember concentrations within the sedimentary lithogenic fraction since the geochemical data used to partition sediment composition are expressed on an organic free basis. Thus, we must use lithogenic fraction, or biogenic-free, mass accumulation rates (MARs) to estimate endmember fluxes. Biogenic-free MARs are estimated as:

\[
\text{MAR}_{\text{biogenic-free}} = \text{MAR}_{\text{total}} - (\% \text{ biogenic matter} \times \text{MAR}_{\text{total}}),
\]

where:

\[
\% \text{ biogenic matter} = \% \text{ biogenic opal} + \% \text{ carbonate} + (2.5 \times \% \text{ organic carbon}).
\]

Organic carbon contents are multiplied by 2.5 to estimate sedimentary organic matter concentrations. Sedimentary biogenic opal, carbonate and organic carbon data for the surface sediment samples were provided by Mammone and are discussed elsewhere (Mammone, 1998). Total MAR data are compiled from published studies, as described above. An error analysis for the calculated endmember fluxes is included in Appendix B.

4. Results

Modeled percent abundances of the geochemical endmembers in Siberian shelf sediments are shown in Fig. 3. To evaluate the model's effectiveness at partitioning the sediment samples into contributions from the endmembers consider the coefficients of determination listed in Table 1, and Fig. 4, which compares measured element concentrations with those predicted by the least-squares regression model. The coefficients of determination express for each variable the percent variance in the data explained by the model. The model does a good job predicting sample Sr and rare earth element contents (coefficients of determination greater than 91%). Si, Al and Mg are predicted fairly well (coefficients of determination greater than 81%), while K is predicted relatively
poorly (coefficient of determination of 66%). The endmembers were originally identified, in part, on the basis of factor analysis of the geochemical data (Viscosi-Shirley et al., 2003). Endmember percent abundance distributions seen here are similar to previously observed factor distributions. This correspondence between factor and endmember distributions and the fairly high coefficients of determination suggest we have done a reasonable job defining the primary geochemical endmember compositions present in Siberian shelf surface sediments and partitioning the surface sediment samples according to these endmembers.

The compiled published sedimentation rate data and their sources are summarized in Table 2. While sediment accumulation rate data are available for Chukchi and Laptev sediments, there are no published sedimentation rates for East Siberian sediments. Thus we focus on the Chukchi and Laptev Seas in this investigation. The distributions of Chukchi and Laptev shelf sedimentation rates are shown respectively in Figs. 5a and b. Note that Chukchi shelf MARs generally exceed those on the Laptev shelf.

Estimated sedimentary geochemical-endmember fluxes, their standard deviations, and the data used in the flux calculations are summarized in Table 3. With the exception of region B (see below), endmember fluxes are calculated at locations specified by the distribution of available MAR data. In the Chukchi Sea, these locations include region A (inner central shelf), region B (mid-central shelf), and region C (western shelf near Wrangel Island) (Fig. 5a). In the Laptev Sea, endmember fluxes are determined at individual core locations D through L, which similarly span north/south and east/west trending gradients (Fig. 5b). In region B, there are no measured total MARs and we infer accumulation rates based on gradients in existing central- and
eastern-Chukchi-shelf total MAR data. Central- and eastern-shelf total MARs gradually decrease offshore as sediment sources become more distant, from the inner shelf (159–223 mg/cm²/yr), to the central and outer shelf (115–167 mg/cm²/yr), and finally approaching the shelf break (83 mg/cm²/yr). The only exception to this trend is between Herald and Hanna shoals, where total MARs are at a maximum (>300 mg/cm²/yr) (Baskaran and Naidu, 1995; Huh, personal communication). Given the general offshore decline in sedimentation rates, we assume that region B total MARs are roughly 119–156 mg/cm²/yr, as seen in two cores just offshore from here. For the Chukchi Sea, we determine fluxes of the basalt endmember (Figs. 6a–c) and shale endmember (Figs. 7a–c) in
regions A–C. In order to make the flux calculations on a regional basis, we use the average endmember abundances and biogenic matter concentrations for each region. Basalt endmember fluxes are 92–129 mg/cm²/yr in region A and a fairly comparable 88–114 mg/cm²/yr in region B, whereas they are much lower in region C, ~3 mg/cm²/yr (Fig. 6c). In contrast, shale endmember fluxes increase to the north/northwest, from 0.0 mg/cm²/yr in region A, to 3–4 mg/cm²/yr in region B, and 4 mg/cm²/yr in region C (Fig. 7c).

For the Laptev Sea, we calculate shale endmember fluxes (Figs. 8a–c) at individual core locations D–L. To make these calculations, we grid shale endmember abundances and biogenic matter concentrations at our sample locations to estimate values for these parameters at sites D–K. Site L lies west of the area encompassed by the surface sediment samples and thus the gridded data. Here we assume contents equivalent to those at our westernmost sample location and the one closest to site L. This is a conservative assumption since the shale endmember is discharged to the eastern Laptev Sea and its percent abundance, which decreases westward with increasing distance from its source, has already dropped close to zero in our westernmost sample. We find that shale endmember fluxes range from <1 to 37 mg/cm²/yr, and are generally highest close to the Lena River delta (Fig. 8c).

5. Discussion

5.1. Sediment source strength

Endmember percent abundances are useful in evaluating the relative contributions of the endmembers and thus the strength of individual lithogenic sediment sources on different parts of the Siberian shelf. A detailed discussion of the provenance of the sedimentary geochemical endmembers is presented in Viscosi-Shirley et al. (2003); here, we focus on the implications of endmember percent abundances for sediment source strength. Because our samples represent on the order of several centuries of sedimentation, findings regarding sediment source strength and accumulation patterns (see below) reflect the net effect of variability in precipitation, river outflow, currents and sediment ice rafting over this time period. The Laptev Sea receives detrital inputs from multiple sources. Western Laptev shelf sediments are 40–80% immature sandstone endmember (Fig. 3). Possible sources of the immature sandstone endmember include sedimentary rocks overlying the Siberian platform and New Siberian Islands. This endmember consists of coarse-grained sediment and may also represent a lag
Table 3
Siberian-shelf sedimentary geochemical endmember fluxes

<table>
<thead>
<tr>
<th>Region</th>
<th>Total mass accumulation rates (MARs) (mg/cm²/yr)</th>
<th>Biogenic matter concentration (wt%)</th>
<th>Biogenic-free MARs (mg/cm²/yr)</th>
<th>Endmember % abundances</th>
<th>Endmember fluxes (mg/cm²/yr)</th>
<th>Standard deviation</th>
<th>Endmember fluxes (mg/cm²/yr)</th>
<th>Standard deviation</th>
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<tr>
<td>Chukchi Sea</td>
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<td></td>
<td></td>
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<td>12</td>
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<td>156</td>
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<td>29</td>
<td>7</td>
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<td>83</td>
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<td>NA b</td>
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<tr>
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<td>21</td>
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<td>2</td>
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<tr>
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<td>7 maximum</td>
<td>0.8 maximum</td>
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</table>

aThe average endmember abundances and biogenic matter concentrations for each region are used in order to make flux calculations on a regional basis. Region A contains only sample and we assume its characteristics are representative of conditions throughout region A. This appears to be reasonable since samples in the general vicinity of region (south of 69°N and east of 173°W) are similar. For example, they have an average basalt endmember abundance of 68% with a standard deviation of only 4%.

bWe cannot estimate errors in these fluxes as there is insufficient information regarding accumulation rates or the calculated fluxes are zero.
deposit resulting from particle reworking by currents and ice. The presence of the basalt and shale endmembers in Laptev Sea sediments can be clearly linked to inputs from the Siberian flood basalt, and the Lena and Yana Rivers, respectively. While the basalt endmember accounts for 20% or less of western Laptev shelf sediments, the shale endmember comprises up to 40% of sediments in this area. Thus detritus originating from the eastern Laptev Sea makes up a significant fraction of western Laptev shelf sediments relative to local inputs. Eastern Laptev Sea sediments are likewise a mixture of the shale, basalt and sandstone endmembers. Here, however, local inputs predominate with the Lena/Yana River-derived shale endmember most prevalent. On the basis of isotopic data, Eisenhauer et al. (1999) similarly report that Laptev Sea sediments reflect inputs from the Siberian flood basalt province and Lena River drainage basin, as well as sediment reworking to separate coarse and fine grained material. Their analysis of Nd isotope data, which
are not affected by grain size sorting, indicates the mean isotopic values of western Laptev samples lie between mean values for the Siberian flood basalt and eastern Laptev Sea. From these data they estimate that only about 25% of western Laptev sediments are derived from the Siberian flood basalt province. In the Chukchi Sea, sediments are more homogeneous in composition. Basalt endmember rich sediments originating from the Okhotsk-Chukotsk volcanic belt and Bering Strait inflow dominate, constituting over 60% of Chukchi shelf sediments except near Wrangel Island and along sections of the Siberian coast. Sediments in these areas mainly reflect local input from the Chukotka terrain and erosional processes (mature sandstone endmember), with some contribution from the East Siberian Sea (shale endmember).
5.2. Dominant sediment transport pathways

A key advantage to mapping endmember fluxes, as opposed to endmember abundances, is that each endmember’s distribution is unaffected by dilution from other sources. This allows us to infer the dominant dispersal pathways for sediment accumulating on the shelf, based on observed spatial variability in endmember fluxes. In the Chukchi Sea portion of our study area, the distribution of basalt endmember fluxes enables us to identify its primary transport pathways from its southern Chukchi source region. Derived from southern Alaskan volcanic rocks and Siberia’s Okhotsk-Chukotsk volcanic belt, the basalt endmember is delivered to the Chukchi Sea primarily via Bering Strait inflow and runoff from the Okhotsk-Chukotsk volcanic belt (Fig. 6c) (Viscosi-Shirley et al., 2003). Basalt endmember fluxes are 92–129 mg/cm²/yr in region A, which is located closest to the basalt endmember’s sources. Basalt endmember fluxes are almost as high to the north in region B (88–114 mg/cm²/yr) as they are in region A, indicating northerly transport of the basalt endmember is strong. With regard to northwesterly transport, regions C and B are comparable distances northwest and north, respectively, of the basalt endmember’s source region. Yet basalt endmember fluxes in region C (3 mg/cm²/yr) are roughly one thirtieth of those in region B, implying northwesterly transport of the basalt endmember is very weak compared to
northerly transport. The errors in calculated basalt endmember fluxes for regions A and B are significant in some cases, ranging from 16% to 48% (Table 3). The error in region C’s basalt endmember flux is unknown, and we conservatively assume this flux has an error of 48% (equivalent to the largest estimated error for a basalt endmember flux). Even given these large errors, our observations hold that basalt endmember fluxes in regions A and B are fairly comparable while those in region C are much lower, as do our conclusions that offshore-northerly transport of this endmember is significantly stronger than northwesterly transport.

East Siberian Sea sediments, represented by the shale endmember, enter the Chukchi Sea through Long Strait (Fig. 7c). In the vicinity of the strait (region C), shale endmember fluxes are 4 mg/cm²/yr. East of the strait in the central Chukchi Sea (region B) shale endmember fluxes are a comparable 3–4 mg/cm²/yr, yet there is no accumulation of this endmember southeast of the strait on the inner Chukchi Shelf (region A). These observations suggest the dominant sediment dispersal pathways for sediments in our Chukchi study area are from the Bering Strait region to the north and from Long Strait to the east, into the central Chukchi Sea. At our Chukchi Sea sample sites (water depths >40 m), there appears to be comparatively minimal movement of these sediments parallel to the coast, either to the northwest or southeast.

The Laptev Sea exhibits a different dominant sediment dispersal pattern than the Chukchi Sea. The Lena and Yana Rivers are sources of the shale endmember in the Laptev Sea (Fig. 8c). Discharging about five times more sediment than the Yana River (Gordeev et al., 1996; Lisitzin, 1996), the Lena River is the shale endmember’s primary source. The Lena delta’s eastern branches supply roughly 90% of the river’s suspended matter, with most (64%) of its particulate discharge coming from a single northeast branch (Kuptsov and Lisitsin, 1996). Shale endmember fluxes are highest at sites within several hundred kilometers of the Lena River delta’s main branches (D-37 mg/cm²/yr [error unknown]; E-16 ± 5 mg/cm²/yr; G-36 ± 11 mg/cm²/yr; H-21 ± 6 mg/cm²/yr; I-21 ± 11 mg/cm²/yr) and significantly lower elsewhere on the shelf. This result is consistent with Stein and Fahl’s (2000) observation that fluxes of organic carbon, which is primarily terrigenous in origin in the Laptev Sea (Rachold and Hubberten, 1999; Stein and Fahl, 2000), peak off the Lena River delta and progressively decline offshore. Shale endmember fluxes are only 1 ± 0.3 and 2 ± 0.6 mg/cm²/yr north of the delta at central shelf locations K and J, or 4–67 times less than those adjacent to the delta given the errors in the calculated fluxes. A comparable distance west/northwest of the Lena River delta at site L, shale endmember fluxes are <0.8 ± 1 mg/cm²/yr, or 5–59 times lower than those near the delta. Site F lies east/northeast of the delta, slightly closer to it than the northerly (K, J) and westerly (L) sites just described. Here the shale endmember’s accumulation rate (15 ± 9 mg/cm²/yr) is less than typical fluxes close to the delta but noticeably higher than at sites K, J and L. This pattern indicates that in contrast to conditions in the Chukchi Sea, at our Laptev Sea sample sites (typically >20 m water depth) sediments originating from the Lena and Yana Rivers preferentially move to the east/northeast parallel to the coast, with relatively minimal transport northward to the mid-shelf. Similar to the Chukchi Sea, there is comparatively little dispersal of these sediments to the west/northwest.

Comparing these results for the Laptev Sea with observations based on geographic gradients in shale endmember percentages illustrates the importance of determining dominant sediment transport pathways based on endmember fluxes rather than endmember percent abundances. Shale endmember percentages are high close to its sources, just off the mouths of the Lena and Yana Rivers (Fig. 3). The percentages remain elevated along the length of these rivers’ northerly trending submarine channels but drop significantly immediately east and west of the channels, suggesting that offshore dispersal of these sediments is greater than that parallel to the coast. As described above, an examination of shale endmember fluxes provides a different picture. Shale endmember fluxes are relatively high off the Lena River delta but decrease sharply to the north while declining.
gradually to the east/northeast (Fig. 8c). Thus shale endmember fluxes indicate that Lena River detritus accumulating on the shelf tends to move along the shore to the east/northeast, rather than offshore to the north as suggested by trends in percent abundances.

5.3. Controls on sediment dispersal patterns

The spatial and temporal variability in Siberian shelf currents and ice rafting prevent us from predicting dominant sediment transport pathways a priori. However, assuming the variability documented in shelf physical oceanography over roughly the last half century is typical of that during the past several centuries represented by our samples, we can use our physical oceanographic knowledge to get some idea of the factors controlling observed sediment dispersal patterns. In the Chukchi portion of our study area, the dominant sediment transport pathways reflect currents and bathymetry. Water entering from Bering Strait tends to flow north at all depths following bottom contours, then pass around Herald shoal to exit the region via Hope Sea Valley and Barrow Canyon rather than moving northwest into Long Strait (Fig. 2) (Coachman et al., 1975; Coachman and Shigaev, 1992; Weingartner et al., 1998a). Consistent with this observation, Chukchi sedimentary endmember flux distributions indicate offshore/northerly sediment transport is significantly greater than sediment movement to the northwest, parallel to the Siberian coast. Surface and bottom inflow from Long Strait moves east and southeast, at some point turning north to join the cross shelf flow. Our results indicate that sediments from Long Strait accumulate on the central shelf but are absent from the southern shelf, suggesting the inflowing waters typically turn north before reaching the innermost Chukchi shelf. The sediments considered here, those rich in the shale and basalt endmembers, are likely transported as suspended load. Both the shale and basalt endmembers are fine grained, and according to McManus et al. (1969) Chukchi shelf current velocities are sufficient to transport the silt and clay sized particles found on the shelf in suspension. Because water circulation in the study area is fairly coherent at all depths, it is difficult to distinguish the influence of surface versus bottom currents on sediment dispersal patterns. McManus et al. (1969) describe a turbidity maximum in Chukchi shelf bottom waters and infer bottom currents are a primary dispersal mechanism on the shelf.

A combination of river outflow and water circulation is important in determining sedimentation patterns on the Laptev shelf. River discharge of water and sediment into the Laptev Sea occurs mainly in the summer months, with 90% of the outflow supplied in the warm season (Pavlov et al., 1996; Behrends et al., 1999). A plume of river water is evident off the Lena River delta, extending to the north, northeast, or east depending on the hydro-meteorological conditions (Pavlov et al., 1996). The distribution of river outflow corresponds spatially to that of the highest shale endmember fluxes indicating river discharge is critical in dispersing the shale endmember. Though wintertime currents in the Laptev Sea are poorly characterized, summertime currents are known to flow in cyclonic gyres both at the surface (Pavlov et al., 1996) and at depth (Timokhov, 1994; Hass et al., 1995). Near shore, the Siberian Coastal Current generally flows to the east with occasional reversals to the west (Pavlov, 1995; Weingartner et al., 1998b; Munchow et al., 1998). The northerly and easterly components of this flow pattern also undoubtedly contribute to the elevated shale endmember fluxes off the Lena River delta. It is important to note that there are fluctuations in the relative intensity of the northerly versus easterly branches of cyclonic flow, though the amplitude and frequency of these oscillations is unknown. Above we observed that with increasing distance from the Lena River delta shale endmember fluxes decline relatively gradually to the east/northeast but sharply to the north, indicating sediment dispersal is stronger to the east/northeast than to the north. One possible explanation for this sedimentation pattern is that on average during the time represented by our samples easterly flow has been strong compared with northerly flow.

Sediment ice rafting is another potential cause of the low shale endmember fluxes evident on the northern and western Laptev shelf. Although the
magnitude of sediment entrainment and export vary a great deal spatially and temporally, published studies suggest a significant amount of ice rafted debris is exported from the Laptev shelf to the central Arctic (Nürnberg et al., 1994; Dethleff, 1995; Eicken et al., 1997, 2000; Pfirman et al., 1997). Pfirman et al. (1997) identify the Laptev’s New Siberian Island region as a source of sediment-laden ice. Hölemann et al. (1999) documented sediment entrainment off the Lena River delta, in the New Siberian Island region, and in the western Laptev Sea both near the Khatanga River mouth and along the coast. Existing budgets place ice rafted debris export from sections of the central and eastern Laptev at about 3.5–4 million tons/yr (Dethleff, 1995; Eicken et al., 1997) and from the New Siberian Island region at 18.5 million tons/yr (Eicken et al., 2000). These observations suggest sediment ice rafting may help cause the low shale endmember fluxes on the northern and western Laptev shelf through a combination of factors. First, much of the inner shelf sediment that is entrained in sea ice and carried offshore may bypass the central shelf (sites H and K) and be redeposited farther offshore or exported into the central Arctic. In addition, our northerly and westerly sites (H, K and I) are located in zones of active turbid sea ice formation. Sea ice entrainment and removal of sediment from sites H, K and I may be significant enough compared with the magnitude of sediment inputs to these areas to produce some of the lowest terrigenous fluxes seen in our study area. Additional data are needed to test these ideas, including better constrained estimates of Siberian shelf sediment inputs (via river discharge, coastal erosion, Bering Strait inflow, etc.) and outputs (by currents, ice rating, etc.). Such data also have broader implications for understanding general sediment accumulation patterns on the shelf. Our results indicate that endmember fluxes and biogenic-free MARs in the Chukchi Sea exceed those in the Laptev Sea (Fig. 5), implying there is greater input relative to output of lithogenic sediment in the Chukchi Sea. Such data will help determine why this pattern exists, when the Laptev Sea receives high sediment input from rivers (20–25 × 10^6 tons/yr; Gordeev et al., 1996; Lisitzin, 1996; Are, 1999) and coastal erosion (58.4 × 10^6 tons/yr; Rachold et al., 2000), while the Chukchi Sea lacks large delta forming rivers and likely receives less river born sediment.

5.4. Implications

As the globe and the Arctic become increasingly industrialized, it is critical to consider how contaminants produced by this industrialization will impact the environment for future generations. The inferred sediment transport patterns have important implications for the fate of particle reactive contaminants released to the Siberian shelf. A primary concern is the exposure of biological organisms, and through the food chain potentially humans, to particle reactive pollutants that may remain in Arctic ecosystems for a long time (AMAP, 2002). Compared with the slope and basin, Arctic continental shelves are sites of concentrated biological activity. If particle reactive contaminants were released to the Chukchi Sea, the comparatively weak sediment transport we observe parallel to the Siberian coast (water depths > 40 m) would help limit the pollutants contact with, and thus detrimental effects on, shelf biota. There is considerable sediment movement from the inner to the central Chukchi shelf, as evidenced by the negligible drop in basalt endmember fluxes from just north of Bering Strait to the mid-shelf. However, in a core from the Chukchi shelf edge, Darby et al. (1999, 2002) find that over the last millenium easterly and westerly sources of Fe oxide grains are much more important than southern Chukchi sources, with < 5% of Fe oxide grains originating in the south. The core has a sedimentation rate of 20 cm/kyr in the middle to late Holocene. Assuming 5% of bulk surface sediments at this outer shelf location are derived from the southern Chukchi shelf implies a flux of 0.8 mg/cm^2/yr (for porosity ~ 0.7 and grain density 2650 mg/cm^3), or up to 160 times less than basalt endmember fluxes on the shelf. Overall, these observations suggest that much of the sediment supplied to the Chukchi Sea is sequestered there rather than being transported along the shore or off the shelf, making this region an effective trap for particle reactive pollutants.
In contrast, Laptev shelf sediments move primarily eastward/northeastward, parallel to the coast. According to Pavlov et al. (1996) there is significant water flow from the Laptev Sea to the East Siberian Sea (0.1 Sv/yr on average). As a result, Laptev sediments may be dispersed eastward into the East Siberian Sea. Additionally, sea ice exports considerable amounts of ice rafted debris from the Laptev shelf to the central Arctic (Nürnberg et al., 1994; Dethleff, 1995; Eicken et al., 1997, 2000; Pfriman et al., 1997). Behrends et al. (1999) and Schoster et al. (2000) identified the Laptev Sea as a source of central Arctic seafloor sediments by comparing shelf and basin sediment chemistry and mineralogy. Thus instead of acting as a sink for particle reactive pollutants as the Chukchi Sea does, the dominant sediment dispersal pattern and occurrence of sediment ice rafting in the Laptev Sea make this region a potential pollutant source for both the Siberian shelf and Arctic basin. In agreement with this idea, Meese et al. (1997) investigated $^{137}$Cs concentrations in ice and ice born sediments collected from across the Arctic Basin. The sediment sample with the highest $^{137}$Cs content was found in the Beaufort Sea and had a significantly higher $^{137}$Cs level than bottom sediments in the same area. On the basis of discriminant function analysis and ice transport model results, the authors inferred the Laptev/Kara Sea region to be the source of the contaminated sediment.

6. Conclusions

We previously demonstrated in Viscosi-Shirley et al. (2003) that Siberian shelf surface sediments have distinct, endmember geochemical compositions, representing lithogenic sediment inputs from different source regions. Here we partition 81 shelf surface sediment samples (Fig. 1b) to determine the percent abundances of these endmembers, or sediment sources, in each sample. These results are used to evaluate the relative strength of individual sediment sources at various locations on the shelf. We then compile published sedimentation rate data for the Chukchi and Laptev Seas. Sedimentary geochemical endmember fluxes are determined by combining our calculated endmember percentages with the published sedimentation rate data. From spatial variability in sedimentary geochemical endmember fluxes, we infer the dominant transport pathways for sediments accumulating in the Chukchi and Laptev portions of our study area. Comparing the inferred sediment transport and accumulation patterns with physical oceanographic data, we look for evidence of the factors controlling these patterns.

We find that in the western Laptev Sea, sediments from the Siberian flood basalt (basalt endmember) account for $<20\%$ of surface sediments, while detritus from the Lena and Yana Rivers (shale endmember) constitutes as much as 40% of seafloor sediments (Fig. 3). The remaining coarse-grained sediment (immature sandstone endmember) is either eroded from sedimentary rocks overlying the Siberian platform and New Siberian Islands, or results from grain size sorting. Thus sediment from eastern Laptev sources makes up a significant fraction of western Laptev shelf sediments relative to local inputs. These results are similar to Eisenhauer et al.’s (1999) findings based on isotopic analyses that the Siberian flood basalt province supplies only about 25% of western Laptev sediments. Sediments in the eastern Laptev Sea are likewise a mix of the basalt, shale and immature-sandstone endmembers. Here, however, local inputs from the Lena and Yana Rivers are most prevalent. By comparison, Chukchi Sea sediments are much more homogeneous in composition. Detritus supplied by Bering Strait inflow and the Okhotsk-Chukotsk volcanic belt makes up over 60% of Chukchi shelf sediments, except near Wrangel Island and along portions of the Siberian coast. Sediments here reflect local input from the Chukotka terrain and erosional processes, with some contribution from the East Siberian Sea.

The dominant transport pathways for sediments in the Chukchi portion of our study area are from the Bering Strait region to the north and from Long Strait to the east, into the central Chukchi Sea (Figs. 6c and 7c). There appears to be comparatively minimal sediment movement parallel to the Siberian coast at our sample sites ($>40$ m water depth), either to the northwest or southeast. The Laptev Sea exhibits a different dominant
sediment dispersal pattern (Fig. 8c). At our Laptev Sea sample sites (typically >20 m water depth), sediments supplied by the Lena and Yana Rivers move primarily eastward/northeastward parallel to the coast, with relatively minimal transport northward to the central shelf. Similar to the Chukchi Sea, there is comparatively little movement of these sediments to the west/northwest.

Good correspondence between Chukchi-shelf sediment accumulation patterns and currents, which are fairly coherent at all water depths, indicates water circulation is an important sediment transport mechanism in this marginal sea. Consistent with this observation, sedimentological analyses by McManus et al. (1969) provide evidence that the fine sediments predominant on the Chukchi shelf are transported as suspended load by bottom currents. A combination of river outflow, cyclonic water circulation and the Siberian Coastal Current controls sediment distribution in the Laptev Sea. We speculate that ice rafting, which is known to export significant amounts of sediment from the Laptev shelf (Nürnberg et al., 1994; Dethleff, 1995; Eicken et al., 1997, 2000; Pfirman et al., 1997), may also affect sedimentation patterns through a combination of factors. Sediment fluxes are comparatively quite low on the central shelf near the New Siberian Islands and the western shore. These regions are zones of active turbid sea ice formation (Pfirman et al., 1997; Hölemann et al., 1999). In these areas sea ice entrainment and removal of sediment may be significant enough compared with the magnitude of sediment inputs to suppress sediment accumulation rates. Additionally, much of the ice rafted sediment that is entrained on the inner shelf and carried offshore may bypass these regions of the central shelf, and instead be re-deposited on the outer shelf or in the central Arctic.

While previous studies have identified directions of sediment movement on the Siberian margin (Naidu et al., 1982; Nürnberg et al., 1994; Behrends et al., 1999; Eisenhauer et al., 1999; Rachold, 1999; Rossak et al., 1999; Wahsner et al., 1999; Schoster et al., 2000), here we have mapped flux distributions and identified the dominant dispersal pathways of sediments in the Chukchi and Laptev Seas originating from several key source regions. These results have implications for the impact of particle reactive pollutants released to the shelf, allowing us to identify zones most threatened by contamination. This information is also essential to accurately characterizing links between modern Arctic-shelf depositional patterns and the physical environment, and thus is a necessary prerequisite to interpreting the record of paleoenvironmental change preserved in Arctic sediment stratigraphy. To conclude, we have made an initial attempt at characterizing modern sediment source strength, transport pathways, and accumulation patterns on parts of the Siberian shelf, and we feel it is important to expand on these efforts. In particular, additional Siberian-shelf MAR estimates are necessary to provide a clearer picture of recent sedimentation patterns. To better define the processes controlling these patterns will require quantification of sediment transport by currents and refined estimates of ice rafted debris export from the shelf.

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Appendix A. Linear sedimentation rate conversion

Linear sedimentation rates are converted to total mass accumulation rates (MARs) as
total MAR in mg/cm²/yr
= (linear sedimentation rate in cm/kyr)
× (average grain density in mg/cm³)
× (1 kyr/1000 yr) × (1 − φ),

where φ is downcore average sediment porosity. This calculation was made for entries in Table 2 for which both linear sedimentation rates and MARs are listed. We estimate that the average grain density is typically about 2650 mg/cm³, based on the abundance of various mineral types (Silverberg, 1972; Naugler et al., 1974; Stein and Korolev, 1994) and their respective densities (Pye, 1994). The primary constituents of shelf sediments all have similar grain densities (quartz, 2650 mg/cm³; feldspars, ~2650 mg/cm³; clay minerals, ~2600 mg/cm³). Heavy minerals common to the shelf have notably higher grain densities (3200–3500 mg/cm³), but comprise less than ~10% of shelf sediments (estimate based on data from Silverberg (1972) and Naugler et al. (1974)). Changes in total heavy mineral concentration appear to be the main cause of variability in the average grain density, although they typically amount to variations of less than ~ ±3%. Thus in our error analysis (see Appendix B) we take 3% as the average grain density’s standard deviation. Regarding sediment porosity, in the Chukchi Sea, we use data from Baskaran and Naidu (1995) to determine downcore average sediment porosities for six cores collected close to those for which we have measured linear sedimentation rates. The average downcore-average porosity of these cores is 57% with a standard deviation of ±5%. Thus we set φ equal to 0.57, and for our error analysis we take 5% as the standard deviation in Chukchi sediment porosity. In order to parameterize φ for the Laptev Sea we use sediment porosity data for a central Laptev core from Kassens et al. (1995). We consider only measurements made in the upper 25 cm, as this is the approximate length of Laptev Sea cores for which we have linear sedimentation rate estimates. Over this depth interval, the core has an average sediment porosity of 67%, or φ equal to 0.67. Since we cannot determine the standard deviation in Laptev sediment porosity based on a single core, for the error analysis we assume it is equivalent to that of Chukchi sediments (5%).

Appendix B. Error analysis

Endmember fluxes are estimated as the product of MAR and endmember percent abundance data. According to Taylor (1982), when several quantities are multiplied together the fractional error of the product, defined as the standard deviation (SD) of the product divided by the product, is the sum of the quantities’ fractional errors. Thus the fractional error on an estimated endmember flux is the sum of the fractional errors in the MAR and percent abundance values:

$SD_{flux/flux} = SD_{MAR/MAR} + SD_{% abundance/% abundance}$

and the error on the flux is consequently:

$SD_{flux} = (SD_{MAR/MAR} + SD_{% abundance/% abundance}) \times flux.$

Note that although biogenic-free MARs are used in calculating endmember fluxes, to simplify our error analysis we approximate the fractional errors in the biogenic-free MARs as the fractional errors in the corresponding total MARs. This approximation is reasonable since the biogenic matter concentrations used in converting total to biogenic-free MARs are small values with relatively high accuracies and consequently excluding the errors in these terms does not noticeably change the estimated errors in endmember fluxes. Where linear sedimentation rates are used instead of MARs, fractional errors for average sediment porosity and density are included in the equation. Fractional errors for these terms are calculated from their standard deviations, specified in Appendix A.

To determine the fractional errors in endmember percent abundances that result from inaccuracies in measured surface-sediment sample multi-element chemistry we use a Monte Carlo approach. Geochemical data for six surface sediment samples, chosen for their diverse compositions, which represent both extreme and typical
shelf sediment chemistries, form the basis of this part of the error analysis. Given each sample’s elemental composition and each element’s accuracy, we use a random number generator to create six data sets whose mean elemental concentrations equal that of the samples and where each element’s standard deviation is defined by that element’s accuracy. We partition the resulting data sets using the constrained least squares technique described in the Methods. Taking the standard deviation of each endmember’s percent abundance in each of the six data sets yields six estimates of the error on that endmember’s percent abundance values, given the accuracy of the geochemical data. Based on the calculated standard deviations, we find modeled endmember abundances are accurate to within: 7% for the shale endmember; 4% for the mature sandstone endmember; and 5% for the immature sandstone endmember.

The approach for calculating fractional errors in the MARs varies depending on whether the sedimentation rates are \( ^{210}\text{Pb} \) or \( ^{14}\text{C} \) based estimates. \( ^{210}\text{Pb} \) based MARs and linear sedimentation rates are calculated by regressing \( \ln^{210}\text{Pb}_{\text{excess}} \) versus cumulative dry mass and depth, respectively. Fractional errors in these estimates are equivalent to the fractional errors on the slopes of the regressions, or \( \text{SD}_{\text{slope}} \)/slope, where the standard deviation of the slope is calculated as (Draper and Smith, 1966):

\[
\text{SD}_{\text{slope}} \quad \text{(e.g. for a linear sedimentation rate)} = \sqrt{\left( \sum \left( \frac{\ln^{210}\text{Pb}_{\text{excess}}-\text{mean} \ln^{210}\text{Pb}_{\text{excess}}}{2} \right)^2 \right) \times \left( 1 - R^2 \right) / (n - 1)} + \sqrt{\left( \sum \text{depth} - \text{mean depth} \right)^2}.
\]

\( ^{14}\text{C} \)-based sedimentation rates used in the endmember flux calculations are determined based on a single \( ^{14}\text{C} \) age \( A \) (in kyr) at depth \( z \) (in cm) as \( z/\sqrt{A} \). Given the error on the \( ^{14}\text{C} \) age, \( E \), each calculated sedimentation rate may range from \( z/(\sqrt{A}+E) \) to \( z/(\sqrt{A}-E) \). Based on the statistics of small sample sets (Wetherill, 1967), when two values describe the range of an estimate the error on the estimate is equal to the range multiplied by 0.886. Thus, \( ^{14}\text{C} \) based sedimentation rates have a fractional error of \( \text{SD}_{\text{sedimentation rate}}/\text{sedimentation rate} \) where \( \text{SD}_{\text{sedimentation rate}} \) is:

\[
\text{SD}_{\text{sedimentation rate}} = 0.886 \times (z/(\sqrt{A} - E) - z/(\sqrt{A} + E)).
\]

Endmember flux errors are summarized in Table 3.

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