A sediment and organic carbon budget for the Canadian Beaufort Shelf

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Received 28 June 1997; accepted 12 August 1997

Abstract

The Arctic Ocean accounts for 20% of the world's continental shelves. Because the Arctic is sensitive to global change, budgets of organic carbon for its shelves are of immediate interest. The Mackenzie Shelf of the Canadian Beaufort Sea is the best North American proxy for the enormous Eurasian Shelves (large area, large river input) and the only site for which a complete organic carbon budget can be attempted, due to an extensive data base. A mass balance for the Mackenzie Shelf has been constructed for sediments, terrestrial organic carbon, and primary produced carbon. We have considered allochthonous inputs from the Mackenzie River, from coastal erosion, from smaller rivers, from groundwater, from the atmosphere and import by ice. The Mackenzie River dominates the supply to the Beaufort shelf of inorganic sediment (127 Mt a\(^{-1}\)) and particulate and dissolved terrestrial carbon (2.1 Mt a\(^{-1}\) POC, 1.3 Mt a\(^{-1}\) DOC). The combined input from all other sources contributes only about 5% of the Mackenzie load. Using sediment accumulation data we estimate that about half of the sediment supply is trapped in the delta, about 40% on the shelf and the remainder escapes the shelf edge by various processes. Autochthonous primary production in the delta and on the shelf adds a further 3.3 Mt a\(^{-1}\) of particulate organic carbon. A box model has been constructed to account for sediment, terrestrial organic carbon and primary produced carbon. Whereas about 60% of the terrestrial POC is preserved in delta and shelf sediments, it appears that most (97%) of the primary produced carbon is recycled and not preserved in sediments. Confidence in the budget should be improved by focusing future research on the determination of modern sedimentation rates on the delta and shelf, measurement of organic carbon content of deltaic sediments, determination of primary production on the shelf, and determination of the relative proportions of terrestrial and marine organic carbon preserved in sediments. © 1998 Elsevier Science B.V.

Keywords: Arctic; budget; carbon; continental shelf; sediments

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PII S0025-3227(97)00106-0
1. Introduction

Continental shelves and margins are the most important locations in the ocean for sequestering sediments and for recycling and sequestering organic carbon (Berner, 1982; Jahnke et al., 1990; GESAMP, 1992; Smith and Hollibaugh, 1993; Romankevich, 1994) and the ‘burndown’ of carbon in marine sediments significantly influences the global cycling of many other elements (Bender et al., 1989; Shaw et al., 1990; Sundby et al., 1992; Canfield et al., 1993a,b; Christensen, 1994). Shelves, as the interface between land and the open ocean, are thought to be important not only for biological productivity (cf. Romankevich, 1994; Denman et al., 1996) but they are also the regions where human activity is likely to have the greatest impact.

Of the world oceans, the Arctic contains the largest relative proportion of shelf (30%) and at $5 \times 10^6$ km$^2$, the Arctic shelves contribute about 20% of the world’s continental shelf area. Despite their importance in terms of both area and sensitivity to global change, the Arctic shelves tend to be ignored in, for example, global maps of productivity (Berger and Wefer, 1991) and in reviews of ocean margins (Mantoura et al., 1991). This is due partly to a thin data base and partly to a lack of awareness of the data that do exist. The Arctic shelves have recently witnessed accelerated research fed by a concern about priority contaminants, many of which are particle-reactive and enter the ocean at margins (Macdonald and Bewers, 1996); therefore, particulate and organic carbon budgets will be a crucial first step for constructing contaminant budgets.

We focus on the Canadian portion of the Beaufort Shelf which we will call the Mackenzie Shelf (Fig. 1). This is the largest shelf on North American side of the Arctic Ocean and it receives the inflow from a very large, sediment-rich river (the Mackenzie). As such, it provides the only North American proxy for the wide Eurasian shelves onto which the Arctic’s largest rivers discharge water and sediments (cf. Gordeev et al., 1994). Because both the Mackenzie Shelf and River have been studied extensively for the past two decades, there exists one of the most comprehensive baseline data sets for any Arctic shelf with which to attempt a budget.

Here we construct a budget for sediments and for terrestrial and marine organic carbon for the Mackenzie Shelf by considering it as a multi-box system into and out of which these components flow. To produce such a budget is fraught with difficulty because this region has multiple sediment sources, dynamic transport processes, and an open communication with the Arctic Ocean. We approach the problem by considering as many lines of evidence as possible to produce a consistent and credible set of numbers, and by emphasizing the refereed literature. Where possible, we provide errors or ranges; we note that a number of the literature sources are not accompanied by error estimates. Fortunately, uncertainty can be estimated for the most significant contributors to the budgets.

2. A brief overview of the Mackenzie Shelf

The Mackenzie Shelf is about 100 km wide and encompasses an area of about 60,000 km$^2$ (Fig. 1; Thomas et al., 1986). The shelf is seasonally ice covered; freeze-up usually starts in mid-October, about 2 m of first-year ice forms during winter, and breakup commences in early June.

The Mackenzie River, the fourth largest in the Arctic, provides a seasonally varying input of both freshwater and suspended sediment (Fig. 2, Thomas et al., 1986). The Mackenzie Basin, from which the river derives its materials, is extensive ($1.8 \times 10^6$ km$^2$). The westernmost portion is characterized by high elevations and associated high levels of sediment supply. Hirst et al. (1987) estimate that approximately half of the annual sediment load supplied to the Mackenzie Delta is derived from the Liard River drainage alone. This is due in part to the absence of large lakes within the Liard’s drainage area that could trap sediment prior to reaching the Mackenzie River (Church et al., 1986). The central portion drains the interior plains and the easternmost region is located within the Canadian Shield. Relief and associated sediment supply is relatively low in these latter two areas.
The shoreline of the Mackenzie Shelf is composed of unconsolidated, frozen sediments; predominantly fine sands with lesser amounts of clay and poorly sorted terrestrial muds. Most of the coastline consists of low cliffs (1 m to 50 m) which are undergoing erosional retreat. Barrier islands and spits and other types of accretional landforms characterize about 40% of the coastline (Harper et al., 1985).

3. Inputs of sediment and organic carbon to the Mackenzie Shelf

3.1. The Mackenzie River

The Mackenzie River discharges about $3.3 \times 10^{11} \text{ m}^3 \text{ a}^{-1}$ of freshwater most of which comes between May and September (Fig. 2; Table 1). There is a large interannual variability in the freshwater discharge ($\pm 25\%$) and in the amount of sediment carried. Sediment load is considerably more difficult to measure. Having reviewed the literature (Table 1), we accept as the best estimate $127 \pm 6 \text{ Mt a}^{-1}$ delivered to the delta which is based on daily sediment loads and discharges where available, and on stage–discharge curves and sediment ratings for a 15-year period (Carson, 1988, 1994a).

The suspended particulates in the Mackenzie River have been found to contain $4.8 \pm 1.3\% \text{ C (n = 18)}$ in winter and about $1.4 \pm 0.2\% \text{ C (n = 10)}$ in freshet (Yunker et al., 1993). This latter number matches the organic carbon content of surface sediments on the inner shelf (Pelletier, 1975, 1984).
Fig. 2. The Mackenzie River hydrology for the years 1973–1990 (Water Survey of Canada). The solid line shows the average daily rate of inflow whereas points show daily values. Differences between years and events within years can be seen by the patterns inherent in the data.

Table 1
Summary of estimates of Mackenzie River freshwater discharge and sediment load

<table>
<thead>
<tr>
<th>Reference</th>
<th>Freshwater discharge (km$^3$ a$^{-1}$)</th>
<th>Sediment load (10$^6$ t a$^{-1}$)</th>
<th>Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Levinson et al. (1969)</td>
<td>300</td>
<td>–</td>
<td>Varied$^a$</td>
</tr>
<tr>
<td>Thomas et al. (1986); Davies (1975)</td>
<td>370</td>
<td>220</td>
<td>1974–1975</td>
</tr>
<tr>
<td>Telang et al. (1991)</td>
<td>249$^c$</td>
<td>139$^d$</td>
<td>not given</td>
</tr>
<tr>
<td>Milliman and Syvitski (1992)</td>
<td>306</td>
<td>142$^d$</td>
<td>not given</td>
</tr>
<tr>
<td>Carson (1994a,b)</td>
<td></td>
<td>127 ± 6</td>
<td>1974–1990</td>
</tr>
</tbody>
</table>

$^b$ Given as 90 x 10$^6$ t a$^{-1}$ for 1989–1985.
$^c$ Arctic Red River.
$^d$ Back calculated from POC data assuming 1.4% carbon on particulates (Yunker et al., 1993).
$^e$ Due to a typo this value was erroneously reported as 42 x 10$^6$ t a$^{-1}$ in the cited paper (Syvitski, pers. comm.).

To estimate the annual delivery of POC to the delta (2.1 Mt a$^{-1}$) we have assumed that 7% of the particle loading is delivered in winter and the remainder during May to August (Carson, 1988). Telang et al. (1991) used the Mackenzie River discharge and their POC data to arrive at a similar figure of 1.8 Mt a$^{-1}$ (cf. Degens et al., 1991). According to Telang et al. (1991) the POC is
accompanied by an approximately equal amount of DOC (1.3 Mt a\(^{-1}\)), which is paralleled in other world rivers (Smith and Hollibaugh, 1993). The bulk of the terrestrial particulate organic carbon from the Mackenzie River is non-colloidal (Whitehouse et al., 1989), probably refractory (Ittekkot, 1988), and therefore it is expected to preserve better than organic carbon produced in the marine system (Hedges et al., 1988; Hedges, 1992).

3.2. Coastal erosion

Shoreline erosion rates for the Mackenzie Shelf are rapid, reaching values of up to 20 m a\(^{-1}\) (Harper et al., 1985; Harper, 1990; Hill et al., 1986), but more typically 2 m a\(^{-1}\). Volumes of material supplied to the coast by erosion are a function of the linear rate of retreat (e.g., m a\(^{-1}\)), coastal bluff height, sediment type and ice content. Harper and Penland (1982) used long-term (decadal) cliff retreat rates together with cliff heights to estimate that 2.9 \times 10^6 m^3 a\(^{-1}\) of sediment is produced by coastal erosion. More recent estimates suggest that the erosion rate used for parts of the coastline may be low, but this certainly would not change the sediment volumes by more than a factor of 2. Hill et al. (1991) estimate coastal erosion at 3.5 \times 10^6 m^3 a\(^{-1}\), which they convert to 5.6 Mt a\(^{-1}\). Although coastal erosion may be important locally, it is clearly much less than the Mackenzie River delivery (Table 2).

Organic carbon content of coastal soils is variable and not well known. Drained lake basins and modern delta-front soils are highly organic. For example, Yunker et al. (1993) report the organic carbon content of lacustrine basin/moraine peat to be 15–32%, and unpublished data from one lake indicates that the organic carbon content of lake bottom sediments is about 5–10%. In contrast, eroding soils underlying upland tundra surfaces and spit/barrier complexes are less organic rich. It is not presently known what fraction of the coastline is composed of drained lake soils. Modern delta soils are probably similar to the lake basin sediments. Organic carbon content of soils collected from beaches along outer coastal islands, the modern Mackenzie delta front and the Tuktoyaktuk Peninsula varies from non-detectable to 16.8%, with most samples in the range of 1–3% (Lawrence et al., 1984).

The organic carbon data and peat/shoreline erosion estimates in Yunker et al. (1991) imply that the active delta contributes 0.013 Mt a\(^{-1}\) organic carbon and peat erosion contributes a further 0.042 Mt a\(^{-1}\) for a total of 0.055 Mt a\(^{-1}\). Since the peat calculation does not include co-eroded soil (mostly sand or glacial till with low organic content) it should be regarded as conservative. If we assume that the mixture of eroded soil and peat for the entire coastline contains up to 5% organic carbon by weight, and use the coastal erosion rates given by Hill et al. (1991), the organic

Table 2
Summary of inputs to the Mackenzie Shelf

<table>
<thead>
<tr>
<th>Source</th>
<th>Sediment (10^6 t a(^{-1}))</th>
<th>Particulate organic carbon (10^6 t a(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mackenzie River (POC)</td>
<td>127 ± 6</td>
<td>2.1 ± 0.3</td>
</tr>
<tr>
<td>Coastal erosion</td>
<td>3.6 ± 2.5</td>
<td>0.06 (&lt;0.3)</td>
</tr>
<tr>
<td>Other rivers</td>
<td>1.5</td>
<td>0.02</td>
</tr>
<tr>
<td>Shelf production *</td>
<td></td>
<td>3.0 ± 1.2</td>
</tr>
<tr>
<td>Delta production *</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Land based</td>
<td>0.16</td>
<td></td>
</tr>
<tr>
<td>Aquatic based</td>
<td>0.16</td>
<td></td>
</tr>
<tr>
<td>Atmosphere</td>
<td>0.004</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Import by ice</td>
<td>1.6</td>
<td>0.03</td>
</tr>
<tr>
<td>Groundwater</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Total input</td>
<td>136</td>
<td>5.5</td>
</tr>
</tbody>
</table>

* Based on the following areas: delta – 6400 km\(^2\), shelf – 60,000 km\(^2\).
carbon contributed annually by coastal erosion is not likely to exceed 0.3 Mt a\(^{-1}\).

3.3. Other small rivers

All evidence suggests that inputs from these sources are small relative to the Mackenzie River and have only local importance (Hill et al., 1991; Forbes, 1981). Rating the drainage areas against the yield of the Babbage River, Harper and Penland (1982) estimated that the rivers along the Yukon coast delivered collectively 1.45 Mt a\(^{-1}\) of sediment. In Table 2 we estimate organic carbon input 0.02 Mt a\(^{-1}\) by assuming it to be 1.6% of the particulates.

3.4. Primary production over the shelf and delta

Due to their massive area, seasonal clearing of ice, and nutrient input from rivers or upwelling, the Arctic shelves should be especially significant in the production of biogenic carbon in the Arctic Ocean (Walsh, 1991; Legendre et al., 1992). Estimating annual primary production and its associated carbon flux is complicated by the extreme seasonality and patchiness of phytoplankton both in the water column and in ice, especially in the dynamic marginal ice zones (Niebauer and Alexander, 1985; Honjo, 1990; Horner, 1990; Niebauer, 1991; Welch et al., 1991, 1992; Legendre et al., 1992; Hargrave et al., 1994) and the difficulty of working in the Arctic during breakup, the peak season for biological production. On the Mackenzie Shelf a further complication is produced by the Mackenzie River which partitions the shelf into at least two distinct biological communities (Parsons et al., 1988, 1989), and whose turbid waters may at times limit production for the river delta and large parts of the inner shelf (Grainger, 1975).

The data set available to evaluate annual production for the Mackenzie Shelf is small. Exportable carbon or ‘new production’ has been estimated from nitrate budgets to be about 20 g C m\(^{-2}\) a\(^{-1}\) (Macdonald et al., 1987). This figure compares reasonably well with more general estimates of exported Arctic shelf production by Anderson et al. (1990) (45 \(\pm\) 20 g C m\(^{-2}\) a\(^{-1}\)). Wallace et al. (1987) (8–13 g C m\(^{-2}\) a\(^{-1}\)) or with the average total shelf production estimated by Subba Rao and Platt (1984) (27 g C m\(^{-2}\) a\(^{-1}\)). It appears that much of the organic carbon produced by plankton over the shelf is remineralized.

Ice algae cannot be ignored for estimates of production or carbon fluxes (Horner, 1990). Algal mats formed on the bottom of the ice have been observed to be shed from the melting ice during spring breakup and produce a rapid and relatively undegraded pulse of carbon to deeper water (Macdonald et al., unpublished) or to the sediments (Yunker et al., 1995). Such episodic export events decouple consumption from production and may therefore dominate the flux of organic carbon to the shelf sediments or to the deep sea (Legendre et al., 1992).

Benthic algae are thought to provide only a very small contribution for the Mackenzie Shelf and can probably be ignored in a first order budget (Horner and Schrader, 1982; Macdonald and Thomas, 1991). Macrophytes, which can be important producers in some regions of the Arctic (e.g., Henley and Dunton, 1995) play virtually no role on the Mackenzie Shelf.

In consideration of the references cited above and others (e.g., Bergmann et al., 1991; Welch et al., 1991, 1992), we make the following estimates for the Mackenzie Shelf. Total annual primary production is about 50 g C m\(^{-2}\) (confidence range of 30–70). About 5–10% of the total production is contributed by ice algae and 40% (20 g C m\(^{-2}\)) of it is nitrate based (new production). For the 60,000 km\(^2\) area, this leads to a total production of 3.0 Mt a\(^{-1}\) (Table 2).

There are few data for estimating primary production in the delta. Within a shallow tundra lake on the adjacent Tuktoyaktuk Peninsula, total photosynthesis was measured at 38 mmol C m\(^{-2}\) d\(^{-1}\) (Ramlal et al., 1994). In constructing a carbon budget for this lake, Ramlal et al. (1994) estimated that 50% of the carbon was produced by benthos, 20% by phytoplankton, 30% was allochthonous, and that the total photosynthesis was approximately equalled by respiration. About 60% of the delta surface is comprised of similar environments (Hirst et al., 1987) from which we estimate total delta phytoplankton productivity to be about 0.16
Mt C a⁻¹ (assuming a 100 day season). Although some productivity occurs in the river during freshet (Yunker et al., 1995), turbidity in the river and in lakes connected to the river is thought to limit such production to low values (Guildford et al., 1991) give a range of 3.8 to 7.7 g C m⁻² a⁻¹). In addition to the aquatic production in the delta should be added a terrestrial component, for which we have found no information. Here we assume that the land-based production is equivalent to aquatic production. Because the area of the delta is small relative to the shelf, error in this estimate has only a small effect on the overall regional budget.

3.5. Atmospheric deposition

Atmospheric (eolian) fluxes of particulates to the Canadian Beaufort Sea have not been directly measured but several lines of evidence suggest that they are very low (Reimnitz and Maurer, 1979; Darby et al., 1989; Reimnitz et al., 1992). We estimate the flux of atmospheric particulates to the Mackenzie Shelf using Arctic data for sulphate deposition by assuming the following: sulphate accounts for about 60–70% of the particulate mass (Barrie and Hoff, 1985); carbon black in aerosols contributes 1/15 the amount of sulphate (Hopper et al., 1994); dry deposition velocity is within the range 0.04–0.15 cm s⁻¹ (Voldner et al., 1986); and wet deposition contributes about two times the dry deposition (Barrie, pers. comm). Using a sulphate aerosol concentration of about 1 ng m⁻³ (Voldner et al., 1986; Barrie and Barrie, 1990), the maximum dry deposition works out to 4.7 × 10³ t a⁻¹ over the whole shelf, which implies a total (wet and dry) deposition of about 1.4 × 10⁴ t a⁻¹. Jickells et al. (1990) estimated that 0.25 Mt a⁻¹ of sulphur is deposited within the Arctic north of the Arctic circle (2.1 × 10¹³ m²). Following parallel reasoning this deposition rate implies an aerially prorated particulate deposition on the Mackenzie Shelf of 3.6 × 10⁴ t a⁻¹. For comparison, Darby et al. (1989) used snow samples from the western central Arctic pack ice to estimate the contribution by eolian dust to marine sedimentation. Their figure, 0.02–0.09 mm ka⁻¹, would imply about 0.001–0.006 Mt a⁻¹ for the entire Mackenzie Shelf.

3.6. Import by ice

The Mackenzie Shelf is a net exporter of ice during winter due to surface divergence as witnessed by the large flaw lead over the mid-shelf that opens intermittently in winter (cf. Omstedt et al., 1994; Macdonald et al., 1995; Melling and Riedel, 1996). Since the shallow regions of the inner shelf can supply sediments, it is likely that the net transport of particulates and organic carbon by ice is off the shelf. On the other hand, substantial quantities of pack ice transported in the Beaufort Gyre transit the outer shelf (Melling and Riedel, 1993). It is expected that such ice would not carry much sediment because sediment sources toward the east are minimal. However, since the Alaskan and Chukchi shelves border the Beaufort Gyre, and since these regions are known to incorporate bottom sediments into ice (Reimnitz et al., 1994), there is the potential for ice to arrive at the outer shelf after making almost a complete circuit of the Gyre, melt, and drop some of its sediment burden. Reimnitz et al. (1993a) estimate that the average particle concentration in ice from the Beaufort Gyre is about 40 g m⁻³. If we assume that approximately 1 m of sea-ice melt is contributed to the outer two-thirds of the shelf by the advection of ice from the Beaufort Gyre onto the shelf (Macdonald et al., 1989, 1995), this would imply a sediment import about 1.6 Mt a⁻¹. The organic carbon content of the sediment carried by ice was about 2% (Reimnitz et al., 1993b) which, using the above figures, implies a particulate organic carbon delivery of about 0.03 Mt a⁻¹.

3.7. Groundwater

Although there is mounting evidence that groundwater is an important contributor of freshwater and dissolved matter to some coastal regions (Moore, 1996; Church, 1996), ice-bonded soils in the Arctic coastal zone extending from terrestrial to subaqueous environments provides an effective barrier to downward movement of seasonal meltwaters. It is likely that during summer and freeze-up some transfer of groundwater occurs from land to sea. However, groundwater probably contains mainly dissolved materials (primarily
salts) and does not contribute any meaningful quantities of solids or organic carbon.

4. Sinks for sediment and organic carbon on the Mackenzie Shelf

Sediments presently accumulating in the delta and on the shelf act as long-term reservoirs for allochthonous and autochthonous materials (Table 3). Allochthonous materials (from rivers, shore erosion and ice rafting) make up the bulk of the Mackenzie shelf sediments (Pelletier, 1975, 1984). Autochthonous materials include organic carbon from marine primary production, opaline silica and carbonate shells. Sedimentation rates, which are fundamental to the estimation of fluxes to sinks, are poorly known for the entire region.

4.1. Mackenzie Delta sedimentation

Lewis (1988) estimated the quantity of sediment deposited in the delta during the Holocene using the stratigraphic record, horizontal dimensions and the deltaic cross-section. Borehole and seismic data were used by Hill et al. (1993) to arrive at an average deposition rate in the delta during the past 10,000–12,000 years of 136–163 Mt a\(^{-1}\). Although these rates fall within the range of sediment loading estimates given in Table 1, they clearly exceed the estimate of the present-day supply by the Mackenzie River (Table 2).

Pearce (1993) suggests that modern sedimentation rates on the delta-top are much lower (76–82 Mt a\(^{-1}\)). An independent check on this estimate using radiocarbon dates obtained on boreholes drilled in the delta (Johnson and Brown, 1965; Dallimore pers. comm.), indicates that delta-top sedimentation rates range from 0.3 to 0.8 cm a\(^{-1}\) (17 m of sediment in the past 2100 years) which yields a corresponding sedimentation rate of 69 Mt a\(^{-1}\). Hirst et al. (1987) estimate modern sedimentation on the delta (13,000 km\(^2\)) to be in the range of 64–153 Mt a\(^{-1}\), but they questioned the upper estimate because it exceeds the present annual sediment delivery by the river. Finally, Carson (1994a,b) estimated that of the 127 Mt a\(^{-1}\) delivered to the top of the delta, 116 Mt a\(^{-1}\) passed the mid-delta and perhaps 100 Mt a\(^{-1}\) reached the outer delta implying a net deposition of about 27 Mt a\(^{-1}\) within the delta. However Carson cautioned that loads at the outer-delta stations may have been overestimated by the hydraulic model (i.e., net deposition in the delta would be underestimated). In view of the above discussion we accept 65 ± 15 Mt a\(^{-1}\) as the best estimate of modern sedimentation in the delta.

The average organic carbon content of the deltaic sediments is not easily determined. The modern delta sediments, which are accumulating river particulates (organic carbon content of 1.4% in freshet, 4.8% in winter), are also potentially burying organic carbon produced within the delta. As already outlined, delta and coastal sediments vary widely in their organic carbon contents (0–32%) depending on the location and quantities of peat. Lawrence et al. (1984) surface samples for the delta coast \((n=42)\) contained 2.2±1.3% organic carbon; Yunker et al. (1991) reported 0.9%–3.5%. Here we have chosen the weighted average for organic carbon content of sediment delivered by the river (1.64%) but suggest a wide range of uncertainty (±0.6) to bracket most of the measurements. This number yields 1.07±0.4 Mt C a\(^{-1}\) for the flux to surface sediments in the delta.

4.2. Mackenzie Shelf sedimentation

Modern sedimentation rates on the open shelf are poorly known. This is partly due to the dynamic reworking of sediments that occurs on the shelf from ice scour, storm resuspension and bio-mixing (Hill and Nadeau, 1989), and partly due to the lack of effective tools to measure modern
Sediment rates in this region (Macdonald and Thomas, 1991).

Sediment accumulation rate on the Mackenzie Shelf can be estimated from seismic data by making the assumption that the widely observed near-surface unconformity represents the Holocene transgressive surface (Fig. 3a). Accordingly, a variety of sediment thickness maps and relative sea level curves sharing a common lineage but evolving with time have been used (Meagher, 1978; O’Connor et al., 1980, 1981; Harper and Penland, 1982; Pelletier, 1984; Fissel and Birch, 1984; Hill et al., 1991). Variable sedimentation rates, inadequate dating of the transgressive surface, and poorly constrained relative sea level curves, along with the difficulty in mapping the unconformity due to the presence of gas and ice-bonded permafrost, make this approach problematic. However, there is presently no better way to estimate the flux of sediments to this shelf.

According to Harper and Penland (1982), sedimentation rates for shelf sediments are in the range 0.01–0.3 cm a⁻¹ with the greatest rates in the Kugmallit Channel and relatively high rates in the Ikit and Mackenzie Troughs (Fig. 3a). Sedimentation rates over the plateaux range from 0.01–0.1 cm a⁻¹. In these calculations, the area of southern Mackenzie Shelf where modern sediments are accumulating was estimated to be 49,000 km² (Harper and Penland (1982) based on Meagher (1978) measurements). The total sediment accumulation was estimated as 6.1 x 10¹¹ t of which approximately 42% is contained in the Mackenzie Trough. Using satellite imagery together with sedimentation rate estimates, Harper and Penland (1982) postulate that significant amounts of sediment are deposited inshore of the 10 m isobath along the modern Mackenzie Delta front and at the mouth of Kugmallit Bay.

Hill et al. (1991) base their estimate of sedimentation rate on an isopach map showing sediment thickness in a restricted area between Kay Point and Atkinson Point. Assuming a bulk density of 1.6 t m⁻³ they calculate a shelf sediment mass of 5.5 x 10¹¹t and a mean annual sedimentation rate of 46–55 Mt a⁻¹ (this range reflects only the choice of age for the transgressive surface from 8 ka to 10 ka and is not an estimate of total uncertainty). Harper and Penland (1982) estimate 46–78 Mt a⁻¹, pointing out that the calculations are very sensitive to the sedimentation rate assumed for the <10 m shelf area immediately fronting the modern Mackenzie Delta. For the <10 m shelf region, sedimentation estimates range from 0.22 cm a⁻¹ (Harper and Penland, 1982) to 0.5 cm a⁻¹ (Johnson and Brown, 1965) to 1.0 cm a⁻¹ (Vilks et al., 1979). Here we have chosen 0.5 cm a⁻¹ based on sediment thickness estimates.

To estimate the shelf sediment sinks (Table 3) for this study, we obtained digital files of the maps produced by O’Connor et al. (1981). The sedimentation rates were determined by O’Connor et al. (1981) based on sediment thickness in each polygon divided by the time since transgression at that polygon based on the Hill et al. (1985) sea-level curve (Fig. 3a). Inner shelf sediment thickness in Kugmallit Bay, Ikit Trough and the Mackenzie Trough were estimated from information in Hill et al. (1991) and data from nearshore surveys (Solomon et al., 1992). There are few published data from the Western Beaufort Shelf (the region west of the Mackenzie Delta and Trough referred to informally as the Natsek Plain). Unpublished reports and comparison with the stratigraphy from the Alaskan Beaufort Sea (Reimnitz et al., 1988) suggest that the Natsek Plain is predominantly erosional. The area occupied by this feature is 3100 km² up to the international border and about 6600 km² in total. In several of the inshore areas, direct measurements of sedimentation rate were obtained from radiocarbon dates. To convert from depth accumulation rate to the sediment mass flux shown in Fig. 3b, we assume a porosity of 60% and solids density of 2.6 g cm⁻³.

To calculate the accompanying organic carbon fluxes to shelf sediments, we obtained Pelletier (1975) surface sediment organic carbon data (n = 50). These data agree well with more recent organic carbon determinations reported for five box cores collected by Gobeil et al. (1991). The organic carbon data were gridded at 0.1° intervals and values were assigned to each polygon associated with a sediment thickness (Fig. 3c). Organic carbon flux (Fig. 3d) was obtained by multiplying the sediment flux by the surficial organic carbon content to yield a total sediment flux of 53 Mt a⁻¹ and a surficial organic carbon flux of 0.71 Mt a⁻¹.
Fig. 3. Maps showing (a) the sedimentation rate for shelf sediments calculated from isopach thickness, (b) the sedimentation rate for shelf sediments converted to g cm$^{-2}$ a$^{-1}$ by assuming a porosity of 60% and a solids density of 2.6 g cm$^{-3}$, (c) the distribution of organic carbon in surface sediments and (d) the organic carbon flux calculated from the distributions given in (b) and (c).
5. Losses of sediment and organic carbon at the shelf edge

The difference between the estimated supply of particulates (Table 2) and the particulates accounted for in delta and shelf sediments (Table 3) of 18 Mt a\(^{-1}\) implies a leakage off the shelf of about 13% of the total sediment input. Taking a difference between large and uncertain numbers is not a good way to estimate the shelf-edge particulate transport and, given only the ranges in Tables 2 and 3, net transport could even be onto the shelf. However, independent lines of argument, given below, suggest that the Mackenzie shelf is indeed a net exporter of sediments, and the estimated rate (13% of the input) is entirely consistent with what is thought to occur on other wide shelves (cf. Milliman, 1991; Eisma et al., 1995).

Processes that export sediments from the Mackenzie shelf include transport by ice (Reimnitz et al., 1993b), transport within the Mackenzie plume (Giovando and Herlinveaux, 1982), resuspension and off-shelf transport of nearshore sediments during late-season storms (Hodgins, 1988), escapement in brine drainage (Melling and Lewis, 1982), and downslope movement and debris flows (Campbell and Clark, 1977; Hill et al., 1982).

5.1. Export by ice

The entrainment of bottom and suspended sediment during ice formation in winter is known to play a substantial role in the sediment budget of the Alaskan Arctic Shelf (Reimnitz et al., 1993b, 1994; Reimnitz and Barnes, 1987). According to Reimnitz et al. (1993b), suspension freezing in a coastal polynya off Alaska produced sediment burdens in ice of over 289 t km\(^{-2}\) with subsequent export of sediment estimated at \(6.7 \times 10^4\) t during a 3-month period. Assuming a similar event occurred on the Mackenzie shelf producing ice covering one quarter of the shelf, implies a potential transport of 4.3 Mt. This is small relative to the Mackenzie River input, about equivalent to coastal erosion (Table 2), and well within the estimate of total sediment loss at the shelf edge (Table 3). Unpublished data from several sites in the vicinity of Kugmallit Bay during 1993 and in ice cores collected predominantly from the landfast ice in 1987 (Macdonald and Carmack, 1991) and 1991 (Macdonald et al., 1995) indicate that sediment concentrations in nearshore ice is low. Hopky et al. (1994) determined an average concentration of 13 mg L\(^{-1}\) \((n=22)\) which, for a 2-m ice cover, would correspond to 26 t km\(^{-2}\). Clearly ice transport is a process that requires further investigation within the region.

5.2. Sedimentation on the slope

Sedimentation rates on the continental slope are not confidently known; O'Connor et al. (1981) suggest very low rates whereas Hill et al. (1982) give higher rates of about 0.1 cm a\(^{-1}\). Taking this higher sedimentation rate, and using the same porosity and density values as above, 18 Mt a\(^{-1}\) would be accounted for by an area of about 17,000 km\(^2\). Thus sedimentation on the slope/rise seems a plausible fate for much of the sediment we estimate to leave the shelf. Using surface sediment values from the shelf edge for organic carbon of 1.2% (Pelletier, 1975, 1984) suggests that these inorganic shelf sediments probably sequester about 0.17 Mt a\(^{-1}\) of organic carbon.

5.3. Biological transport of carbon

Although organic carbon may be lost through mammal migration, rough calculations show that this process can be safely neglected. For example, 20,000 beluga feeding on the Mackenzie Shelf might export 10 kg C each. Together with 8000 bowhead whales these large animals might remove \(2.8 \times 10^3\) t a\(^{-1}\). Ringed seal energy flow is higher but there is not likely to be a net flow out of the system.

6. A preliminary budget for the shelf

6.1. Total sediment budget

Within the uncertainties of the various calculations, the sediment inputs (Table 2) can be accounted for by the sinks (Table 3). The scenario that the delta captures 50% of sediments entering it while the shelf captures about 75% of the shelf input is credible (Fig. 4, top panel). This leaves
about 13% unaccounted to escape the system. Because the loss at the shelf edge is calculated by difference this term is not well constrained.

6.2. Organic carbon budgets

6.2.1. Terrestrial carbon versus marine carbon

Marine organic carbon produced on Arctic shelves tends to be easily regenerated whereas terrestrial organic carbon supplied by rivers and coastal erosion tends to be refractory and of limited bioavailability (cf. Schell, 1983; Hedges, 1992). Because the two types of organic carbon are produced, cycled and preserved differently, a complete organic carbon budget for any shelf should distinguish between the terrestrial and marine components.

Terrestrial organic carbon eroded from the
Mackenzie Basin and subsequently buried without transformation in the delta or shelf sediments simply transfers sequestered carbon from one sink to another. The important question for the terrestrial organic carbon is, therefore, what fraction becomes oxidized or metabolized during its passage from land to burial in deltaic or shelf sediments. For marine organic carbon, the important question is what fraction of the primary production is removed permanently by burial in sediments or by transfer to the deep ocean (cf. Hedges, 1992). Global steady-state budgets of these two processes — oxidation of terrestrial carbon/ sequestering of marine carbon — are large and uncertain making it extremely difficult to detect the effects of global change (Smith and Hollibaugh, 1993; Denman et al., 1996).

Estimating the carbon budgets is not as straightforward as the sediment budget because we must account for an additional 'sink' of carbon lost through oxidation or metabolism (Berner, 1982; Ittekkot, 1988; Walsh, 1989; Smith and Hollibaugh, 1993). This loss can take place either in the water column or in the sediments. Although we have been able to estimate separate source terms for terrestrial and marine carbon (Table 2), the sink terms for organic carbon (Table 3) combine the two types of carbon. To overcome this difficulty, we have used the literature to estimate what proportion of the aquatic production is preserved in sediments.

6.2.2. Primary produced carbon (aquatic)

Using the data in Table 2 as a starting point, we construct the middle panel of Fig. 4. We assume that <10% of the annual aquatic primary production of the delta (0.16 Mt) is buried in sediments (<0.02 Mt) and the rest (0.14 Mt) is regenerated in the water column or in the sediments (cf. Ramalal et al., 1994). Negligible amounts of the delta production are exported to the shelf via the river. Similarly, we assume that shelf sediments capture about 2% of the shelf's primary production of 3 Mt (cf. Walsh, 1989; Pocklington et al., 1991) and that the remainder is either remineralized or exported. A net export of marine POC is likely to take place at the shelf edge because shelves tend to be more productive than the interior ocean. We have little idea what this transport is except to note that a large net export would tend to reduce the flux to shelf sediments.

6.2.3. Terrestrial carbon budget

Our constraints to the terrestrial carbon budget presented in Fig. 4 are (1) the input of terrestrial carbon (Table 2), (2) the estimated fluxes of total carbon (aquatic plus terrestrial) to surface sediments of delta and shelf (Table 3) and (3) the aquatic carbon budget (middle panel). In Fig. 4 (bottom panel) each year the riverine POC (2.1 Mt) is augmented by land-based production in the delta (0.16 Mt). The flux of terrestrial carbon to surface deltaic sediments is calculated as the difference between the total flux and the marine portion (1.07 Mt - 0.02 Mt = 1.05 Mt). Based on literature, we can expect an oxidative loss of about 20% for carbon buried in delta sediments (Berner, 1982; Ittekkot, 1988) and we have shown this as a deep arrow (0.21 Mt) and an oxidation arrow (0.02 Mt). The remaining POC (1.21 Mt) escapes to the shelf where it is augmented by carbon from coastal erosion, other rivers and ice (0.11 Mt). As before, we estimate the flux of terrestrial carbon to shelf sediments by difference (0.71 Mt - 0.06 Mt = 0.65 Mt). Based on the literature and on data from five box cores (Gobeil et al., 1991) we estimate an oxidative loss of about 20% before the carbon becomes deeply buried. Finally, the remaining POC (0.67 Mt) escapes the shelf. This final figure is probably an overestimate because it includes POC that has been metabolized on its transit through the system — taking a few months to a year (Macdonald et al., 1995).

Not included in the budget is terrestrial DOC (1.3 Mt) which enters the coastal DOC pool where it can become oxidized, metabolized or escape into the interior ocean. Since the residence time of the surface water is short on the shelf in summer we suspect that much of the riverine DOC simply transits the shelf to enter the surface pool of the interior ocean.

Our budget implies that the terrestrial carbon accounts for 90% or more of the carbon in delta and shelf sediments. In support of this picture, selective preservation of terrestrial carbon is clearly reflected in carbon and nitrogen isotope composi-
tion (Minagawa et al., 1991) and in hydrocarbon and sterol geochemistry of shelf sediments (Yunker et al., 1993, 1995). The Mackenzie Shelf sediments may be compared to sediments from the Washington coastal margin at the mouth of the Columbia River where terrestrial carbon was approximately 60% (Prahl et al., 1994), or to sediments on the shelf off East Liberia which also were estimated to contain 60% terrestrial carbon (Westerhausen et al., 1993). The outcome that much of the organic carbon in the Mackenzie Shelf sediments is terrestrial is, however, contrary to the conclusions about shelves in general reached by Jickells et al. (1991).

7. Conclusions

Using published and unpublished data we have constructed preliminary budgets for sediments, terrestrial organic carbon and aquatic produced carbon. The Mackenzie River is clearly the dominant supply for inorganic sediment to the region. Within the uncertainties of the estimates, the delta and the shelf each capture about equal amounts of sediment with approximately 13% of the inputs escaping the shelf. Our budget implies that about 60% of the terrestrial POC supplied by rivers and coastal erosion can be accounted for in delta and shelf sediments and less than 30% escapes past the shelf. The remainder is either oxidized or metabolized. Of the primary produced organic carbon (aquatic), only small capture rates in delta and shelf sediments are likely; the rest probably becomes remineralized before it can be permanently buried. The budget (Fig. 4) suggests that presently the delta/shelf is net heterotrophic (respiration exceeds production by 0.1 Mt a⁻¹ or more, depending on how much of the export term, 0.67 Mt a⁻¹, has been metabolized) and therefore is a source of CO₂ to the atmosphere.

Berner (1982, 1989) estimated the burial of carbon in world-wide deltaic-shelf sediments to be 9 x 10¹² mol a⁻¹. Assuming that world shelves occupy 2.6 x 10⁷ km², this would imply for the Mackenzie Shelf a prorated burial of about 0.3 Mt a⁻¹. Our budget suggests that the Mackenzie delta-shelf at 1.4 Mt a⁻¹ is considerably above this global average carbon burial rate.

To improve the budget presented here, future research should focus on the determination of (1) modern sedimentation rates in the delta and on the shelf, (2) organic carbon content of sediments in the delta, and (3) primary production for the region. Mass-based budgets are extremely difficult to construct and generally have large uncertainties associated with them. This is true even for Mackenzie Shelf which has an extraordinarily good data base by most standards. Additional constraints to the organic carbon budget can best be provided by determining the relative amounts of terrestrial and marine organic carbon preserved in sediments using for example stable isotopes (Keil et al., 1997) or biomarkers.

Acknowledgements

We thank the numerous researchers cited herein who over the years have collected the data sets used to make the budgets. We gratefully acknowledge P. Delaney, K. Falkner, D. Gordon, R. Keil, S. Pfirman and K. Ruttenberg, C. Schubert, J. Syvitski and P. Wheeler for reviewing earlier versions of the manuscript and providing numerous helpful suggestions and encouragement during this work. Figures were prepared by P. Kimber.

References

Discussion of the iron hypothesis. Limnol. Oceanogr. 36. 1899, 1918.


GESAMP, 1992. Anthropogenic influences on sediment discharge to the coastal zone and environmental consequences. GESAMP Reports and Studies No. 52. 67 pp.


eral transport in major north American, Russian Arctic, and Siberian rivers: the St. Lawrence, the Mackenzie, the Yukon, the Arctic Alaskan rivers, the Arctic Basin rivers in the Soviet Union, and the Yenisei. In: Degens, E.T., Kempe, S., Richey, J.E. (Eds.). Biogeochemistry of Major World Rivers, SCOPE 42. Wiley, New York, pp. 75-104.


