Accumulation of organic carbon in western Barents Sea sediments

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ABSTRACT

Seafloor sediment dynamics operating in the western Barents Sea modulate the accumulation of particulate organic carbon on the shelf. As part of the CABANERA project, an integrated study of carbon dynamics in the marginal ice zone, we quantify burial rates of organic carbon (OrgC) at 11 sites. We further assess physical and biological mixing of surface sediments using the radionuclide tracers 234Th and 210Pb. The study was undertaken in order to evaluate carbon sequestration in shelf sediments for this biologically productive Arctic shelf sea. 234Th was detected below the sediment surface at only 3 of 11 stations (VIII, XII, XVIII). At these stations, 234Th sediment-mixing coefficients ranged from 1 to 12 cm² yr⁻¹. Among all stations, 210Pb-derived mass sediment accumulation rates quantified below the depth of surface sediment mixing vary from 320 to 650 g m⁻² yr⁻¹. With the exception of stations in Hopen Trench (OrgC = 1.9–2.6%), sedimentary OrgC content ranges from 1.0% to 1.6%, decreasing only slightly from present-day (surface sediments) back to 1860 (∼10 cm depth). The resulting OrgC burial rates range from 3.7 to 8.5 g C m⁻² yr⁻¹. Rates are highest (>7 g C m⁻² yr⁻¹) in troughs (Hopen Trench and N. Kvivøya Trench) with an average for all other stations of 5.5 ± 1.7 g C m⁻² yr⁻¹. Burial rates are tightly coupled to mass sediment accumulation except in Hopen Trench where OrgC burial rates are high (7.5 g C m⁻² yr⁻¹) despite low mass accumulation (∼330 g m⁻² yr⁻¹). Homogenization of surface sediments through mixing diminishes the time-scale of resolution for our derived carbon burial rates to 10–25 years. We find that modern sediments accumulating on the shelf represent on average 5–7% of the annual integrated pelagic primary production or 11–15% of the vertical flux for the Barents Sea.

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1. Introduction

The Barents Sea marginal ice zone is characterized by high spatial and temporal variability in the vertical flux of particulate organic carbon to the seafloor (Wassmann et al., 1991; Wassmann and Slagstad, 1993; Wassmann, 2001; Olli et al., 2002). This is largely driven by seasonal and inter-annual variability in the spring bloom connected with the melting and retreat of the ice edge in association with lengthening daylight (Sakshaug, 2004). According to Wassmann et al. (2006), the annual integrated primary production is higher and less variable in Atlantic (~130 g C m⁻²) compared to Arctic (~70 g C m⁻²) water-influenced areas with an overall average of 93 g C m⁻² for the Barents Sea. During the spring bloom, a strong vertical flux attenuation with depth leads to a reduced vertical export of phytoplankton. But the average annual export production from phytoplankton alone to depth in the Barents is estimated at 40 g C m⁻² yr⁻¹ (Wassmann et al., 2006). In connection with sea-ice melt within the marginal ice zone, ice algae provides an additional source of primary productivity contributing to the vertical export production of the Barents Sea to the benthos (Søreide et al., 2006; Tammelander et al., 2006; Carroll and Carroll, 2003). Although ice algae are quantitatively less important for the Barents Sea as a whole, they can be locally important during the on-set of the spring bloom (Tammelander et al., 2006). Hence the vertical flux, which consists of these two sources of organic matter, combined with horizontally advected supplies provides the pool of available carbon to support the energetic requirements of benthic communities in the Barents Sea.

Compared to organic carbon cycling processes in the water column of the Barents Sea, much less is known about the fate of sedimentary carbon on the seafloor (Piepenburg et al., 1995; Vandieken et al., 2006; Renaud et al., 2008). Once at the sediment–water interface, this pool of organic carbon may be utilized by macro-benthic communities living in or on top of the sediment surface, undergo bacterial remineralization in surface sediments, accumulate in shelf sediments or be transported...
off-shelf to the Arctic basin (Belicka et al., 2002; Alperin et al., 1999; Schubert and Stein, 1996; Kuehl et al., 1993). Continental shelves, in general, store a disproportionately large fraction of ocean sedimentary organic carbon relative to their aerial extent (Silverberg et al., 2000; Schubert and Stein, 1996; Kuehl et al., 1993). Over the Holocene period, on average 79% of the pool of organic carbon buried on the seafloor of the Arctic Ocean, is stored on continental shelves (Stein and Macdonald, 2004). Water depth is a major controlling factor, whereby the shorter distance that particulate organic matter must sink before reaching the seafloor, the better are both the quantity and quality of organic input to the seabed (Klages et al., 2004; Demaison and Moore, 1980; Suess, 1980). However, bottom topography of the Barents Sea shelf consists of shallow banks and a number of submarine canyons and trenches leading to a highly complex depositional environment. Thus, while the bulk of sedimentary material is preferentially delivered to shallow bank areas, due to strong bottom currents the sediment deposits in these areas contain coarser, and typically less carbon-rich sediments (Sternberg et al., 2001), suggesting that these areas are not major sites for long-term carbon accumulation. Over longer time scales submarine canyons and trenches serve to convey sediments containing organic carbon to the deep-sea (Grebmeier and Cooper, 1994; Devol et al., 1997; Clough et al., 2005).

Long-term carbon burial rates based on thickness of Holocene (0–11 kyr BP) sediments are available from the comprehensive carbon budget analysis of Vetrov and Romankevich (2004). These authors establish that, among Arctic shelf seas, the Barents Sea is the largest source of marine-derived organic carbon and the largest sink of carbon on the seafloor. According to Vetrov and Romankevich (2004), sedimentary organic carbon in the Barents Sea is derived from 30% terrigenous sources, i.e. eolian input, river discharge, and coastal erosion, while 70% is derived from marine primary production. Over the Holocene, the amount of organic carbon buried in sediments as a percentage of Barents Sea primary production is roughly 2%.

Here we examine carbon burial processes during the most recent past (~10^3 yr). While the work of Vetrov and Romankevich (2004) provides information for the entire Holocene period (~10^4 yr), the present study uses naturally occurring radioactive tracers to provide previously unavailable information on short time-scale processes of carbon burial within this important region. We quantify the burial fraction of sedimentary organic carbon at 11 stations on the northwest Barents seafloor (Fig. 1). These sites cover water depths from 200 to 500 m and underlie Atlantic- to Arctic-influenced areas. Carbon remineralization is a function of oxygen penetration depth, and as a result is tightly coupled with the intensity of biological mixing (Ambrose et al., 2001; Alperin et al., 1999). Here we evaluate carbon burial rates in context with information on sedimentary mixing derived from the radioactive tracers, $^{234}$Th and $^{210}$Pb. These tracers further establish the timescale of integration for our derived burial rates. Zaborska et al. (2008) present detailed information on variations in sediment accumulation at all sites while this study contributes to the overall understanding of the carbon cycle in this highly productive Arctic marginal sea.

2. Materials and methods

2.1. Field activities

Sediment cores were collected by multi-corer (four cores per cast) or box corer (0.25 m²) from 11 stations along a general south to north latitudinal gradient of 6° (75°–81°N) in the western Barents Sea (Fig. 1). Sampling was performed in June 2003 (stations I–IV), August 2004 (stations VIII–XII), and May 2005 (stations XVI–XVIII). Sub-sampling of the box corer was...
performed as follows: overlying bottom water was gently siphoned from the sediment surface prior to insertion of four core tubes (50 cm long; 10 cm diameter). The walls of the box corer were then removed and the undisturbed core tubes were extracted and cleaned. Each sediment core was sectioned into 0.5-cm intervals to a depth of 5 cm and 1 cm intervals thereafter. One sediment core from each cast was sub-sampled for determining sediment properties (organic carbon, grain size, porosity, density). Similar depth intervals from three cores from the same cast were combined to provide enough material for $^{234}$Th analyses (20 g). Sediments were dried at 60°C and homogenized onboard the ship. Dried and homogenized samples were stored frozen in plastic bags until analyses.

2.2. Radionuclide analyses

Measurements of gamma-emitting radionuclides: $^{210}$Pb, $^{137}$Cs, and $^{226}$Ra (supported $^{210}$Pb) were carried out at ENEA (The Italian National Agency for New Technologies, Energy and the Environment) using ORTEC high-purity planar germanium detectors. The analyses were carried out on individual samples (20 g) packed in vials of a standard geometry. After initial measurement to quantify total $^{210}$Pb activities, samples were stored for 21 days to allow for ingrowth of $^{222}$Rn and then re-measured. Sediment activities were corrected for self absorption (Cutshall et al., 1983). Excess $^{210}$Pb ($^{210}$Pbx) activity is the difference between total $^{210}$Pb and supported $^{210}$Pb (in equilibrium with the parent radionuclide $^{226}$Ra). For additional details on $^{210}$Pb sample analyses and data handling, see Zaborska et al. (2008).

After initial measurement of $^{234}$Th, the samples were stored for a minimum of 60 days (up to 1 year) to allow for the decay of excess $^{234}$Th ($^{234}$Thex). After correcting both measurements for the elapsed time since collection, $^{234}$Thex was calculated for surface sediment intervals ($z<3$ cm) as the activity difference between the two $^{234}$Th measurement time points.

Detector efficiencies were calibrated using several sources and verified using the IAEA standard (IAEA-300). Detector blanks were determined from measurements performed on empty sample vials over a few days and these were found to be similar to natural background.

2.3. Organic carbon and grain size analyses

Samples were dried in a drying chamber at 70°C. Approximately, 0.22 g of sample were weighed into a porous crucible, treated with 10% hydrochloric acid (HCl) and washed a minimum of three times to remove CaCO$_3$. Samples were subsequently washed with distilled water at least six times and dried at 100°C overnight. Total organic carbon (TOC) analyses were performed on a Leco IR 212 carbon analyzer. Carbon content is determined by measuring CO$_2$ release during combustion at 480°C, quantified as weight percent TOC. The instrument is calibrated against a standard sediment sample (12.00% TOC) with CaCO$_3$ before every series of analyses. Measurement uncertainty is $\pm$ 1.0%.

For grain size analyses, samples were split into coarse (i.e. $>0.063$ mm) and fine (i.e. $<0.063$ mm) fractions by means of wet sieving, and dried in a drying chamber at approx. 60°C. Dry sieving was performed for the fraction above 0.063 mm and electronic particle counting on a Sedigraph 5100 was used for the fraction below 0.063 mm.

2.4. Sediment-mixing rates

Mixing rate coefficients in surface ($D_{b1}$) and subsurface ($D_{b2}$) sediment layers were quantified assuming diffusive transport whereby individual transport steps are small compared to the overall tracer distribution in sediments (Berner, 1980). This common approach assumes mixing results in small-scale dispersion and an associated spreading of a tracer (e.g. Goldberg and Koebe, 1962; Guinasso and Schink, 1975; Robbins et al., 1979; Boudreau, 1986; Gerino et al., 1998). Here we assume that vertical advective transport is assumed to be related to only sediment accumulation, excluding the possibility of bioadventive transport related to more complex non-local transport by benthic organisms (Carroll and Lerche, 2003), such as conveyor-belt feeders Boudreau and Imboden, 1987; Blair et al., 1996). This assumption is justified by the fact that we do not observe deep-layer maxima in our tracer profiles as shown by Zaborska et al. (2008). The general equation is:

$$\frac{\partial^2 C}{\partial z^2} = \frac{D_{b1}}{2} \frac{\partial^2 C}{\partial z^2} - \omega \frac{\partial C}{\partial z} - \lambda C$$

with variables: tracer concentration ($C$), sediment depth ($z$), sediment accumulation rate ($\omega$), mixing coefficient ($D_{b1}$), tracer decay rate ($\lambda$) in yr$^{-1}$ and $P$ is the production of supported tracer equal for all layers.

Model assumptions are as follows:

1. Diffusion-like sediment mixing
2. Constant $^{210}$Pb ($^{234}$Th) flux to the sediment surface
3. Constant burial velocity
4. Constant $D_{b1}$ in each layer
5. $D_{b1} > D_{b2}$
6. $\omega = 0.031$ yr$^{-1}$
7. $\lambda = 11.36$ yr$^{-1}$

With model solutions:

Layer 2: $C_2(z) = Ce^{-(\omega-z/\lambda)}$

where

$$\lambda_2 = \omega - \sqrt{(\omega^2 + 4zD_{b2})} \quad \text{if } \omega = 0 \rightarrow \lambda_2 = \frac{\lambda}{\sqrt{D_{b2}}}$$

$$\lambda_2 = \omega - \sqrt{(\omega^2 + 4zD_{b2})} \quad \text{if } D_{b2} = 0 \rightarrow \lambda_2 = \frac{\lambda}{\omega}$$

Layer 1: $C_1(z) = a e^{\lambda_1 z} + b e^{\lambda_1 z}$

where

$$\lambda_1 = \omega - \sqrt{(\omega^2 + 4zD_{b1})}$$

and

$$\lambda_1 = \omega + \sqrt{(\omega^2 + 4zD_{b1})}$$

and the coefficients ‘$a$’ and ‘$b$’ calculated by imposing $C_1(z) = C_2(z)$ and $D_{b1}(\hat{C}(z)/\hat{z}) = D_{b2}(\hat{C}(z)/\hat{z})$.

Maximum $^{234}$Th-mixing rates were quantified assuming a single mixed layer with only mixing ($\omega = 0$) extending to the depth of $^{234}$Th penetration (Fig. 2). $^{210}$Pb-mixing rates were determined assuming two layers to describe the $^{210}$Pb$_{ex}$ depth ($z$) profiles. In this case, we derive minimum mixing coefficients (surface only) assuming mixing and sediment accumulation ($\omega = 0$) in the surface layer ($z<\hat{z}$) and only sediment accumulation below the mixed depth ($z>\hat{z}$; $D_{b2} = 0$) and maximum mixing coefficients (surface and deep) assuming mixing in both surface
and deep layers ($\omega = 0$). $^{210}$Pb$_{ex}$ profiles and sediment accumulation rates in cm yr$^{-1}$ are presented in Zaborska et al. (2008).

2.5. $^{210}$Pb mass sediment accumulation rates

Mass sediment accumulation rates (MSR in g m$^{-2}$ yr$^{-1}$) were derived using the $^{210}$Pb$_{ex}$ profiles reported by Zaborska et al. (2008) after converting sediment depth to mass depth (Robbins, 1978). Rates were quantified below the surface mixed-layer depth (z$^*$). We found that z$^*$ is sensitive to slight changes in the surface distribution of $^{210}$Pb$_{ex}$; thus, rather than assuming the z$^*$ derived from the mixing model alone, we evaluated the sensitivity of MSR to the depth of mixing by determining MSR values for three cases: (a) no mixing, (b) mixing in first two sediment depth intervals, and (c) mixing in first four sediment depth intervals. For cases b and c, mass accumulation rates were quantified below the mixed layer. In all cases, the surface sediment (0 mg cm$^{-2}$) $^{210}$Pb$_{ex}$ value was allowed to vary to achieve a best fit exponential profile based on a minimum least-squares fit criteria for the entire profile (surface to depth). For the three scenarios, MSR varied less than ±5% from the mean except for stations IV (±15%) and XI (±18%). Both stations had the highest sand content among all stations suggestive of a less stable sedimentary environment.

3. Results

3.1. $^{234}$Th and $^{210}$Pb sediment-mixing rates

Subsurface excess of $^{234}$Th was found at all stations but only penetrated below the surface interval (0–0.5 cm) at three stations: VIII, XII and XVIII. $^{234}$Th-mixing rates at these three stations resulted in mixing coefficients ($D_b$) ranging from 1 to 12 cm$^2$ yr$^{-1}$ (Table 2). $^{234}$Th inventories were determined as the cumulative sum of $^{234}$Th$_{ex}$ (Bq g$^{-1}$) multiplied by cumulative mass of each sediment layer (g cm$^{-2}$), and expressed as total $^{234}$Th$_{ex}$ inventories in Bq m$^{-2}$. $^{234}$Th$_{ex}$ inventories ranged from 328 to 568 Bq m$^{-2}$ at the three stations where $^{234}$Th$_{ex}$ penetrated below 0.5 cm and from 0 to 194 Bq m$^{-2}$ at all other stations (Table 1). Lalande
et al. (2007) report an average POC/\(^{234}\)Th ratio of 8.0 ± 2.3 (n = 8); for particles retrieved from 24-hour sediment trap deployments carried out at selected CABANERA stations in 2003 and 2005. If the POC/\(^{234}\)Th ratio for sinking particles is relatively invariant, our observations of higher \(^{234}\)Th inventories at stations VIII, XII and XVIII indicate enhanced supplies of fresh organic matter to the seafloor compared to the other investigated stations.

In deriving the mixing rate coefficients, the introduction of uncertainty caused by the dependency of the mixed-layer depth on the shape of the \(^{210}\)Pb\(_{ex}\) profile necessitates a degree of caution when interpreting the results. Therefore, we do not attempt a station by station evaluation but rather focus on some general observations on mixing for the region as a whole. Visual inspection of \(^{210}\)Pb\(_{ex}\) profiles versus sediment depth in centimeters indicates a clear surface mixed layer at some stations, i.e. stations II, IV, VIII, and X (Zaborska et al., 2008) and signifies the occurrence of mixing either by physical or biological processes over short and/or long time-scales. Assuming mixing and sediment accumulation in a surface layer (\(z<z^\prime\)) at these stations, minimum estimates for mixing rate coefficients range from 0.07 to 0.4 \(\text{cm}^2\text{yr}^{-1}\) (Table 2). Applying the same model assumptions, surface sediment mixing is also indicated at stations I, XI, XII, and XVI with mixed depths ~1 cm and mixing coefficients ranging from 0.03 to 0.2 \(\text{cm}^2\text{yr}^{-1}\). Alternatively, maximum coefficient values (mixing only) in the surface layer (\(z<z^\prime\)) are generally in the range of 0.2–1 \(\text{cm}^2\text{yr}^{-1}\), or approximately an order of magnitude higher compared to the previous results. For the deep layer (\(z>z^\prime\)), the coefficients range from 0.01 to 0.1 \(\text{cm}^2\text{yr}^{-1}\). With sediment accumulation rates on the order of 0.04–0.13 cm and mixed depths ranging from 0 to 2 cm on the western Barents Sea shelf, surface sediment properties, including carbon burial rates, are integrated over a time scale of approximately the previous 10–25 years. The three stations where we detect more recent mixing events based on the presence of \(^{234}\)Th (VIII, XII and XVIII) may be the exceptions to this general conclusion.

### Table 2: Mixing coefficients derived from \(^{210}\)Pb and \(^{234}\)Th sediment depth profiles using a two-layer mixing model

<table>
<thead>
<tr>
<th>Station</th>
<th>210Pb data</th>
<th>234Th data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Surface-layer mixing and accumulation ((D_{z=0}) = 0)</td>
<td>Mixing only ((z = 0))</td>
</tr>
<tr>
<td></td>
<td>(D_{z1}) ((\text{cm}^2\text{yr}^{-1}))</td>
<td>Mixed depth, (z^\prime) (cm)</td>
</tr>
<tr>
<td>I</td>
<td>0.08</td>
<td>1</td>
</tr>
<tr>
<td>II</td>
<td>0.07</td>
<td>1.5</td>
</tr>
<tr>
<td>III</td>
<td>--</td>
<td>0</td>
</tr>
<tr>
<td>IV</td>
<td>0.07</td>
<td>1.75</td>
</tr>
<tr>
<td>VIII</td>
<td>0.4</td>
<td>1.5</td>
</tr>
<tr>
<td>X</td>
<td>0.2</td>
<td>2</td>
</tr>
<tr>
<td>XI</td>
<td>0.03</td>
<td>1</td>
</tr>
<tr>
<td>XII</td>
<td>0.1</td>
<td>0.75</td>
</tr>
<tr>
<td>XVIII</td>
<td>--</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>--</td>
<td>0</td>
</tr>
</tbody>
</table>

Model equations and assumptions are given in the text for derivations of the surface-layer (\(D_{z1}\)) and deep-layer (\(D_{z2}\)) mixing coefficients.
OrgC burial rate for all other stations is $5.5 \pm 1.7 \text{g C m}^{-2} \text{yr}^{-1}$ (range = 3.7–8.4 g C m$^{-2}$ yr$^{-1}$).

4. Discussion

With 80% of the harvestable fisheries production channeled through the deep-water communities and benthos, pelagic–benthic coupling is considered to be important in the Barents Sea (Wassmann et al., 2006). This connection between pelagic and benthic food webs depends on the balance between organic carbon utilization and export. Once particles reach the seafloor, organic matter preservation depends on the sedimentation rate, bioturbation rate, oxygen concentration, organic carbon flux and carbon degradation rate (Jahnke et al., 1982; Emerson et al., 1985; Rutgers van der Loeff, 1990). Here we quantify carbon burial rates on the seafloor, providing further evidence with which to assess the balance between carbon utilization and export in this biologically rich Arctic marginal sea.

4.1. Sediment mixing

Both the depth and intensity of biological mixing within seafloor sediments are factors influencing the preservation of organic carbon (Alperin et al., 1999; Clough et al., 1997). In the Barents Sea, various species of polychaetes as well as molluscs, mainly burrowing bivalves, dominate the benthic communities both in terms of abundance and biomass (Wassmann et al., 2006). By far the most abundant functional groups found in the macrofaunal assemblages are both surface and subsurface deposit feeders. These subsurface deposit feeders are well-known to be
efficient bioturbators of fine sediment deposits (Reineck and Singh, 1973; François et al., 2002; Hughes et al., 2005). Among the CABANERA stations, total biomass (wet mass) ranges from 10 to 160 g m\(^{-2}\), while abundance per m\(^2\) ranges from 1200 to 8000 (Carroll et al., 2008). Station VIII at 500 m water depth, is our deepest station exhibiting biologically depauperate conditions with total biomass of only 10 g m\(^{-2}\), or an order of magnitude lower than stations at 200–300 m water depths (Carroll et al., 2008).

In connection with the strong seasonal nature of productivity and the associated coupling between pelagic and benthos in the Barents Sea (Wassmann et al., 2006; Tammelander et al., 2006), an associated increase in intensity and depth of biological mixing in surface sediment deposits is expected during peak biological productivity (spring–summer). This should be quantifiable through interpretation of sedimentary profiles of \(^{234}\)Th\(_{ex}\). \(^{234}\)Th\(_{ex}\) is detected below the sediment surface (>0.5 cm) at only 3 of the 11 stations (VIII, XII, XVIII). These stations cover a depth range of 286–503, making them among the deepest stations occupied during this investigation. The northern stations VIII and XII are part of the Kvitøya trench system that serves as a conduit for sediment transport to the Arctic basin. While station XVIII, located in Hopen Trench, is a deep trench in the central Barents Sea.

The \(^{210}\)Pb mass sediment accumulation rate at the deepest station (station VIII) is among the highest measured in this study (600 g m\(^{-2}\) yr\(^{-1}\)). This high MSR and associated \(^{234}\)Th\(_{ex}\) in sediments is probably not due solely to the vertical flux but also to non-local supplies of organic material from the surrounding slopes into this trough as previously suggested by Vandieken et al. (2006). Rates of benthic oxidation (Vandieken et al., 2006) and sediment oxygen demand (Renaud et al., 2008) are also high at this station. These rates are also high at station XII (Vandieken et al., 2006; Renaud et al., 2008) but we report a \(^{210}\)Pb mass sediment accumulation rate of only 330 g m\(^{-2}\) yr\(^{-1}\). The associated \(^{234}\)Th-mixing coefficient is also much lower at station XII, only 1 cm\(^2\) yr\(^{-1}\), compared to 7 cm\(^2\) yr\(^{-1}\) at station VIII. We consider that conditions at both trench stations, although to a lesser extent at station XII, are due to the input of non-local supplies of organic material through the process of sediment focusing.

The deepest southern station XVIII, in Hopen Trench (340 m), like station XII, exhibits a relatively low \(^{210}\)Pb MSR (330 g m\(^{-2}\) yr\(^{-1}\)). However, due to the passage of a storm just prior to sampling, the entire water column at this station was well-mixed at the time of sampling. Vertical flux determinations based on 24h sediment trap deployments indicate a high particulate organic carbon flux (720 mg C m\(^{-2}\) dy\(^{-1}\) @90 m) or three times the average flux for other stations (201 ± 97 mg C m\(^{-2}\) dy\(^{-1}\) @90 m) (Reigstad et al., 2008). It is reasonable to assume that \(^{234}\)Th\(_{ex}\) in the sediments resulted from this or similarly recent storm-driven events, leading to a pulse input of particulate organic matter from the water column to the seafloor. The \(^{234}\)Th-mixing coefficient (12 cm\(^2\) yr\(^{-1}\)) and reasonably high sediment oxygen demand (4.0 ± 0.8 mmol O\(_2\) m\(^{-2}\) d\(^{-1}\)) (Renaud et al., 2008) for this station indicate that the benthos had already responded to this fresh supply of carbon to the seafloor.

We conclude that the presence of \(^{234}\)Th\(_{ex}\) at these three stations provides evidence of recent inputs of ‘fresh’ sedimentary carbon from different sources. At station XVIII, carbon supplies are linked to short-term increases in vertical flux driven by primary productivity events in the water column, exemplifying pelagic–benthic coupling events, while at stations VIII and XII, enhanced deposition is more likely related to topographic features which lead to the focussing of sediments derived from surrounding slopes. The lack of \(^{234}\)Th\(_{ex}\) below the sediment surface at all other stations indicates that there were no detectable increases in benthic-mixing activities in response to inputs of carbon to the seafloor around the time of our sampling.

\(^{210}\)Pb-mixing rate coefficients were quantifiable at 8 of the 11 investigated stations (Table 2). Unlike \(^{234}\)Th which integrates processes over short (seasonal) time scales, mixing coefficients based on \(^{210}\)Pb\(_{ex}\) sediment profiles integrate processes over timescales of decades and longer (Gerino et al., 1998; Pope et al., 1996; Smith et al., 1993). As described previously, the two-layer mixing model is based on the assumption that both diffusive mixing and sediment accumulation occurs in the surface mixed layer and only sediment accumulation below the surface mixed-layer depth from which we derive minimum estimates of mixing coefficients. Surface-layer mixing coefficients at most stations range from 0.03 to 0.1 cm\(^2\) yr\(^{-1}\). Alternatively, the \(^{210}\)Pb\(_{ex}\) depth profile may be interpreted as solely the result of sediment mixing with no net accumulation; coefficients derived under this assumption represent upper limit estimates of the mixing intensity. In this case, the surface-layer coefficients (0.1–1 cm\(^2\) yr\(^{-1}\)) are a factor of 10 higher than deep-layer mixing coefficients. Taken as a whole, the zone of mixing, which extends only a few centimetres below the sediment–water interface, and associated rate coefficients are on the low end of the range of values reported for most continental shelf seas (e.g., Gerino et al., 1998; Alperin et al., 1999; Soetaert et al., 1996; Kuehl et al., 1993), suggesting that the mixing activities of benthic organisms, their type, intensity and zone of impact, result in a low degree of disturbance to the Barents seafloor sedimentary environment. Therefore, despite the prevalence of surface and subsurface deposit feeding organisms on the shelf, we find that bioturbation in this region of the Barents Sea leads to a low intensity of sediment mixing and shallow mixed depth.

### 4.2. Mass sediment accumulation rates

Sediment accumulation rates influence the long-term preservation of organic matter in marine sediments (Henrichs and Reeburg, 1987; Berner, 1988; Canfield, 1989; Inglav and Van Cappellen, 1990). Higher sediment accumulation rates facilitate rapid burial of organic matter, reducing the residence time in the bioturbation zone and oxic decomposition, and thereby enhancing preservation (Klages et al., 2004; Kuehl et al., 1993). Mass sediment accumulation rates below the depth of surface sediment mixing vary from 320 to 650 g m\(^{-2}\) yr\(^{-1}\) among the 11 stations (Fig. 4). The rates are generally higher at the more northerly, Arctic-associated stations (>350 g m\(^{-2}\) yr\(^{-1}\); II, XI, III, XII, X, XVI) compared to southern stations (<350 g m\(^{-2}\) yr\(^{-1}\); I, IV, XVII, XVIII). This is in contrast to water column primary productivity that is higher in Atlantic- versus Arctic-water-influenced areas. Hence depositional processes over-ride the influence of vertical flux on the long-term accumulation of sediments on the seafloor. Sediments in the region to the north are composed of more mud, while to the south, sediments contain a higher fraction of sand (Wassmann et al., 2006). However, we do not find a relationship between sediment grain size and MSR among our individual study sites. While grain size is indirectly involved in structuring the depositional regimes, resuspension processes on sediment deposits in the south in connection with a higher frequency of high-velocity bottom currents and an associated higher probability of achieving the threshold shear stress value for sediment resuspension at times of spring forcing has previously been documented by Sternberg et al. (2001). The presence of sea-ice in the north during a large part of the year is linked to more quiescent seafloor current conditions and more stable conditions which facilitate the accumulation of...
fine-grained sediments (Sternberg et al., 2001). Of course, as noted previously, the Barents Sea shelf bottom topography is irregular. Seabed geomorphology in combination with prevailing ocean currents is thought to facilitate the off-shelf transport of sediments to the deep-sea through trenches (Walsh et al., 1988; Biscaye et al., 1994).

Fig. 4. (A) Mass accumulation (g m$^{-2}$ yr$^{-1}$) and (B) carbon burial (g C m$^{-2}$ yr$^{-1}$) rates on the western Barents Sea shelf.
4.3. Carbon burial rates

Carbon burial rates in the northwest Barents Sea vary by a factor of 2 from 3.7 to 8.5 g C m⁻² yr⁻¹. Surface sediment homogenization by physical and/or biological mixing indicates that these rates represent the integration of processes over a time scale of approximately 10–25 years. However, sedimentary carbon content varies little with sediment depth implying that there is little variation in carbon burial rates over decadal to 100-year timescales. This indicates that our profiles reflect a system where carbon reaching the seafloor is efficiently utilized by benthic organisms prior to burial. Thus, our derived burial rates reflect the sedimentary carbon component that is available for long-term accumulation and storage in shelf deposits. This is in accordance with our previous analysis of sediment-mixing processes, which indicates a low degree of impact from bioturbation events in surface sediments throughout the study area over both seasonal and decadal timescales. As a result, we would expect carbon remineralization to be confined to a relatively shallow surface depth interval, which in turn, and in accordance with our observations, would eliminate any strong down-core gradient in sedimentary OrgC content.

Carbon burial rates at the deepest stations (I, XVIII, and VIII) are among the highest measured in this study. In Hopen Trench (I, XVIII), OrgC burial rates (~7.5 g C m⁻² yr⁻¹) are high despite low mass sediment accumulation (~330 g m⁻² yr⁻¹). Interestingly, carbon burial at all other locations except Hopen Trench is a function of MSR (see final plot of Fig. 3) because the sedimentary OrgC content varies over such a small range of values 1.0–1.6%. Hopen Trench has previously been identified as a region of high productivity (Wassmann and Slagstad, 1993) which may explain why the organic carbon content of these sediments (2.7–2.9%) is considerably higher compared to sediments from our other sampling locations. Primary production and vertical flux studies carried out during the CABANERA program lend further support to this (Reigstad et al., 2008; Hodal and Kristiansen, 2008).

4.4. Importance of burial as a sink for carbon

Despite the importance of obtaining good estimates of present-day carbon production, utilization, and burial in different areas of the world ocean for developing an accurate global ocean carbon budget, few studies have been performed in Arctic shelf margins. The overall average carbon burial rate in the northwest Barents Sea derived in the present investigation is 6.1 ± 1.8 g C m⁻² yr⁻¹. Rates are highest (~7 g C m⁻² yr⁻¹) in troughs (Hopen Trench and N. Kvitøya Trench) with an average for all other stations of 5.5 ± 1.7 g C m⁻² yr⁻¹.

Terrigenous supplies of organic carbon to the Barents Sea are minor (~5%) compared to the marine supply. However, modern sediment deposits in the Barents Sea generally reflect organic carbon contributions from both marine and terrigenous sources. According to Vetrov and Romankevich (2004), 30% of sedimentary organic carbon is of terrigenous origin. Not unexpectedly, we also observe a mixed source composition in sediment deposits from our stations in the western Barents Sea. Analysis of C/N ratios (Zaborska et al., 2008) and δ¹³C signatures (Tammelander et al., 2006) at selected stations confirm that the sediments investigated in the present study are predominantly of marine origin.

Knowing that terrigenous source contributions to surface sediment deposits in the Barents Sea are spatially and temporally variable, we may estimate the fraction of surface productivity sequestered on the seafloor within the study region by assuming the percentage of terrigenous organic carbon in sediment deposits is negligible to up to 30%. On the basis of an average carbon burial rate for all stations of 6.1 ± 1.8 g C m⁻² yr⁻¹, 5–7% of the annual integrated pelagic primary production (93 g C m⁻²) is sequestered on the seafloor. This burial percentage is higher (by a factor of 3) than the burial fraction derived for the entire period of the Holocene (Vetrov and Romankevich, 2004). This difference is related to the short averaging time scale associated with the present study (~10² years) compared to the study of Vetrov and Romankevich (~10⁴ years). Thus, the two approaches, with focus on different time-scales, provide critical, yet complimentary, carbon burial rate information. Compared to annual integrated pelagic primary production (40 g C m⁻² yr⁻¹), 11–15% of the annual vertical flux to the seafloor is preserved in surface sediment deposits of the western Barents Sea.

A significant fraction of carbon accumulating on the Arctic shelves bordering the Canada Basin is composed of highly degraded ancient carbon (27% ancient and 14% modern). Correcting for this component, the burial percentage for surface productivity on the Canadian Beaufort Shelf is ~3% (Goñi et al., 2005), and is low compared to our estimate for the northwest Barents Sea. Carbon burial rates for the Gulf of St. Lawrence on the north-eastern Atlantic continental margin were assessed under the Canadian Joint Global Ocean Flux Study (Silverberg et al., 2000). An average carbon burial rate of 6 g C m⁻² yr⁻¹ was derived for this region and the reported percentage of sedimentary organic preservation is 4–5% (Silverberg et al., 2000).

The fraction of carbon preserved in sediments of the northwest Barents Sea is high compared to the global average organic carbon burial rate in near-surface sediments of the coastal ocean (0.8% of primary production) (Berger et al., 1989). Additional effort is currently underway to derive sediment mass and carbon burial rates for the central Barents Sea which, together with the present work, will allow us to better constrain estimates of sedimentary organic carbon preservation for the Barents Sea as a whole.

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