Is there a $^{230}\text{Th}$ deficit in Arctic sediments?

Sharon Hoffmann a,*, Jerry McManus b

a MIT–WHOI Joint Program in Oceanography, Department of Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, MA 02543 USA
b Department of Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, MA 02543 USA

Received 14 November 2006; received in revised form 29 March 2007; accepted 2 April 2007
Available online 11 April 2007
Editor: M.L. Delaney

Abstract

In most of the global ocean, the radionuclide thorium-230 is removed from the water column by adsorption onto particles and deposition in seafloor sediments, at a rate approximately in balance with its local production by the decay of uranium dissolved in seawater, allowing its use in assessing rates of marine processes. However, several previous studies have suggested that the flux of $^{230}\text{Th}$ to the sediments of the Central Arctic is far too small to balance its production in the overlying water column. If this is so, $^{230}\text{Th}$ produced in the low particle-flux Central Arctic basins would be deposited elsewhere, either by boundary scavenging at the margins or by export from the Arctic to lower latitudes. In order to evaluate this possibility, we compare the expected $^{230}\text{Th}$ production and measured inventories for five sites in the Western Arctic, combining previously published $^{230}\text{Th}$ data with reported AMS radiocarbon dates, and find no evidence for a substantial deficit of $^{230}\text{Th}$ in these sediments. Instead, we find evidence for near balance in the $^{230}\text{Th}$ budget during both the Holocene and late glacial periods. These intervals are separated by a brief deglacial period of apparently higher sedimentation rates and $^{230}\text{Th}$ deposition. During the Holocene, the average sedimentary inventory of $^{230}\text{Th}$ at these sites is largely within 30% of the water column production, in good agreement with observations and model results from other ocean basins.

© 2007 Elsevier B.V. All rights reserved.

Keywords: $^{230}$-thorium; Arctic Ocean; sedimentation; scavenging

1. Introduction

Uranium-234 is well mixed in the global ocean [1] and decays at a constant rate to produce thorium-230. This particle-reactive radionuclide is primarily removed locally by scavenging to sediments, rather than by transportation through advection or eddy diffusion [2]. The excess of $^{230}$Th ($^{230}\text{Th}_{ex}$) in sediments, unsupported by uranium decay in crystal lattices or authigenic grain coatings of sediments, is thus assumed to be derived from the water column. The extreme particle reactivity and constant production of $^{230}\text{Th}$ allow it to be used to estimate sediment fluxes to the seafloor (e.g. [3,4]), as a chronometer [5], or as a normalizer to which the behavior of other isotopes, such as $^{231}\text{Pa}$, can be compared [6–8]. Excess $^{230}\text{Th}$ in sediments can be a powerful tool to investigate sedimentary processes such as sediment focusing or winnowing [9]. Sediment trap studies [10] and modeling [11] support the conclusion that most $^{230}\text{Th}$ production in the water column is...
balanced locally by deposition, and that net advective or eddy diffusive transport of $^{230}$Th away from its production site is minimal for much of the open ocean. Production and removal over most of the global ocean are estimated to agree to within 30% [11]. In the Atlantic, with possible spatially limited exceptions, the agreement appears to be even better, to near 10% [10].

The Arctic may be an exception to this rule. Sedimentation rates are low in the deep central basins, due in part to the sea ice cover, which both blocks windborne terrigenous particles and keeps productivity low. Traditionally, sedimentation rates here, most determined from paleomagnetic polarity measurements in cores, have been estimated to be on the scale of mm/kyr (e.g. [12]). With such low particle fluxes to scavenge it, $^{230}$Th might remain in the water column longer, and thus be susceptible to transport to the shelf edge or to other basins. However, recent studies reinterpreting paleomagnetic data, and using other methods such as biostratigraphy and geophysical sensing of depth to bedrock, indicate that long-term Arctic sedimentation rates are often higher, on the cm/kyr scale (e.g. [12]). Such sedimentation rates are similar to those of the mid-Pacific [15] but lower than rates in many Atlantic cores.

Excess $^{230}$Th could be a powerful tool to examine sedimentation rates in the Arctic if its budget is found to be in balance there. For example, a significant increase in sedimentation rate during Marine Isotope Stages 4 through 1 has been observed in cores from Lomonosov Ridge [16]. $^{230}$Th$_{xs}$ has the potential to provide insight into the causes of such changes, through Th-normalized sediment flux estimates and sediment focusing studies. If the overall water column and sedimentary $^{230}$Th budget appears to be in balance, $^{230}$Th may be used to look for sedimentation irregularities such as turbidites or hiatuses, both of which are concerns in Arctic stratigraphy [17–19].

Excess $^{230}$Th measurements can also provide a rough check on chronology for stratigraphies in Arctic cores: if excess Th is present in a sample, the sample age must be less than five half lives of $^{230}$Th, roughly 380 kyr. The thorium budget of the Arctic is also of interest to paleoceanographers, who use thorium-230 and protactinium-231 to investigate thermohaline overturning rates in the North Atlantic ([8,20,21]). Recent work on $^{230}$Th and $^{231}$Pa in the water column [22–24] and in surface sediments [25] of the Arctic has done a great deal to improve our understanding of the behavior of these nuclides in the Arctic, including the possibility of their export to the Atlantic. Downcore sedimentary studies to establish the history of the Arctic budgets and distribution will be key to using these nuclides as paleoproxies in the Arctic. The fate of $^{230}$Th in the Arctic also has implications for our understanding of the paths of anthropogenic radionuclides in this region: if the extremely particle-reactive $^{230}$Th can be exported, it is likely that less reactive nuclides, such as the naturally-occurring $^{231}$Pa and anthropogenic plutonium isotopes, may be exported from the region as well.

All previous studies of $^{230}$Th in Arctic sediments [26–30]; see Section 4.1 for further discussion) have concluded that a significant imbalance between production and sediment burial exists, resulting in large deficits of sedimentary $^{230}$Th$_{xs}$ relative to the water column production. Several of these studies used $^{230}$Th$_{xs}$ to estimate sediment accumulation rates, which were then used to calculate apparent $^{230}$Th$_{xs}$ accumulation rates. This approach works when sedimentation rates are constant and $^{230}$Th$_{xs}$ measurements show exponential decay

### Table 1

230Th$_{xs}$ inventories for the Holocene, deglacial, and glacial intervals

<table>
<thead>
<tr>
<th>Core</th>
<th>Water depth (m)</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Holocene measured inventory (dpm/cm$^2$)</th>
<th>Holocene predicted inventory (dpm/cm$^2$)</th>
<th>Holocene measured/predicted ratio</th>
<th>Deglacial measured inventory (dpm/cm$^2$)</th>
<th>Deglacial predicted inventory (dpm/cm$^2$)</th>
<th>Deglacial measured/predicted ratio</th>
<th>Glacial measured inventory (dpm/cm$^2$)</th>
<th>Glacial predicted inventory (dpm/cm$^2$)</th>
<th>Glacial measured/predicted ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC 08</td>
<td>1000</td>
<td>78.13</td>
<td>−176.88</td>
<td>40.0</td>
<td>23.6</td>
<td>1.7</td>
<td>21.4</td>
<td>8.5</td>
<td>2.5</td>
<td>51.8</td>
<td>71.1</td>
<td>0.7</td>
</tr>
<tr>
<td>BC 16 (P)</td>
<td>1520</td>
<td>80.33</td>
<td>−178.72</td>
<td>38.2</td>
<td>43.3</td>
<td>0.9</td>
<td>70.9</td>
<td>10.4</td>
<td>6.8</td>
<td>145.5</td>
<td>122.2</td>
<td>1.2</td>
</tr>
<tr>
<td>BC 16 (D)</td>
<td>1520</td>
<td>80.33</td>
<td>−178.72</td>
<td>38.2</td>
<td>38.9</td>
<td>1.0</td>
<td>96.0</td>
<td>20.9</td>
<td>4.6</td>
<td>93.3</td>
<td>91.8</td>
<td>1.0</td>
</tr>
<tr>
<td>BC 19</td>
<td>2400</td>
<td>82.45</td>
<td>−175.73</td>
<td>50.0</td>
<td>68.2</td>
<td>0.7</td>
<td>43.1</td>
<td>18.8</td>
<td>2.3</td>
<td>123.0</td>
<td>147.7</td>
<td>0.8</td>
</tr>
<tr>
<td>BC 20</td>
<td>3145</td>
<td>83.18</td>
<td>−174.09</td>
<td>76.4</td>
<td>88.7</td>
<td>0.9</td>
<td>43.5</td>
<td>15.7</td>
<td>2.8</td>
<td>153.6</td>
<td>235.3</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Average ratio 1.1 0.9
Standard deviation 0.4 0.3
Standard error 0.2 0.1

* No deglacial or glacial inventories are calculated for BC 17, Darby et al. age model, due to an age reversal in this interval.
profiles, but can be complicated by changing sedimentation rates.

The addition of an independent constraint on chronology and sedimentation rate, such as radiocarbon dates, can help to improve interpretation of the features of $^{230}$Th$_{xs}$ profiles, as well as rates of $^{230}$Th deposition. We have revisited the Arctic $^{230}$Th$_{xs}$ budget using the best available independent dating tool, radiocarbon measured by AMS in planktic foraminifera. We use $^{230}$Th$_{xs}$ data from Huh et al. [28] and radiocarbon dates acquired for the late glacial, deglacial, and Holocene periods in the same box cores by Darby et al. [31] and by Poore et al. [18,19] to calculate sedimentary $^{230}$Th$_{xs}$ inventories for comparison to water column $^{230}$Th production rates at five sites in the Western Arctic (Table 1). These radiocarbon dates suggest sedimentation rates in the cm/kyr, rather than mm/kyr, range, for the period following the Last Glacial Maximum. Our calculations suggest that there is no substantial $^{230}$Th$_{xs}$ deficit in these cores relative to the predicted water column production. Instead we find that in this region the $^{230}$Th budget has generally been in balance during the glacial and Holocene, with a brief deglacial pulse of rapid $^{230}$Th deposition. This finding appears to hold true for both the modest sediment accumulation rates that characterize the Holocene and for the much slower accumulation rates associated with the glacial sections.

2. Methods and sources

The $^{230}$Th and radiocarbon data [18,19,28,31] used in this study were generated from sediments from sites cored on cruise AOS 94 of the USCGC Polar Sea (locations in Table 1; map, Fig. 1). These sites sit on the Mendeleev Ridge and nearby Wrangel Abyssal Plain, at depths from 1000 to over 3000 m, lying underneath the interior of the Beaufort Gyre circulation [18]. Sediments consist of silty IRD-bearing muds with varying amounts of foraminifera present [18,31]. From each box core, a subcore was sampled at high resolution, and the samples were digested and analyzed for $^{230}$Th and $^{232}$Th, using methods described in Huh et al. [28]. $^{232}$Th measurements were used to estimate uranium contents and hence supported crystal lattice $^{230}$Th contents of the samples, which were subtracted from the total measured $^{230}$Th to estimate excess $^{230}$Th [28]. Supported detrital $^{230}$Th activities were between 1 and 2 dpm/g for almost all samples, roughly the same magnitude as the smallest calculated excess contents. No estimate for possible authigenic U in these sediments was available. Sediment density was measured on a salt-free basis [28].

Other subcores from the same box cores were analyzed for $^{14}$C dates on planktonic foraminifera by Darby et al. [31] and by Poore et al. [18,19]. We converted the radiocarbon dates to calendar years using the CALIB 5.0 calibration program [32] and Marine04 calibration dataset [33] for samples whose radiocarbon ages were less than 21,880 yr, and using the calibration curve of Fairbanks et al. [34] for older samples. Calendar ages calculated for comparison using the Fairbanks calibration for samples younger than 21,880 yr did not differ from the CALIB-calculated ages by more than 3%. In addition to the reservoir age of 440 yr used by both Darby et al. [31] and Poore et al. [18,19], we assumed an additional reservoir age offset ($\Delta R$) of 250 yr due to the blocking of gas exchange in the Central Arctic by sea ice [35; Curry, personal communication]. We constructed age models by linear interpolation between dated
intervals in the cores. Where dates from two subcores of the same box core are available, in BC 16 and BC 17, it is clear that different subcores can have slightly different dates for the same sample depth (Fig. 2), resulting in differing age models. For these two box cores, we have calculated $^{230}$Th inventories and sedimentation rates twice, using age models from both published radiocarbon stratigraphies. Sensitivity tests indicate that our

Fig. 2. Data used in this study. $^{230}$Th$_{xs}$ profiles reported by Huh et al. [28], uncorrected for decay since burial. Concentration units are decays per minute per gram (dpm/g). Radiocarbon data from Poore et al. [18,19] ("$^{14}$C dates (P)" in legend) and from Darby et al. [31] ("$^{14}$C dates (D)"), calibrated to calendar years as explained in Section 2.
$^{230}$Th budget calculations are not significantly altered by small differences to the age models.

Using the age models described above, we corrected the $^{230}$Th$_{xs}$ data of Huh et al. [28] for radioactive decay to estimate the excess $^{230}$Th concentration at the time of sediment deposition. These corrected concentrations were then multiplied by the sample sediment densities and adjusted for the sampling interval to obtain $^{230}$Th$_{xs}$ inventories for each 1–2 cm interval in the core. The cumulative expected inventories, assuming that all $^{230}$Th produced in the water column was scavenged to the seafloor at each site, were calculated using the equation of Suman and Bacon [9]: production (dpm cm$^{-2}$ ky$^{-1}$) = 0.00263 $\times$ water column depth (m).
In this paper, we define the Holocene as encompassing the last 11 kyr, the deglacial as the period between 15 kyr and 11 kyr, and the glacial period as before 15 kyr. The glacial sections of the box cores in this paper thus include both Marine Isotope Stage 3 and Stage 2 sediments.

3. Results

3.1. Core $^{230}$Th profiles and inventories

As noted by Huh et al. [28], $^{230}$Th$_{xs}$ concentrations generally decline down each core, then increase to a
subsurface maximum before decreasing again (Fig. 2). Subsurface maxima occur between 33 and 15 ka, although they appear within only a few closely spaced samples in each core. Below this interval in each core, $^{230}$Th$_{xs}$ concentrations begin to decrease again, with at least one more small increase at depth. In all cases there is measurable excess $^{230}$Th in the deepest samples analyzed.

When the decay-corrected $^{230}$Th$_{xs}$ profiles are plotted by their age models (Fig. 3), their structure can be interpreted in light of sedimentation rate changes as well as global changes occurring through the glacial, deglacial, and Holocene. The age models in the deepest part of the core include reported dates close to or beyond the sensitivity limit of radiocarbon dating, and thus cannot be considered as strong as the Holocene age models. However, the upper parts of the glacial sections are within the radiocarbon dating range, allowing us to make some interpretations of this part of the record. $^{230}$Th$_{xs}$ glacial concentrations vary in the cores but tend to be high just before the deglacial, suggesting low sedimentation rates at this time. In cores BC 16, 17, 19, and 20, the oldest dated interval with a deglacial date has a $^{230}$Th$_{xs}$ concentration higher than Holocene samples, which drops off steeply in younger deglacial samples. $^{230}$Th$_{xs}$ values then rise again through the Holocene.

The sum of the predicted $^{230}$Th production in the overlying seawater increases down each core at a constant rate over time (Fig. 4). The cumulative measured sedimentary inventory increases down each core and can be compared to the production. In each core the two curves, predicted and measured decay-corrected inventory of $^{230}$Th, have similar values in the Holocene section, although BC 08 appears to have an episode of rapid sediment and $^{230}$Th$_{xs}$ accumulation in its Holocene interval which substantially increases its measured inventory. Below the Holocene section, the measured total exceeds the predicted production in BC 08, 16, and 17, and is close to the predicted production in BC 19 and 20, due largely to an apparent rise in $^{230}$Th deposition during the deglacial period. Below 15-12 ka, the slopes of the two cumulative curves become similar again, indicating similar rates of production and deposition. There is no systematic deficit evident in the cumulative measurements, and only limited intervals where there is evidence of a deficit in any given core. The more general relationship is of a measured inventory similar to the predicted one, with an overall excess that is primarily driven by the rapid increase in burial between 15 and 12 ka. With the exception of the 8-ka event in BC 08, the past 10,000 years appear to have been a relatively stable sedimentary environment in the Western Arctic, with no large changes in $^{230}$Th deposition or sedimentation rates. The average Holocene inventory of all five cores is 110% of production, with a standard error of 20% (Table 1). If BC 08, with its anomalous Holocene $^{230}$Th burial event, is omitted from these calculations, the average measured/predicted Holocene inventory ratio is 95%, with a standard error of 11%.

A compressed glacial section, possibly containing a hiatus thought to correspond to the Last Glacial Maximum, has been previously noted in these cores [18,31]. Fig. 2 shows the jump in a few cm from ages predating the LGM, in MIS 3, to deglacial-aged samples (15–11 ka). The increased $^{230}$Th$_{xs}$ concentrations from the glacial sections of these box cores (Fig. 3) are consistent with lower sediment accumulation rates. However, the cumulative glacial $^{230}$Th$_{xs}$ inventories from BC 16 and BC 17 show no missing $^{230}$Th$_{xs}$, while the other three cores show only a modest deficit in their glacial sections. The average measured/predicted inventory ratio for the glacial period in the five cores is 93%, with a standard error of 14%. These results suggest that there is no substantial hiatus involving removal of sediment or cessation of sedimentation in this region. Rather, sedimentation appears to have continued at a greatly reduced rate.

In BC 16, Poore et al. [18,19] report an age reversal, which in our age model affects the modeled ages of samples within the glacial period, but does not affect the assignation of samples to the glacial or deglacial periods. In BC 17, an age reversal reported by Darby et al. [31] makes identification of the boundary between glacial and deglacial sediments difficult, and hence we have not attempted to calculate glacial and deglacial inventories using this age model.

4. Discussion

4.1. Previous estimates of Arctic $^{230}$Th burial

The few studies of $^{230}$Th$_{xs}$ sediment inventories in the Arctic that have been published have each come to the conclusion that a sedimentary $^{230}$Th$_{xs}$ deficit exists. Ku and Broecker [29] first suggested that the $^{230}$Th$_{xs}$ concentrations they measured in sandy layers of core T3-63-1 from the Alpha Ridge were lower than would be expected from a purely radioactive-decay-driven profile, possibly due to a lack of suitable particles to scavenge water column $^{230}$Th effectively. Resolution of this profile was roughly 3 samples per 10 cm, and the sedimentation rate derived from the profile was 0.21 cm/kyr. Finkel et al.’s [26] study of $^{10}$Be and $^{230}$Th$_{xs}$ in cores from the Chukchi Plain and the Alpha Ridge,
sampled at 10 cm intervals, found rising and falling downcore \(^{230}\)Th concentrations in several cores. Somayajulu et al. [30] and Herman et al. [27] calculated very low sedimentation rates from decay-curve fits to \(^{230}\)Th\(_{xs}\) profiles in the top 25 cm of sediment at a number of sites in the central Arctic, with resolution varying from 2 to 5 cm. Combining these sedimentation rates, which ranged from 0.8 to 5 mm/kyr, with \(^{230}\)Th\(_{xs}\) inventories for their samples, they calculated \(^{230}\)Th accumulation rates that were between 2 and 20% of the expected water column production.

The most thorough study of \(^{230}\)Th\(_{xs}\) in Arctic sediments, by Huh et al. [28], used box cores from a transect across the Western Arctic. This study produced measurements of excess \(^{230}\)Th every 1 to 2 cm in the top 30 cm from ten sites, greatly improving resolution over previous studies. As noted in Section 3.1, the profiles had subsurface minima and maxima which did not conform to exponential decay models, and in all cores excess \(^{230}\)Th\(_{xs}\) was present at the bottom of the profile. The \(^{230}\)Th\(_{xs}\) budget was estimated in two ways. From exponential regressions of the upper parts of the profiles above the subsurface \(^{230}\)Th\(_{xs}\) maxima and from correlation of these maxima between cores, Huh et al. calculated rough sedimentation rates which were very low, between 0.019 and 0.189 cm/kyr for all sites except a shallow shelf site. These sedimentation rates were then multiplied by coretop \(^{230}\)Th\(_{xs}\) concentrations to estimate the \(^{230}\)Th fluxes to the seafloor. Sedimentary fluxes were also calculated by measuring the inventories of \(^{230}\)Th\(_{xs}\) in the cores, and assuming that \(^{230}\)Th deposition rates must balance the decay rate of these inventories. Using these methods, Huh et al. found that the \(^{230}\)Th\(_{xs}\) measured in these cores could account, on average, for less than half the expected production of \(^{230}\)Th in the water column, with burial/production ratios ranging between 0.06 to 0.62. They suggested that the \(^{230}\)Th that appeared to be “missing” from the central basin sediments was probably exported in the water column to continental margins, where particle fluxes are often higher, and removed from the water column there, a process known as boundary scavenging.

Thus, all previous studies have concluded that there is a buried \(^{230}\)Th\(_{xs}\) deficit in Arctic sediments, with only 2–62% of expected \(^{230}\)Th water column production balanced by flux into the sediments. Each study, however, assumed a constant sedimentation rate, at least for the upper portions of the profiles. The \(^{230}\)Th\(_{xs}\) concentration in sediment often depends more on dilution and concentration by changing sedimentation rates than on decay (e.g. [36,37]), as evidenced by subsurface maxima and minima in most downcore profiles in the Arctic. This deviation from idealized exponential decay can hamper efforts to estimate sedimentation rates from \(^{230}\)Th\(_{xs}\) by altering the slopes of the profiles which are used to fit the decay curves. In addition, the Huh et al. approach of balancing the entire sedimentary inventory of \(^{230}\)Th\(_{xs}\) against production may have underestimated the total inventory, as none of the measured box core profiles actually reaches zero excess Th at depth, suggesting that part of the total buried inventory remains unsampled.

4.2. Holocene budgets of \(^{230}\)Th and modern evidence for scavenging

Overall, the calculations of production and burial in this study are much closer than previous estimates of \(^{230}\)Th flux to the sediments and \(^{230}\)Th production that were not constrained by radiocarbon dating. Rather than being anomalous, at these sites in the central Western Arctic, the production and deposition of \(^{230}\)Th over the last 11 kyr has proceeded in a similar fashion to the rest of the world’s ocean. Although the limited range of \(^{14}\)C dating precludes its use to determine whether the Arctic \(^{230}\)Th budget has always been in near balance, the Holocene estimate discussed here can be considered robust. This is an interval for which the decay correction for \(^{230}\)Th\(_{xs}\) is negligible, there are abundant foraminifera for \(^{14}\)C dating, there is relatively little uncertainty in the conversion to calendar age, and the radionuclide data are resolved every cm.

This finding has implications for other areas of Arctic research. Arctic Ocean cycling of other particle-reactive nuclides, particularly anthropogenic ones, is likely to proceed similarly to cycling in other basins. The ability of Arctic particle fluxes to effectively scavenge \(^{230}\)Th suggests that they may also play a role in the scavenging and removal of other elements. The increase through the Holocene in \(^{230}\)Th\(_{xs}\) concentration is intriguing, and could be related to a number of factors, including particle type changes or a sedimentation rate slowdown. It presents an interesting question for Holocene paleoceanography.

Present-day water column measurements may provide insight into thorium cycling in the premodern Holocene. The first study of Arctic water column \(^{230}\)Th and \(^{231}\)Pa [38], from a site at the Alpha Ridge, found higher concentrations of \(^{231}\)Pa and \(^{230}\)Th in the water column than have been found in other oceans and interpreted this as evidence of reduced scavenging at the site. However, subsequent water column measurements indicate that \(^{230}\)Th and \(^{231}\)Pa concentrations vary from basin to basin within the Arctic, with highest
values at the Alpha Ridge and Makarov Basin [24], and lower values in the Beaufort Sea [22], and in the Amundsen and Nansen Basins [39]. These variations may reflect differences in particle fluxes or types, water mass residence times in the basins, or fractionation of \( {\text{Th}} \) and \( {\text{Pa}} \) between dissolved and particulate species. Differences in these various influences can allow the effective scavenging of \( {\text{Th}} \) at differing seawater concentrations. Models of scavenging behavior based on water column measurements in the Canada Basin indicate that \( {\text{Th}} \) is highly scavenged there [22,40], consistent with our findings that \( {\text{Th}} \) has been efficiently removed from the water column to the sediments during the interglacial. Our new estimates of \( {\text{Th}} \) burial thus bring sedimentary evidence into agreement with water column evidence for effective scavenging in this region.

Our calculations indicate that no removal of \( {\text{Th}} \) from the central Western Arctic is required to balance the thorium budget there. However, if \( {\text{Th}} \) is exported at all from the region, where might it be going? Two possibilities are to the boundaries of the deep Arctic basins, and to the Atlantic through Fram Strait. Calculations of \( {\text{Th}} \) export through Fram Strait [25], based on water column concentrations and advection rates, suggest that only 10% of the \( {\text{Th}} \) produced in the Arctic may be lost from the basin to the Atlantic. This is consistent with our conclusion that most \( {\text{Th}} \) in the western central Arctic is being buried in sediments locally.

The broad shelf seas of the Arctic, although high in productivity and particles, are not a likely sink of \( {\text{Th}} \), as most \( {\text{Th}} \) production occurs in the deep basins. Isopycnal mixing is therefore unlikely to bring much \( {\text{Th}} \) up onto the shallow shelves. However, scavenging along the deeper continental slope at the edges of the deep basins is a possibility. Huh et al. [28] noted the possibility of boundary scavenging of \( {\text{Th}} \) in one high-accumulation-rate core from the Chukchi slope, and measurements of \( {\text{Th}} \) in Arctic sediments have shown evidence for boundary scavenging of this element as well [41]. Recent water column and coretop studies [23,25] of Arctic \( {\text{Th}} \) and \( {\text{Pa}} \), which is more sensitive to boundary scavenging than thorium, do not show the pattern of high marginal \( {\text{Pa}}/\text{Th} \) ratios considered typical of boundary scavenging in other basins (e.g. [42]), although they note that boundary scavenging may nevertheless occur in this region. While boundary scavenging thus is a possible sink of Arctic thorium, we have shown it is not required to balance the \( {\text{Th}} \) budget in the central western Arctic.

4.3. Glacial sedimentation rates and implications for ongoing \( {\text{Th}} \) scavenging

Our findings of relatively balanced budgets at these sites prior to the deglaciation are important for understanding longer-term thorium cycle dynamics in the Arctic. A balance that holds during interglacial conditions might not be expected to hold when ice cover is thicker and productivity is lowered, driving particle fluxes to a minimum as occurred during the late glacial. However, the measured inventories and estimated production for the period just before the deglaciation, when sedimentation rates were at their lowest, suggest that \( {\text{Th}} \) was nevertheless scavenged by the few particles that did fall. In fact, the lowest ratio of measured inventory to production that we calculated for the glacial, 0.65 for BC 20, is higher than the highest previous estimate of the Arctic \( {\text{Th}} \) burial/production relationship [28]. Our findings of a generally balanced Arctic \( {\text{Th}} \) budget thus are not dependent on sedimentation rate: the balance holds whether particle fluxes are relatively high or low. Our calculations also suggest that, despite the large change in age between deglacial and glacial samples only a few centimeters apart, there may have been no true lapse in sedimentation at that time. The cores thus appear to contain a very highly compressed late glacial section, rather than a substantial hiatus.

4.4. High \( {\text{Th}} \) inventories in deglacial sediments

Thorium burial during the deglacial period (roughly 15–11 ka) differs greatly from the relatively balanced budgets of the Holocene and glacial periods bracketing the deglaciation. During the deglaciation, the sediment accumulation rate increased and the \( {\text{Th}} \) concentration in sediments declined from their glacial values (Fig. 3). While these two observations are consistent with dilution of buried \( {\text{Th}} \) by greater amounts of settling particles, the deglacial \( {\text{Th}} \) inventories of these cores nevertheless appear to be higher than required to balance the expected production during this relatively brief interval. Burial/production ratios range between 2.3 and 6.8, all greater than the “balanced” ratio of 1. While the high \( {\text{Th}} \) concentrations seen at the start of the deglaciation in several cores contribute to this imbalance, they do not account for all of the extra deglacial \( {\text{Th}} \), and other contributing processes must be considered. Because this event is the single notable departure from a balanced \( {\text{Th}} \) budget for these Arctic sites, it merits additional discussion.

One possible explanation for the transient increase in \( {\text{Th}} \) flux is that bioturbation has redistributed clay
particles and $^{230}$Th$_{xs}$ in the sediment column. During the late glacial period, particle fluxes were extremely low, and the accumulating sediments had very high excess $^{230}$Th concentrations (Fig. 3). If bioturbation later mixed some of these particles upward into deglacial sediments accumulating above them, it would raise the $^{230}$Th$_{xs}$ concentration, and thus apparent flux, within the more rapidly accumulating deglacial sediments. A slight stratigraphic offset between the radiocarbon-dated subcores and the subcores analyzed for $^{230}$Th$_{xs}$ might also result in samples being assigned to the deglacial in our calculations which might be older than our age models suggest. Similarly, abundant foraminifera accumulating above glacial sediment might be mixed downward, shifting downcore the apparent sedimentation rate transition inferred from radiocarbon ages. Mixing by bioturbation in the Arctic varies from core to core and is often limited (BC17 is relatively unbioturbated, for example), but may extend to a depth of 2–4 cm [43], allowing for the possibility of sediment mixing out of the compressed high-Th glacial section.

A strong possibility is lateral transport of sediments to these sites. The assumption that local deposition and production balance each other requires that sediments accumulate only by vertical sinking of particles. If sediments from other parts of the basin were re-suspended and transported to these sites to be re-deposited, the $^{230}$Th adsorbed onto these laterally transported sediments would boost the sediment inventory above local $^{230}$Th production [9]. The much higher deglacial sedimentation rates apparent in these cores relative to the Holocene possibly reflect such a lateral input of sediments. Oxygen isotope measurements [18] suggest that the onset of this change coincides with Meltwater Pulse 1a, the largest deglacial melting episode, during which global sea level rose more than 20 m [44]. The flooding of circum-Arctic shelves may have increased sediment availability and destabilized the shelf-breaks, leading to episodic re-deposition in the central basins. Such an event could account for the similar deglacial sedimentation pattern occurring at very different depths along the slope and basin. A similar jump in $^{230}$Th accumulation in BC 08 occurred around 8000 yr ago, although it is difficult to know if this younger event can be explained by the same processes. If sediment focusing might be responsible for high deglacial inventories, we must consider the possibility that it may also contribute to the Holocene and glacial inventories, producing the appearance of balance in the $^{230}$Th budgets for these times. Circulation in the intermediate and deep waters of the Arctic is strongly steered by topography [45–48]; deep eddies have also been suggested to occur [47]. Such water mass movements could redistribute sediments along the continental slope. We cannot rule the possibility out; however, it seems unlikely that focusing occurs throughout the Holocene at just the rates needed to produce the impression of a balanced thorium budget at five sites whose depths differ by up to 2000 m.

5. Conclusions

(i) A comparison of measured sedimentary inventories of $^{230}$Th$_{xs}$ with $^{230}$Th production during the time of sediment accumulation, as estimated from radiocarbon dating, indicates that the $^{230}$Th budget at each of five sites in the western Arctic is far closer to being in balance than was previously estimated. This region therefore appears similar to much of the world ocean in the cycling of this particle-reactive element.

(ii) Holocene $^{230}$Th production is largely balanced by burial in sediments, as was late glacial production, indicating that effective scavenging of thorium is not dependent on high sedimentation rates.

(iii) Deglacial $^{230}$Th$_{xs}$ burial appears to have occurred at a faster rate than production, suggesting that another process was at work during this time, possibly sediment focusing, or that there are slight stratigraphic uncertainties in the cores due to bioturbation or age model assumptions.

(iv) If export is not required to balance the Arctic $^{230}$Th budget, we may also now be able to use the behavior and sediment accumulation of thorium as a normalizer, to understand the sedimentation processes of the Arctic and the scavenging processes which affect the less particle-reactive radionuclides, such as $^{231}$Pa [8,23,25]. This finding has important implications for our understanding of the cycling of reactive elements in the Arctic Ocean, and for paleoceanographic studies as well.

Acknowledgements

We thank C.-A. Huh for generously sharing sedimentary $^{230}$Th data. Reviews by H. Edmonds and G. Henderson greatly improved this paper, as did an anonymous review of an earlier draft. We thank W. Curry for his assistance with the manuscript and with maps, R. Francois and O. Marchal for their valuable discussions, and N. Goodkin and M. Jackson for their comments on the manuscript. We acknowledge support from NSF grants ARC-0520073 to W. Curry, and OCE-0402565.
and OCE-0550637 to J. McManus. S. Hoffmann was supported by a JOI Schlanger Ocean Drilling Fellowship and by the WHOI Academic Programs Office.

References


