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Recent sediment dynamics in hadal trenches: evidence for the influence of higher-frequency (tidal, near-inertial) fluid dynamics

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Abstract

In addition to high hydrostatic pressure, scarcity of food is viewed as a factor that limits the abundance and activity of heterotrophic organisms at great ocean depths, including hadal trenches. Supply of nutritious food largely relies on the flux of organic-rich particulate matter from the surface ocean. It has been speculated that the shape of hadal trenches helps to ‘funnel’ particulate matter into the deeper parts of the trench, leading to sediment ‘focussing’ and improved benthic food supply. Here we investigate for five Northwest Pacific trenches the efficiency of sediment focussing by evaluating ratios of measured (sediment-derived) and expected (water-column-derived) sedimentary inventories of the naturally occurring and radioactive particulate-matter tracer $^{210}$Pb$_{ex}$. The sites comprise a broad range of surface-ocean productivity and physical-oceanographic regimes. Across the five trench-axis settings the inventory ratio varies between 0.5 and 4.1, with four trench-axis settings having ratios > 1 (sediment focussing) and one trench-axis setting a ratio < 1 (sediment winnowing). Although the fluid- and sediment-dynamical forcing behind sediment focussing remains unclear, this study finds evidence for another mechanism that is superimposed on, and counteracts, the focussing mechanism. This superimposed mechanism is related to higher-frequency (tidal, near-inertial) fluid dynamics. In particular, there is evidence for a strong and negative relation between the intensity of propagating internal tides and the extent of sediment focussing in the trench-axis. The relation is near-exponential and the most intense drop in sediment focussing already occurs at moderate internal-tide intensities. This suggests that propagating internal tides may have a subtle but significant influence on particulate-matter dynamics and food supply in hadal trenches in particular, but possibly also in the deep seas in general. A mechanism for the influence of internal tides on sediment dynamics is proposed.

Keywords: hadal trench; benthos; sediment; inertial oscillation; internal tide; lead-210 ($^{210}$Pb)
1. Introduction

The deepest parts of the deep sea are the ‘hadal’ environments which comprise water depths between 6000 m and the deepest point of ~ 10920 m (Nakanishi and Hashimoto, 2011) in the Challenger Deep of the Mariana Trench. Most areas at hadal depths occur within very long (O(1000km)) and narrow (O(10km)) trenches that are associated with tectonic subduction zones. One of the defining factors of these very deep environments is the high hydrostatic pressure, with the pressure in the deepest part of the Challenger Deep being almost 1100 times higher than at the sea surface. It has been known for several decades that these environments support life and harbour organisms that are adapted to, and in some cases even require, high hydrostatic pressures (e.g., ZoBell, 1952; Wolff, 1959-1960; Yayanos et al., 1981; Kato et al., 1998; Howe et al., 2004; Todo et al., 2005; Jørgensen and Boetius, 2007; Bartlett, 2009; Blankenship-Williams and Levin, 2009; Yayanos, 2009; Jamieson, 2011; Meersman et al., 2013).

Sufficient quality and quantity of food is required to sustain heterotrophic life at such great depths. This organic material could be formed through chemoautotrophic and/or photoautotrophic primary production. The relative importance of these two primary sources of organic material as food supply for heterotrophs in hadal settings is not known but is likely to vary spatially and temporally. For the deep Mariana Trench, evidence for the localised occurrence of chemoautotrophic organisms (Hand et al., 2012) as well as evidence for input of fresh sedimentary organic material that must have originated recently from photoautotrophic primary production in the surface ocean have been reported (Gooday et al., 2010; Glud et al., 2013). Evidence for fresh, photoautotrophically produced organic matter in sediments of the hadal trench axis was also provided for the deep Atacama Trench (Danovaro et al., 2003) and for the northern Japan Trench (Oguri et al., 2013).

The Atacama Trench and the northern Japan Trench are comparatively shallow (~ 7800 m and ~ 7550 m at the trench-axis study sites of Danovaro et al. (2003) and Oguri et al. (2013), respectively) and are located under relatively productive surface waters (e.g., Lutz et al., 2007; Watling et al., 2013).
They are also located near larger land masses with possible terrestrial inputs into the sea. These settings and the comparatively fast settling velocities of phytodetrital aggregates (and faecal pellets) probably explain the high accumulation of fresh sedimentary material in the trench axes of these two trenches. The Mariana Trench, however, is located away from larger land masses and the surface waters are oligotrophic. Because of these circumstances and the much greater water depths of the Mariana Trench the relatively high amounts of fresh organic matter in its trench-axis sediments are intriguing (Glud et al., 2013).

The enrichment or comparative abundance of fresh sedimentary material in trench-axis sediments relative to sediments from shallower trench-rim or abyssal depths (Danovaro et al., 2003; Glud et al., 2013) indicates that there is input through quasi-lateral downslope transport of relatively fresh particulate matter. This is in addition to the material constituting the quasi-vertical primary flux from the overlying water column. In the following, we use the term ‘focussing’ if sediments contain more material than expected from the directly overlying water. In the opposite case, we use the term ‘winnowing’.

There is evidence for sediment mass-wasting events (downslope movements of larger amounts of deposited sediments under the influence of gravity), sometimes reaching the seafloor along the trench axis (Jumars and Hessler, 1976; Tendal et al., 1982; Nozaki and Ohta, 1993; Fryer et al., 2003). These events can be triggered by earthquakes (Itou et al., 2000; Oguri et al., 2013) and might move bioavailable material, including dead benthic organisms. But such events only occur on time scales of decades or longer (Nozaki and Ohta, 1993) and they seem insufficiently frequent to maintain the more continuous food supply required to sustain hadal heterotrophic organisms. Consequently, it is expected that there are also more continuous and subtler processes maintaining food supply on sufficiently short time scales (Gooday et al., 2010). However, the fluid- and sediment-dynamic mechanisms leading to focussing in hadal trenches remain unclear.

Moreover, the finding that the Challenger Deep focuses fresh sedimentary material underneath oligotrophic surface waters and far away from larger terrestrial land masses suggests that there may be additional factors that are superimposed onto the basic focussing mechanism and control the efficiency
with which the transport of photosynthetically produced particulate matter into the trenches is occurring. These factors are expected to involve closely intertwined fluid and particulate-matter dynamics.

To improve our understanding of these controlling factors and processes, we evaluate conditions in hadal trenches of the Northwest Pacific (Fig. 1) that cover a broad range of surface-ocean productivities and physical-oceanographic regimes. We combine information on the distribution of a naturally occurring particulate-matter tracer with physical oceanographic results from observational studies and numerical modelling. This study does not identify the precise mechanistic basis of the primary focussing mechanisms. However, we are able to provide evidence for the superimposed influence of higher-frequency (tidal, near-inertial) fluid dynamics on the efficiency with which the pelagic particulate matter is transported down into the trenches, with propagating internal tides playing a particularly important role.

2. Material and Methods

2.1 The lead-210 approach to look for sediment focussing or winnowing

The naturally occurring radioactive lead isotope lead-210 ($^{210}\text{Pb}$) is particle reactive and used to trace particulate matter on time scales of up to several decades (e.g., Bacon et al., 1976; Cochran, 1992). $^{210}\text{Pb}$ (half life: 22.3 years) enters the ocean through radioactive decay of non-particle-reactive and comparatively long-lived $^{226}\text{Ra}$ (half-life: 1600 years) and through atmospheric input of $^{210}\text{Pb}$ into the surface ocean (Cochran, 1992). $^{210}\text{Pb}$ from both sources is partly incorporated into particles settling to the seafloor. In the deep sea, scavenging of $^{210}\text{Pb}$ by, and export towards the seafloor of, rapidly settling particles tend to be fast enough to export $^{210}\text{Pb}$ from the water column before it decays. This leads to radioactive $^{210}\text{Pb}/^{226}\text{Ra}$ disequilibria $< 1$ (i.e., the radioactivity of $^{210}\text{Pb}$ is lower than the radioactivity of $^{226}\text{Ra}$). As $^{210}\text{Pb}$ scavenging onto settling particles occurs throughout the whole water column, downward fluxes of particle-associated $^{210}\text{Pb}$ tend to increase towards the seafloor. Such downward fluxes can be determined from depth-integrated $^{210}\text{Pb}/^{226}\text{Ra}$ disequilibria or from samples
collected by calibrated sediment traps. The flux value at or just above the sediment / water interface can be converted into an estimate of the expected amount of deposited $^{210}\text{Pb}$ in the sediment (the expected or water-column-derived sedimentary inventory) through dividing the flux by the radioactive decay constant of $^{210}\text{Pb}$.

The $^{210}\text{Pb}$ that is deposited in the sediments from the overlying water column adds on to the $^{210}\text{Pb}$ that has been formed within the sediment through radioactive decay of sedimentary $^{226}\text{Ra}$. The former is called ‘excess $^{210}\text{Pb}$’ ($^{210}\text{Pb}_{\text{xs}}$) whereas the latter is called ‘supported $^{210}\text{Pb}$’. Sedimentary $^{210}\text{Pb}_{\text{xs}}$ activity is calculated by subtracting the supported $^{210}\text{Pb}$ activity (equalling the $^{226}\text{Ra}$ activity) from the total $^{210}\text{Pb}$ activity. The total amount of $^{210}\text{Pb}_{\text{xs}}$ as measured in the sediment is called the measured sedimentary $^{210}\text{Pb}_{\text{xs}}$ inventory or sediment-derived $^{210}\text{Pb}_{\text{xs}}$ inventory.

To assess topographically induced influences on the depositional particle flux into the sediment, estimated water-column-derived $^{210}\text{Pb}_{\text{xs}}$ inventories were compared with measured sediment-derived $^{210}\text{Pb}_{\text{xs}}$ inventories (e.g., Turnewitsch et al., 2004, 2013). If the water column-derived $^{210}\text{Pb}$ inventory is higher than the sediment-derived $^{210}\text{Pb}$ inventory this is evidence for lateral, near-seafloor transport away from the sediment sampling site (winnowing). And if the water column-derived $^{210}\text{Pb}$ inventory is lower than the sediment-derived $^{210}\text{Pb}$ inventory this is evidence for additional lateral, near-seafloor transport to the sediment sampling site (focussing). The ratio of sediment- and water-column-derived inventory estimates can therefore be viewed as an indirect indicator of the intensity of sediment dynamics and to some degree also fluid dynamics. This approach was applied here to $^{210}\text{Pb}_{\text{xs}}$ results from several hadal trenches in the Northwest Pacific, capturing a broad range of surface-ocean productivity and physical-oceanographic regimes (Figure 1 and Section 3 below).

Regarding $^{210}\text{Pb}$ dynamics, this work is based on previously published water column-data (Chung and Craig, 1980; Gamo and Horibe, 1984; Nozaki et al., 1998) and sediment data (Mariana Trench: Glud et al. (2013); Izu-Ogasawara Trench: Yamada et al. (1983), Swinbanks and Shirayama (1986); northern Japan Trench: Oguri et al. (2013); northernmost Japan Trench: Mohamed et al. (1996)) as well as new sediment data (trench at the Japan / Izu-Ogasawara Triple Junction).
2.2 Sampling and $^{210}$Pb$_{xs}$ analyses

For the Mariana Trench, sediment samples were collected in November 2010 at two sites (Glud et al., 2013), one at 6035m water depth on the southern trench rim and one at a water depth of approximately 10850 m in the center of the Challenger Deep (Table 1; Fig. S2 of the Online Supplement). Sediment cores were taken by a free-falling benthic camera-lander system (Yokosuka cruise no. YK 10-16, Challenger Deep, Mariana Trench, Pacific Ocean, 20 November – 6 December 2010, Japan Agency for Marine-Earth Science and Technology, JAMSTEC).

The same lander system was also used to collect sediment samples from the Japan / Izu-Ogasawara Triple Junction during Yokosuka cruise no. YK12-09 (Biodiversity and Biogeochemical Cycles in Ultra Deep Trench - T-T-T triple junction, off Boso, 14 - 21 June 2012, Japan Agency for Marine-Earth Science and Technology, JAMSTEC). Due to bad weather, only sediments from the trench axis could be collected. Sample material from three lander deployments was used: CS1: 15/06/2012, 34°0.2’N, 142°0.1’E, 9262 m; CS2: 16/06/2012, 34°0.1’N, 142°0.0’E, 9260 m; CS3: 18/06/2012, 34°0.2’N, 142°0.1’E, 9149 m.

For both cruises, the sediment cores did not show any discernible signs of disturbance. Sediment cores were sliced and sample slices were then sealed and transported to the land-based labs at JAMSTEC and the Scottish Association for Marine Science (SAMS) for further processing.

At SAMS, individual subsample masses of the Japan / Izu-Ogasawara Triple Junction sediments were not always sufficient for $^{210}$Pb$_{xs}$ analyses. In these cases, material from the same sediment-depth interval of 2 or 3 different cores was pooled. This approach seemed to be acceptable as the dry bulk density (DBD) profiles that could be established for four complete sediment cores (2 cores from CS1, 1 from CS2, 1 from CS3) without pooling were very similar (data not shown). SAMS results will therefore be given as a single composite $^{210}$Pb$_{xs}$ profile. Another complete sediment core from the first lander deployment (CS1) was analysed for $^{210}$Pb$_{xs}$ at JAMSTEC without the need to pool sediments.

Procedures for the gamma-spectrometric measurements of $^{210}$Pb$_{xs}$ at JAMSTEC and SAMS were already described by Glud et al. (2013). For completeness, these procedures are also described in detail in Section 1 of the Online Supplement. Further sediment-related information for the Mariana Trench,
the Izu-Ogasawara Trench, the Japan / Izu-Ogasawara Triple Junction, the Northern Japan Trench and
the Northernmost Japan Trench is given in sections 2.1, 3.1, 4.1, 5.1 and 6.1 of the Online Supplement,
respectively.

2.3 Physical-oceanographic information

Regarding observational physical oceanography, this work builds on the ultra-deep current-meter
studies of Fujio et al. (2000), Taira et al. (2004) and Ando et al. (2013). Both current speeds and
directions were recorded. For this study, only data from near-seafloor current meters were considered
(Fujio et al., 2000: 30 meters above bottom (mab); Taira et al., 2004: 25 mab; Ando et al., 2013: 32, 50
and 118 mab). The current meters were based on the rotor-type model RCM5 manufactured by
Aanderaa Instruments, Norway, and its equivalent model by Union Engineering Inc, Japan. Current
speeds and directions were recorded at 30 min or 60 min intervals for a minimum of 122 days and a
maximum of 535 days (only two out of 17 current-meter records are shorter than one year). As we are
interested in higher-frequency (tidal and near-inertial) flow oscillations, the previously unpublished
unfiltered current-meter data sets of the above studies were used. Further current-related information
for the Mariana Trench, the Izu-Ogasawara Trench, the Japan / Izu-Ogasawara Triple Junction, the
Northern Japan Trench and the Northernmost Japan Trench is given in sections 2.2, 3.2, 4.2, 5.2 and
6.2 of the Online Supplement, respectively.

Additional information on flow dynamics was derived from numerical modelling of near-seafloor
current velocities associated with internal-tide generation. The model builds on the work of Nycander
(2005) on energy conversion from barotropic (surface) to baroclinic (internal) tides. The approach to
compute near-seafloor current-velocity time series is described by Turnewitsch et al. (2008, 2013).
Key model inputs are barotropic tidal forcing, buoyancy frequency, geographic latitude (Coriolis
parameter) and seafloor bathymetry (topographic slope angles). Barotropic tides are derived from the
global inverse tide model of Egbert and Erofeeva (2002) and buoyancy frequencies are taken from the
WOCE climatology (Gouretski and Koltermann, 2004). Bathymetric resolution is crucial for
topographically related fluid dynamics (e.g., Mohn et al., 2013) and slope angles were therefore
derived from the GEBCO 30-arc-seconds bathymetry. For this study, the resolution of the model grid was also 30 arc seconds. The model is taking into account the four energetically most important diurnal (K1, O1, P1, Q1) and the four most important semidiurnal tidal constituents (M2, S2, N2, K2). It is therefore capable of producing estimates for maximum (typically spring-tide-related) total (barotropic + baroclinic) current velocities near the seafloor. Model runs were conducted for representative 63-days time series, comprising approximately 5 neap and spring tides.

3. Results and Discussion

3.1 Influences on sedimentary $^{210}$Pb$_{xs}$ inventories

Sedimentary $^{210}$Pb$_{xs}$ inventories for the investigated trenches (Figure 1) are given in Table 1. They include the inventories that were determined according to the methods described in Section 2.2 and Section 1 of the Online Supplement as well as inventories based on previously published data (Yamada et al., 1983; Swinbanks and Shirayama, 1986; Mohamed et al., 1996; Oguri et al., 2013). These inventories are also plotted versus water depth at the seafloor in Figure 2a, together with previously published $^{210}$Pb$_{xs}$ inventories in other, abyssal parts of the central West and Northwest Pacific (Yang et al., 1986; Moon et al., 2003). In the Online Supplement, new and previously published $^{210}$Pb$_{xs}$ profiles are shown (Figure S1).

For cases where the recent influence of sediment slumps and slides and of turbidity currents is unlikely, magnitudes of $^{210}$Pb$_{xs}$ inventories could be controlled by (1) water depth, (2) the magnitude of export fluxes of particulate matter from the surface into the deep ocean and (3) seafloor topography and flow / seafloor interactions, especially over more complex topography. In the following subsections, each of these factors will be discussed individually. This discussion will lead us to conclude that processes in category (3) are of particular relevance.
3.1.1 Importance of water-column length

Downward fluxes of particle-associated $^{210}\text{Pb}$ tend to increase with increasing water depth. To estimate the fluxes and the expected sedimentary $^{210}\text{Pb}_{\text{xs}}$ inventories, radioactive disequilibria between $^{210}\text{Pb}$ and $^{226}\text{Ra}$ need to be known throughout the water column. First, the effective parent nuclide $^{226}\text{Ra}$ will be discussed, followed by the daughter nuclide $^{210}\text{Pb}$.

To the best of our knowledge, there are no $^{226}\text{Ra}$ profiles available for the hadal-trench regions of this study (Mariana, Izu-Ogasawara, Japan). There is, however, fairly comprehensive information on the distribution of $^{226}\text{Ra}$ activities in shallower waters above hadal depths for various stations in other parts of the Northwest Pacific. These data are from Chung and Craig (1980) and from Gamo and Horibe (1984) and are compiled in Figure 2b. Given the magnitude of detectable basin-scale concentration gradients of $^{226}\text{Ra}$ in the deep Pacific (see, e.g., Figure 16A of Chung and Craig, 1980), it seems reasonable to assume that any bathyal and abyssal concentrations in this study’s trench regions would fall into the presently known range of values for the western Central and Northwest Pacific, i.e., the $^{226}\text{Ra}$ range shown in Figure 2b.

To the best of our knowledge, there is also no direct information on $^{226}\text{Ra}$ distributions in other deep-sea trenches, the only exception being three measurements from 6031 m, 6433 m and 7233 m water depth (1269, 867 and 67 m above the trench-axis seafloor) in the Aleutian Trench (Chung and Craig, 1980). Between abyssal and the deepest trench waters, this $^{226}\text{Ra}$ profile shows only a very slight increase of average concentrations with increasing depth (5378 m: 5.3 mBq kg$^{-1}$; 6031 m: 5.6 mBq kg$^{-1}$; 6433 m: 5.6 mBq kg$^{-1}$; 7233 m: 5.7 mBq kg$^{-1}$). This slight increase could be due to $^{226}\text{Ra}$ input into the trench water column through ‘seepage’ of $^{226}\text{Ra}$ from the sediments and exposed bedrock on the sloping sides of the trench. If this topographically related $^{226}\text{Ra}$ increase was more significant in other trenches it could introduce an uncertainty to the water-column-derived inventory estimates. This is because the potentially underestimated $^{226}\text{Ra}$ concentrations in the trench waters would lead to overestimated $^{210}\text{Pb} / ^{226}\text{Ra}$ disequilibria. This, in turn, would result in overestimates of the water-column-derived sedimentary $^{210}\text{Pb}_{\text{xs}}$ inventories and underestimates of ratios of sediment-
and water-column-derived inventories. However, the gradient in the Aleutian Trench suggests that the lateral $^{226}$Ra input is minute.

The notion that the overall influence of any lateral $^{226}$Ra input from trench-slope sediments or rock outcrops is small is supported by another line of reasoning. For example, typical planar across-trench distances between the Mariana-Trench rim and the deepest part of the Challenger Deep are between $\sim 35$ km and $\sim 50$ km (e.g., Figure S2 in the Online Supplement and Figure 2a,b in Fujioka et al., 2002). The depth change over these planar distances is $\sim 4.5-5$ km. Therefore, in comparison to a flat seafloor, the tilt of the trench slopes increases the seafloor area by only up to $\sim 1\%$. Taking smaller-scale topographic roughness into account, this value might only increase by a few percent. We therefore assume that, within the water columns of the hadal trenches of the Northwest Pacific, the range of $^{226}$Ra concentrations is very similar to the measured range of abyssal $^{226}$Ra concentrations in the Northwest Pacific. This justifies the depth-independent extrapolation of $^{226}$Ra in Figure 2b.

For total $^{210}$Pb, a complete water-column profile is available for the waters above and within the Izu-Ogasawara Trench down to 9742 m water depth (Nozaki et al. (1998) and our Figure 2b). As the Izu-Ogasawara Trench is located between the more southern Mariana Trench and the more northern Japan Trench we assume that this total-$^{210}$Pb profile is representative of this study’s hadal trenches.

Henderson and Maier-Reimer (2002) used a general circulation model to try and map the global 3D-distribution of $^{210}$Pb in the oceans. Across the relevant latitudinal range in the Northwest Pacific their model predicts a range of surface-water activities of $\sim 0.33-0.45$ Bq/100kg (their Figure 4c) which is higher than the measured range of near-surface values of Nozaki et al. (1998) above the central Izu-Ogasawara Trench (Figure 2b). This activity range in the surface ocean is largely controlled by a latitudinal gradient in atmospheric $^{210}$Pb input to the sea. However, in comparison to the whole water column, the surface-ocean layer that is influenced by the atmospheric input is thin. Consequently, the uncertainty introduced to water-column-derived sediment inventories of $^{210}$Pb$_{xs}$ by the discrepancy between measured and modelled surface-water $^{210}$Pb activities is small.

The surface excess of total $^{210}$Pb over $^{226}$Ra (Fig 2b) is usually interpreted as being atmospherically deposited $^{210}$Pb and is mainly in the dissolved phase (e.g., Bacon et al., 1976). We assume that this
dissolved $^{210}$Pb will eventually also be scavenged and exported into the deep waters and sediments. Below the topmost ~ 500 - 1000 m of the water column, the situation reverses and there is a deficit of total $^{210}$Pb compared to $^{226}$Ra. We assume all the ‘missing’ $^{210}$Pb is scavenged onto settling particles and transported to the sediments. The sum of the depth-integrated excess and deficit disequilibria therefore allows us to estimate sediment inventories of $^{210}$Pb$_{xs}$ that would be expected to occur if the system was in a steady state and all the surface-ocean excess $^{210}$Pb and deeper-ocean deficit $^{210}$Pb would simply be vertically deposited in the underlying sediments. Any discrepancies between expected and actually observed sediment inventories would indicate focussing or winnowing.

The sediment inventories of $^{210}$Pb$_{xs}$ as expected from water-column disequilibria from our study sites are compiled in Table 1. The uncertainties indicate the range between minimum and maximum estimates based on minimum and maximum values of the deep-water ranges of total $^{210}$Pb and $^{226}$Ra (Fig. 2b). The range of expected water-column-derived inventories is also included in Figure 2a (grey area). The data in Table 1 and in Figure 2a show that, as expected, there is an overall increase of sedimentary $^{210}$Pb$_{xs}$ inventories with increasing water depth of the sampled seafloor. Additionally, in most cases (Mariana Trench, Japan / Izu-Ogasawara Triple Junction, northern and northernmost Japan Trench), trench-axis sediments focus particle-associated $^{210}$Pb$_{xs}$, i.e., measured sediment-derived inventories are higher than expected water-column-derived inventory estimates.

Interestingly, the results also show that sediments from the five trench regions differ significantly in the ratios of sediment-derived and water-column-derived inventory estimates (Table 1), i.e., they differ significantly in the extent or efficiency of $^{210}$Pb$_{xs}$ and sediment focussing. This outcome suggests that the length of the overlying water column is a significant but insufficient controlling parameter for the $^{210}$Pb$_{xs}$ inventories in trench-axis sediments. Therefore, additional factors must be considered.

### 3.1.2 Particulate-matter export from the surface ocean

Along the study region, there is a latitudinal (northward) increase of surface-ocean productivity and particulate-organic-carbon (POC) export from the surface into the deep ocean (Lutz et al., 2007). Recently settled phytodetrital aggregates are easily resuspended (Lampitt, 1985; Beaulieu, 2002). They
and their fragments are likely to be transported laterally in bottom waters for some time before being incorporated into underlying sediments (Turnewitsch and Springer, 2001; Vangriesheim et al., 2001; Turnewitsch et al., 2008). Therefore, material freshly introduced into the near-seafloor waters may be particularly prone to focussing in topographic depressions. Higher surface-ocean productivity could therefore possibly be related to a higher fraction of phytodetrital particles being focussed into topographic depressions.

This relation is reflected to some degree in Figure 3. If the southern three sediment sampling sites (Mariana Trench, Izu-Ogasawara Trench, Japan/Izu-Ogasawara Triple Junction) are compared with the northern two sediment sampling sites (northern and northernmost Japan Trench) there is some evidence for a positive overall relation between the trench-axis $^{210}\text{Pb}_{\text{xs}}$ inventory ratios and approximate POC flux ranges estimated for the seafloor (Lutz et al. (2007) and Table 1).

Moreover, aeolian input of particulate matter to the sea is known to rise northwards across the study region (e.g., Mahowald et al., 2006). And the northern sediment sampling sites (Japan/Izu-Ogasawara Triple Junction and northern and northernmost Japan Trench) are near a major land mass with potentially enhanced riverine input of particulate matter and nutrients into the sea. By contrast, the Mariana and Izu-Ogasawara Trenches are far from major landmasses (Fig. 1). Aggregation of an increased amount of higher-mass-density aeolian and riverine particles with photosynthetically produced particulate organic matter could enhance the sedimentation rates of labile material. Near the seafloor the exported material could then undergo quasi-lateral transport and focussing in topographic depressions. Distance to larger land masses may therefore also contribute to what looks like a positive overall relation between POC fluxes and trench-axis $^{210}\text{Pb}_{\text{xs}}$ inventory ratios (Fig. 3).

However, it needs to be stressed that the relation is not particularly strong. Despite the aforementioned latitudinal gradients, the oligotrophic and remote Mariana Trench and the mesotrophic and much less remote Japan/Izu-Ogasawara Triple Junction have very similar trench-axis inventory ratios. And although the Mariana and Izu-Ogasawara sites are both located underneath similarly oligotrophic surface waters, the latter has much lower trench-axis inventory ratios than the former.
These inconsistencies suggest there are additional factors that influence $^{210}$Pb and sediment dynamics in and near hadal trenches.

3.1.3 Influence of hill-scale flow / topography interactions

The regions around some sediment-sampling sites are structured by topography on spatial scales smaller than the trench scale, i.e., by small hills or ridges superimposed on the trench-scale topography. It could therefore be argued that some of the observed variability in $^{210}$Pb$_{xs}$ inventory ratios between the trench sites could actually be due to smaller-scale interactions between flow and topography (Turnewitsch et al., 2004, 2008, 2013). We have no direct information on such smaller-scale variability in $^{210}$Pb$_{xs}$ inventories for our study regions. But Figure 2a includes relevant results from studies conducted in the abyssal Northeast Atlantic. Here, the influence of interactions between fluid dynamics and smaller-scale seafloor topography on $^{210}$Pb$_{xs}$ inventories was investigated at a short seamount (Turnewitsch et al., 2004, 2013). These seamount-related results show that topographically controlled fluid dynamics at abyssal depths could explain hill-scale variability of $^{210}$Pb$_{xs}$ inventories, covering a range of $\sim 0.5$ Bq cm$^{-2}$. This suggests that, for a given water depth, variability introduced by interactions between fluid dynamics and smaller-scale seafloor topography could in principle partly explain $^{210}$Pb$_{xs}$ inventory differences between the different trench sites. But in virtually all cases of the present study, the offset between expected and measured $^{210}$Pb$_{xs}$ inventories was considerably larger than $\sim 0.5$ Bq cm$^{-2}$. Smaller-scale variability is therefore also unlikely to be the main or even sole reason for the differences in $^{210}$Pb$_{xs}$ inventory ratios between the trench sites.

3.1.4 Conclusions

In one out of five study areas, the trench-axis $^{210}$Pb$_{xs}$ inventory ratio was $< 1$ (Izu-Ogasawara Trench); in the other four cases, the trench-axis ratios were $> 1$ and very variable. This trend supports the long-standing notion that in many settings trench-axis sediments focus $^{210}$Pb$_{xs}$ and associated particulate matter. However, the exact fluid- and sediment-dynamical foundation for the $^{210}$Pb$_{xs}$ and sediment focussing still remains unclear. There is some evidence suggesting that biological
productivity in, and particle export from, the surface ocean are controlling factors on $^{210}\text{Pb}_{xs}$ inventory ratios in hadal trench-axis sediments. Overall, however, this relation looks weak. Interactions between hill-size topography and flow may introduce some ‘noise’ in this relation.

It can be concluded that the above factors seem insufficient to fully explain the geographical distribution of the $^{210}\text{Pb}_{xs}$ inventory ratios in trench-axis sediments. It appears that there is at least one other mechanism that is superimposed on the basic mechanism that controls $^{210}\text{Pb}_{xs}$ and sediment focussing in trench-axis sediments. In this context, the inventory ratios $< 1$ that were found for the central Izu-Ogasawara Trench are of particular interest. This finding suggests that the superimposed mechanism counteracts the focussing mechanism and that the former can overwhelm the latter, leading to winnowing. Intuitively, probable candidates for the counteracting mechanism are fluid-dynamical ones. In the following, potentially relevant fluid-dynamical features near the seafloor and in the water column will be investigated.

### 3.2 Potential influence of higher-frequency fluid dynamics

There is plenty of evidence demonstrating that the scalar parameter of absolute current speed is a key controlling factor for sediment dynamics. There is, however, also more recent evidence for higher-frequency variability of current direction to play a role in the dynamics of sediment (non-)deposition, erosion and resuspension (Turnewitsch et al., 2013). Two main sources of higher-frequency flow variability are tidal and (near-)inertial oscillations. Tides are surface or internal waves at tidal frequencies ($\omega$) where the restoring force is gravity. By contrast, inertial oscillations are a type of internal wave that occurs in a rotating fluid and where the restoring force is the Coriolis force, with the wave frequency depending on the Coriolis frequency ($f$).

#### 3.2.1. Flow indicator $I_F$

To look for a possible combined influence of near-seafloor current speeds and current-direction variability on $^{210}\text{Pb}_{xs}$ inventory ratios, a simple measure $I_F$ is introduced that takes both flow aspects
into account. First, we apply a simple measure of the variability of current direction ($S$) to near-seafloor current measurements from the Mariana Trench (Taira et al., 2004), the Japan/Izu-Ogasawara Triple Junction (Fujio et al., 2000) and the northern Japan Trench (Ando et al., 2013). To estimate $S$, the directional 360° circle (with $0^\circ = 360^\circ$ pointing northwards) was first split into 8 evenly spaced 45° sectors, starting at $0^\circ$. Then, for each inertial period, the number of observed directional sectors was determined ($\overline{S}$) and this number was normalised by the maximum possible number of sectors ($S_{\text{max}} = 8$). The inertial period depends on the geographical latitude and, for the relevant latitudes of this study, reaches from $\sim 19$ hr at $\sim 39^\circ$ (corresponding frequency, $f$: 0.33 hr$^{-1}$) up to $\sim 63$ hr at $\sim 11^\circ$ (corresponding frequency, $f$: 0.10 hr$^{-1}$). This means that, for all study sites, the period of the predominant semidiurnal tide ($\sim 12$ hr; corresponding frequency, $\omega_s$: $\sim 0.5$ hr$^{-1}$) is within the frequency band of the inertial oscillations (i.e., $f < \omega_s$).

To then investigate the possible combined influence of current-direction variability and current speed, we use $S / S_{\text{max}}$ to develop the simple non-dimensional indicator $I_F$, according to $I_F = (V_{\text{max}} / V_c) (S / S_{\text{max}})$ (Turnewitsch et al., 2013). Here, $V_{\text{max}}$ and $V_c$ are used in the unit of m hr$^{-1}$ and $S$ and $S_{\text{max}}$ in the unit of directional sectors per inertial period. $V_{\text{max}}$ is the maximum current speed during a given inertial interval and $V_c \equiv 0.07$ m s$^{-1}$ is the nominal critical near-seafloor current speed for resuspension of freshly deposited phytodetritus (Lampitt, 1985; Beaulieu, 2002). For each current-meter record, $I_F$ was calculated for each consecutive interval defined by the length of the local inertial period. Then, for each complete current-meter time series, a temporal mean, standard deviation, median and maximum $I_F$ were calculated (Table 2). As only two out of 17 current-meter records are shorter than one year, seasonal variability should have only a small influence on site comparisons. There is a slight risk of biases due to inter-annual and longer-term variability though. Overall, however, we are confident that the $I_F$ data are robust and allow for comparison of the different study sites.

It was then attempted to relate $I_F$ to trench-axis $^{210}$Pb$_{xs}$ inventory ratios. Unfortunately, this could only be done for near-seafloor current-meter records from oceanward rims and landward mid slopes. There is not a sufficient number of deep trench-axis current-meter records to look for a relation with trench-axis $^{210}$Pb$_{xs}$ inventory ratios (only for the Mariana Trench and the trench at the Japan/Izu-
Ogasawara Triple Junction there are near-seafloor trench-axis current-meter records). It also needs to be stressed that there are no accessible near-seafloor records of sufficient temporal resolution and duration to calculate $I_F$ for the Izu-Ogasawara sediment sampling region for which the lowest trench-axis $^{210}\text{Pb}_{xs}$ inventory ratio of $\sim 0.7$ was found (Fig. 4; see Section 3.2 of the Online Supplement for more details). This limits the usefulness of $I_F$ in this study.

Keeping these caveats in mind, there is still some evidence suggesting that the flow indicator $I_F$ for near-seafloor currents on the oceanward trench rims shows a negative relation to trench-axis $^{210}\text{Pb}_{xs}$ inventory ratios (Fig. 4). If $I_F$ values from the landward mid slopes are plotted versus trench-axis $^{210}\text{Pb}_{xs}$ inventory ratios there is no clear relation (not shown). Moreover, $I_F$ displays a clearer relation with $^{210}\text{Pb}_{xs}$ inventory ratios than $V_{max}$. This indicates that higher-frequency directional variability of the near-seafloor currents may indeed affect trench-axis $^{210}\text{Pb}_{xs}$ inventory ratios.

The $I_F$ results indicate that the fluid dynamics on the oceanward side of the trenches are more important in controlling pelagic trench-axis sedimentation than fluid-dynamics on the landward (mid) slopes. Moreover, the negative relation between $I_F$ and the trench-axis inventory ratios would suggest that more intense fluid dynamics on oceanward trench rims lead to reduced focussing of $^{210}\text{Pb}_{xs}$ and sediment into trench axes. It can be speculated that these flow conditions keep an increased proportion of particulate matter in suspension near the trench rim, thereby reducing the amount of material available for funnelling and focussing down into the trench.

3.2.2 Internal-tide generation and propagation

As mentioned before, tidal and near-inertial oscillations are main contributors to higher-frequency flow variability. In the current-meter data both these sources of higher-frequency variability are intertwined. Moreover, the tidal signal may be composed of spatiotemporally varying contributions of the surface (barotropic) and internal (baroclinic) tides. In the deep sea, internal tides form if the depth-independent barotropic tidal flow in a density-stratified ocean is forced over a topographic obstacle (e.g., Garrett and Kunze, 2007). The internal tides can take the shape of so-called ‘beams’ that emanate from the topography at which they are generated. For conceptual purposes, examples of modelled
internal tide beams are shown in Figure 5a and b. The examples have been adapted from Balmforth and Peacock (2009) and show the beam geometries for a Gaussian ridge (Fig. 5a) and the accompanying Gaussian trench (Fig. 5b). The beam geometries for the ridge (also see Nycander, 2006) and trench differ notably, with the pattern of seafloor reflections and beam interferences being more complex in the trench. This suggests there could potentially be ‘pockets’ within the deeper trench water column that are characterised by surprisingly vigorous internal-tide dynamics.

It is known that internal waves in general (e.g., Turnewitsch and Graf, 2003) and internal tides in particular (e.g., Cacchione et al., 2002; Peine et al., 2009; Turnewitsch et al., 2008, 2013) may be linked to particulate matter dynamics. Along the internal-tide beams and at their reflection and interference points, current velocities and small-scale shear are enhanced (e.g., Rapaka et al., 2013). This has two potential implications for particulate-matter dynamics. First, areas of beam generation and reflection at the seafloor could be influenced more strongly than ‘shadow’ zones by (transient) non-deposition, erosion or resuspension of surface sediments. Second, particulate matter of the primary vertical flux has to cross the internal–tide beams and, locally, their interference points. This could have consequences for shear-related disaggregation and partial transfer of particulate material from the settling into the suspended form. These hypothetical mechanisms are illustrated in the conceptual sketches in Figure 5c and d. Here, particle dynamics in a trench without intense internal tides (Fig. 5c) are compared with particle dynamics in a trench with intense internal tides (Fig. 5d).

To help develop a more comprehensive picture of the potential importance of tides in the Northwest Pacific, the tide model of Nycander (2005) and Turnewitsch et al. (2008, 2013) was employed. The model allows to map the distribution of current velocities associated with the barotropic tide as well as near-seafloor current velocities associated with the baroclinic tide at its generation sites. In Figure 6, the model results for the southern Mariana-Trench region are shown. In terms of the barotropic tide (Fig. 6a) there are three main points. First, the major axes of the barotropic tidal ellipses (here represented by the energetically predominant semidiurnal M2 constituent) are orientated predominantly in the east-west direction. Second, this means that the barotropic tidal forcing in the Challenger Deep is nearly parallel to the trench axis. And third, the Challenger Deep is
surrounded by topographic highs at which the barotropic tides are amplified. This amplification is particularly strong if the major axis of the barotropic tidal ellipse is at nearly right angles to a ridge-like topography that reaches into the topmost ~1 km of the ocean. These locations are also the ones at which the strongest internal tides are generated and where the highest internal-tide related near-seafloor current velocities are found (Fig. 6b). Within the southern Mariana Trench itself, internal-tide generation does not play any noteworthy role.

The situation along the Japan and Izu-Ogasawara Trenches is depicted in Figure 7. In terms of tidal dynamics there is a distinct difference between the two trenches: in the Japan-Trench region in the north, major axes of barotropic tidal ellipses are near-parallel to the trench axis whereas towards the southern Izu-Ogasawara Trench region they turn and are at nearly right angles to the trench axis (Fig. 7a). The major trench-parallel ridges (Izu-Ogasawara Arc) to the west of the Izu-Ogasawara Trench are also at nearly right angles to the major axes of the barotropic tidal ellipses. This leads to the barotropic tides being strongly amplified at these ridges (Fig. 7a) and the shallower parts of the ridges (water depths < 1-2 km) are associated with intense generation of strong internal tides. The internal-tide generation is associated with high baroclinic tidal current velocities (Fig. 7b).

Direct evidence for the importance of internal-tide generation for sediment deposition was found in the Izu-Ogasawara region for Station 4 of Yamada et al. (1983) on the upper western trench slope (2970 m; grey circle in Figure 7): an extremely low $^{210}\text{Pb}_{\text{ex}}$ inventory is linked to intense internal-tide generation and high internal-tide-related current speeds.

There are also increased tidally related current speeds along the critical latitudes for the energetically most important diurnal tidal constituents $K_1$ (29.99°N) and $O_1$ (27.61°N) (but to a lesser degree also for the weaker constituents $P_1$ (29.81°N) and $Q_1$ (26.44°N)). Polewards of these latitudes their internal tides cannot propagate away from their generation sites (at the critical latitude, the tidal frequency equals the Coriolis frequency). None of the sediment-sampling and current-meter sites were at these latitudes though.

None of the deep trenches themselves seem to be associated with internal-tide generation (Fig. 7b). However, the absence of significant internal-tide generation within the trenches does not necessarily
mean that internal tides do not play any role for fluid and sediment dynamics within trenches. This is because internal tides can propagate away from their generation sites (Fig. 5a, b). For the globally most energetic semidiurnal tidal constituent M2, propagation of internal tides from the generation sites is possible at latitudes < 74.5°. Niwa and Hibiya (2001) conducted a numerical study of the spatial distribution of the M2 internal tide in the Pacific Ocean. Their Plate 2 shows the modelled geographical distribution of the depth-integrated kinetic energy of the M2 internal tide and suggests that there are order-of-magnitude differences between our study regions. The study regions in the northernmost Japan Trench, northern Japan Trench, Japan/Izu-Ogasawara Triple Junction, Izu-Ogasawara Trench and Mariana Trench are characterised by values of approximately $10^{1.0-1.5}$, $10^{1.5-2.0}$, $10^{2.0}$, $10^{2.5}$, $10^{3.0}$ and $10^{2.5}$ J m$^{-2}$, respectively (Tables 1 and 2).

In a separate but related line of study by Arbic et al. (2010, 2012) and Shriver et al. (2012), the global distribution of M2 internal tide intensities and pathways has been investigated using the HYCOM model with 32 layers, astronomical tidal forcing and horizontally non-uniform mass-density stratification. Model results are in good agreement with remotely sensed M2 internal tide amplitudes (see Figure 3 of Arbic et al., 2012). If the propagating M2 internal tide intensity is quantified in terms of the amplitude of the related sea-surface excursions, the emerging geographical pattern in the Northwest Pacific is broadly consistent with the findings of Niwa and Hibiya (2001). The study regions in the northernmost Japan Trench, northern Japan Trench, Japan/Izu-Ogasawara Triple Junction, Izu-Ogasawara Trench and Mariana Trench are characterised by amplitude values of approximately 2-4, 4-7, 9-12, 22-23 and 7-12 mm, respectively (Figure 8a; Tables 1 and 2).

It is very interesting to see that both measures of M2 internal-tide intensity display a rather strong, negative and near-exponential relationship with the trench-axis $^{210}$Pb$_{xs}$ inventory ratios (Fig. 8b, c). The negative nature of the relation indicates that the internal tides reduce the amount of $^{210}$Pb$_{xs}$ (and associated particulate matter) that is deposited at the trench-axis seafloor. This is consistent with the negative relation between the flow indicator $I_F$ and trench-axis $^{210}$Pb$_{xs}$ inventory ratios (Fig. 4). As already speculated above, the negative relation may be due to locally increased current velocities and shear, leading to the partial break-up of settling aggregated particles, a larger proportion of particulate
matter in suspension and a reduced amount of material available for funnelling and focussing down to the trench axis (Fig. 5d).

The relations shown in Figures 4 and 8b,c suggest that the Izu-Ogasawara trench-axis site is most strongly affected by propagating internal tides. In this context it also needs to be mentioned that the Izu-Ogasawara study region, that includes stations between 26°56.9’N and 29°5.4’N (Fig. 7), happens to embrace a ‘critical’ latitude at 28°54’N (28.9°N) for which a particular form of parametric subharmonic instability (PSI) is predicted to reach its maximum (MacKinnon and Winters, 2005; MacKinnon et al., 2013a,b). Here, smaller-scale shear, energy dissipation and energy spectral density may be particularly high in the upper and lower parts of the water column. This PSI phenomenon may have played an additional role in controlling particulate-matter dynamics throughout the water column.

Some further supporting evidence for the importance of internal tides and possibly the PSI in the Izu-Ogasawara Trench comes from studies of the water-column distribution of certain other radionuclides. There is a lack of any clear depth trends in the vertical distribution of naturally occurring particle-reactive radionuclides with very different half lives and chemical behaviour in the trench water column of the Izu-Ogasawara Trench (Nozaki et al., 1998; also see Section 3.3 of the Online Supplement). It could well be that internal-tide beams lead to intensified mixing which could explain the largely invariable radionuclide distributions within the trench. Moreover, some evidence for mixing-related (re)suspension of sediment particles from the bottom of the Izu-Ogasawara Trench is indicated by high $^{232}$Th and $^{239,240}$Pu activities at 12 mab (Nozaki et al., 1998).

A final piece of evidence in support of the occurrence of internal-tide-related effects in some Northwest Pacific trenches comes from the trench at the Japan/Izu-Ogasawara Triple Junction. The frequency distributions of current-speed records from the western (landward) mid slope differ significantly from the records from the eastern (oceanward) trench rim (see Figure S8 in the Online Supplement). Above the western trench-axis seafloor (deployments C4 and I5 in Figure S6 in the Online Supplement), more than 85% of the time, current speeds were below the detection limit. By contrast, above the eastern trench-axis seafloor (deployment J3 in Figure S6 in the Online Supplement and only ~ 15 km from stations C4 and I5 !), current speeds were significantly higher and their
frequency distribution resembled the ones on the western (landward) mid slope (Figure S8 in the
Online Supplement). It could therefore be speculated that the western (landward) mid-slope stations
and the eastern trench-axis station constitute two seafloor reflection areas of the same internal-tide
beam that emanates from the upper western (landward) slopes characterised by internal-tide generation
(Fig. 7).

3.2.3 Conclusions

A flow indicator that combines information on near-seafloor current speed and directional
variability on tidal and near-inertial time scales at oceanward trench rims displays a negative relation
to ratios of sediment- and water-column-derived $^{210}$Pb$_{xs}$ inventories in trench-axis sediments. Another
negative relation was found between the intensity of propagating semidiurnal internal tides and the
inventory ratios in trench-axis sediments.

A hypothetical mechanism for these negative relations between higher-frequency fluid dynamics
and the efficiency with which pelagic sediments are transported into hadal trenches has been proposed.
Increased current speeds and shear within internal-tide beams as well as increased current speeds and
directional variability near the seafloor may result in three sequential processes: (1) partial break-up of
aggregated particulate matter settling from the surface ocean; (2) the consequential transfer of fast-
settling into slowly or not-settling (suspended) particulate matter; and (3) reduced funnelling and
focussing of pelagic particles into trench-axis sediments.

4. Summary and overall conclusions

There are several lines of evidence indicating that many (but not all) trench-axis sediments focus
particulate material originating from the quasi-vertical primary flux and from quasi-lateral downslope
transport near the seafloor. The extent of recent sediment focussing varies a lot between different
trench locations in the Northwest Pacific and in one out of five cases winnowing instead of focussing
was found.
The magnitude of the particle flux from the overlying surface ocean and the proximity to larger land masses are probably amongst the factors that intensify sediment focussing in trench axes. However, these relations are not particularly strong and the exact mechanisms of the intertwined fluid and particulate-matter dynamics that lead to sediment focussing remain unclear. We suggest that another mechanism is superimposed on the basic focussing mechanism and controls the efficiency with which the particulate matter from the surface ocean is transported down into the trenches. In the Izu-Ogasawara Trench, the superimposed mechanism seems to overwhelm the focussing mechanism, leading to net winnowing of sediments. This study identified higher-frequency (tidal, near-inertial) fluid dynamics both in the water column and near the seafloor as likely candidates for the superimposed mechanism. The effect of propagating internal tides seems to be of particular importance.

The relationship between internal-tide intensities and sediment focussing is negative and near-exponential. The hypothetical underlying mechanism for this relation involves the conversion of larger, aggregated and comparatively rapidly-settling particles into suspended (or very slowly-settling) particles. This conversion, in turn, results in reduced focussing of pelagic sediments into trench-axis sediments. It is proposed that the conversion takes place along internal-tide beams, especially at locations in the water column where beams interfere with each other and at seafloor locations where beams reflect. Propagating internal tides could therefore counteract the focussing mechanism and have a reducing influence on supply of ‘fresh’ and more nutritious particulate matter to the hadal-trench benthos.

The near-exponential nature of the negative relation between internal tides and sediment focussing suggests that the influence on sediment dynamics is already high at only moderate internal-tide intensities. This, in turn, implies that internal tides might not only have a significant effect on particulate-matter dynamics and food supply in hadal trenches but potentially also in other deep-sea settings.
Acknowledgements

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**Figure Captions**

Figure 1. Bathymetric map of the study region in the Northwest Pacific. Main study areas are indicated. MT: southern Mariana Trench; IO: Izu-Ogasawara Trench; J/IO: Japan/Izu-Ogasawara Triple Junction; NJ: northern Japan Trench; NMJ: northernmost Japan Trench.

Figure 2. (a) Compilation of measured excess $^{210}\text{Pb}$ ($^{210}\text{Pb}_{xs}$) inventories in deep-sea sediments from different parts of the Northwest Pacific (NWP) that are characterised by different levels of export fluxes of particulate organic carbon (POC) from the surface into the deep ocean. For comparison, further abyssal data from the Northwest Pacific are given (Yang et al., 1986; Moon et al., 2003). To illustrate the potential influence of hill-scale seafloor topography on $^{210}\text{Pb}_{xs}$ inventories, results from the Porcupine Abyssal Plain (PAP) in the Northeast Atlantic are shown (Turnewitsch et al., 2004, 2013). Grey circle with arrow: most likely an underestimate (see Section 5.1 in the Online Supplement). The dashed line shows the mean and the grey area indicates the range of water-column-derived inventory estimates based on the simplified nominal minimum and maximum $^{226}\text{Ra}$ and $^{210}\text{Pb}$ profiles shown in (b). (b) Compilation of $^{226}\text{Ra}$ data from different parts of the NWP (Chung and Craig, 1980; Gamo and Horibe, 1984). They are compared with a total-$^{210}\text{Pb}$ profile throughout the whole water column in and above the Izu-Ogasawara Trench (Nozaki et al., 1998). The solid and dashed lines indicate the simplified $^{226}\text{Ra}$ and $^{210}\text{Pb}$ profiles that were used to estimate representative sediment inventories of $^{210}\text{Pb}_{xs}$ one would expect from depth-integrated $^{226}\text{Ra}$-$^{210}\text{Pb}$ water-column disequilibria.

Figure 3. Relationship between the ratios of measured over expected $^{210}\text{Pb}_{xs}$ inventories and probable ranges of particulate-organic-carbon (POC) fluxes to the seafloor (Lutz et al., 2007). $^{210}\text{Pb}_{xs}$ inventory ratios associated with an arrow and a question mark are most likely underestimates (see Section 5.1 in the Online Supplement). MT: Mariana Trench; IO: Izu-Ogasawara Trench; J/IO: Japan/Izu-Ogasawara Triple Junction; NJ: northern Japan Trench; NMJ: northernmost Japan Trench.
Figure 4. Relationship between the ratios of measured over expected $^{210}$Pb$_{xs}$ inventories and the flow indicator $I_F$ at oceanward trench-rim stations. For each study site, the temporal mean and median of the flow indicator $I_F$ are given. There is no current-meter record for the oceanward rim of the Izu-Ogasawara study area and consequently no $I_F$ value. See Section 3.2.1 for details about $I_F$. Maximum current speeds ($V_{max}$) are also shown for both the landward mid slopes and oceanward rims. $^{210}$Pb$_{xs}$ inventories associated with an arrow and a question mark are most likely underestimates (see Section 5.1 in the Online Supplement). MT: Mariana Trench; IO: Izu-Ogasawara Trench; J/IO: Japan/Izu-Ogasawara Triple Junction; NJ: northern Japan Trench; NMJ: northernmost Japan Trench.

Figure 5. Based on Balmforth and Peacock (2009). (a) In this idealized supercritical 2D-seamount-ridge scenario the locations from which the internal tide beams emanate upwards and downwards are indicated by ‘1’ while the seafloor reflection points of the initially down-going beams are indicated by ‘2’ (for supercritical topography, the topography is steeper than the internal-tide beam). (b) The corresponding ‘inverted-seamount’ trench is depicted. (c) and (d) Conceptual sketches of pelagic sedimentation in trenches (c) without and (d) with intense internal tides. In the former, larger aggregated particles exported from the surface ocean can reach the seafloor largely intact and are partly funnelled and focussed into trench-axis sediments (the exact mechanism of the quasi-lateral or downslope transport near the seafloor is still unclear as indicated by ‘?’). In the latter, the larger aggregated particles are partly ‘shredded’ and converted into suspended (non-settling or very slowly-settling) particulate matter when traversing internal-tide beams, leading to reduced particulate-matter (and associated $^{210}$Pb$_{xs}$) deposition in trench-axis sediments.

Figure 6. Tides in the Mariana-Trench study region. White circles: sediment sampling sites (Tables 1 and 2). (a) Bathymetric map. Every 10' a representative local barotropic tidal ellipse of the energetically most important tidal constituent M2 is superimposed on the bathymetry. Water depths < 0 (grey colour) indicate land. White squares: current-meter sites of Taira et al. (2004). (b) Map of the
maximum near-seafloor current speed associated with the baroclinic internal tide at their generation sites. Velocity contributions of propagating internal tides at seafloor reflection points are not considered by this model. White colour indicates land.

Figure 7. Same as Figure 6, but for the study region of the Japan and Izu-Ogasawara Trenches. PSI: latitudinal band in which parametric subharmonic instabilities (PSI) might play a role (dark (light) grey: intense (weak) PSI). White circles: sediment sampling sites referred to in Tables 1 and 2. Light grey circle: sediment sampling site at 2970 m water depth at which hardly any sedimentary $^{210}$Pb$_{xs}$ was found. At this location the baroclinic tidal current speeds are particularly high. Light grey squares: deployment sites of current meters (Fujio et al., 2000). White diamond symbol in the Izu-Ogasawara Trench: deployment site of the current meter of M. Fukusawa, as mentioned by Owens and Warren (2001): we had no access to these data (see Section 3.2 of the Online Supplement). White triangle in the Izu-Ogasawara Trench: sampling site of Nozaki et al. (1998) for water-column radionuclides. White squares at northern and northernmost Japan Trench: deployment sites of the current meters of Ando et al. (2013).

Figure 8. (a) Redrawn and modified from Arbic et al. (2012). Amplitude of sea-surface excursions associated with the propagating M2 internal tide. White circles: sediment sampling areas. PSI: latitudinal band in which parametric subharmonic instabilities (PSI) might play a role (dark (light) grey: intense (weak) PSI). (b), (c) Relationships between the ratios of measured over expected $^{210}$Pb$_{xs}$ inventories in trench-axis sediments and two internal-tide related parameters: (b) model-derived depth-integrated kinetic energies of the M2 internal tide (Niwa and Hibiya, 2001). (c) Amplitude of vertical excursions of the sea surface due to the propagating M2 internal tide (Arbic et al., 2012). $^{210}$Pb$_{xs}$ inventories associated with an arrow and a question mark are most likely underestimates (see Section 5.1 in the Online Supplement). Approximate ranges of the parameters on the abscissa are given. MT: Mariana Trench; IO: Izu-Ogasawara Trench; J/IO: Japan/Izu-Ogasawara Triple Junction; NJ: northern Japan Trench; NMJ: northernmost Japan Trench.
Table 1. Hadal-trench locations in the Northwest Pacific for which $^{210}$Pb$_{xs}$ inventories are available.

Measured (sediment-derived) and expected (derived from water-column disequilibria) $^{210}$Pb$_{xs}$ inventories at these sites, their ratios, measures of the intensity of internal tides, and POC fluxes estimated to occur at the seafloor are given. Bold numbers indicate data for trench axes.

<table>
<thead>
<tr>
<th>site</th>
<th>coordinates</th>
<th>depth (m)</th>
<th>measured $^{210}$Pb$_{xs}$ inventory (kBq m$^{-2}$)</th>
<th>expected $^{210}$Pb$_{xs}$ inventory (kBq m$^{-2}$)</th>
<th>ratio</th>
<th>depth-integrated kinetic energy of M$_2$ internal tide (J m$^{-2}$)</th>
<th>M2 internal tide, kinetic energy of propagating M$_2$ internal tide, (mm)</th>
<th>POC flux to the seafloor at depths between 3.5 and 6.5 km (g m$^{-2}$yr$^{-1}$)</th>
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<tr>
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<td>143°59.5’</td>
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<td>40.5±4.3 SAMS 42.8 JAMSTEC</td>
<td>21.3±8.0</td>
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<td>1.9</td>
<td>10$^{-14}$ [7-12]</td>
<td>~0.1-0.5</td>
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</tbody>
</table>

1 recalculated after Mohamed et al. (1996): see Section 6.1 of the Online Supplement for details
2 based on Oguri et al. (2013)
3 this study: two $^{210}$Pb$_{xs}$ profiles
4 Yamada et al. (1983); Swinbanks and Shirayama (1986)
5 Glud et al. (2013)
6 a: Niwa and Hibiya (2001): their Plate 2; b: Arbic et al. (2012)
7 a,b,c: upper, mid, lower western trench slope; d: trench axis; e: mid eastern trench slope; f: eastern trench rim
8 a: a few kilometers east of the trench axis which has a maximum water depth of ~7550 m; b: in the trench axis, but strongly affected freshly deposited turbidite sediments (see Section 5.1 of the Online Supplement for details); c: likely to be underestimates (see Section 5.1 of the Online Supplement for details)
9 trench axis
10 southwestern rim of the trench
11 a few kilometers west of the trench axis which has a maximum water depth of >9000 m; a: Swinbanks and Shirayama (1986); b: Yamada et al. (1983)
12 southern trench rim
13 trench axis in the Challenger Deep, the deepest point of the Earth’s recent oceans
14 uncertainties give the range of inventories calculated based on minimum and maximum estimates for the cumulative vertical $^{210}$Pb flux through the water column to the seafloor, derived from water-column $^{210}$Pb/$^{226}$Ra disequilibria
15 from Lutz et al. (2007)
Table 2. Hadal-trench locations in the Northwest Pacific for which ratios of measured and expected $^{210}$Pb fluxes at the sediment/water interface are available; information on measured current speeds and the combined intensity of current speed and higher-frequency (tidal, (near-)inertial) directional variability (as expressed by $I_F$: for a definition see main text) near the seafloor in the trench axis or the landward or oceanward trench rim; and a measure of the intensity of internal-tides. Bold numbers indicate data for trench axes. n.a.: not applicable; n.d.: not determined.

<table>
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<tr>
<th>site</th>
<th>coordinates</th>
<th>depth (m)</th>
<th>ratio</th>
<th>axis current speed (cm s$^{-1}$)</th>
<th>axis $I_F$</th>
<th>landward rim current speed (cm s$^{-1}$)</th>
<th>landward rim $I_F$</th>
<th>oceanward rim current speed (cm s$^{-1}$)</th>
<th>oceanward rim $I_F$</th>
<th>propagating M$_2$ internal tide: kinetic energy (J m$^{-2}$) [sea surface amplitude (mm)]</th>
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<td>n.d.</td>
<td>n.a.</td>
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<td>0.20±0.17 0.13 1.31</td>
<td>G1: 5.4±2.8 5.1 19.4</td>
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<tr>
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</tr>
<tr>
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<td>n.d.</td>
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<td>n.d.</td>
<td>n.d.</td>
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</tr>
<tr>
<td>10°50.3' W: 1.2±1.5 0.3 8.3</td>
<td>142°34.3'</td>
<td>6035</td>
<td>1.6</td>
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<td>n.a.</td>
<td>C12: 1.2±1.5 0.3 8.3</td>
<td>0.21±0.12 0.18 0.58</td>
<td>C32: 1.9±1.9 1.5 10.6</td>
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<td>$10^{23}$ [7-12]</td>
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<tr>
<td>11°22.0' W: 1.5±0.5 0.2 8.1</td>
<td>142°25.6'</td>
<td>10850</td>
<td>1.9</td>
<td>C22: 1.1±1.5 0.2 8.1</td>
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<td>0.30±0.15 0.27 1.01</td>
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<td>n.a.</td>
<td>n.a.</td>
<td>$10^{23}$ [7-12]</td>
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</tbody>
</table>
1 current meter deployment W1: landward rim, 40°N, 144°06'E; 5072 m water depth, 5040 m current-meter depth (32 mab)
2 current meter deployment W2: oceanward rim, 40°N, 144°40'E; 6238 m water depth, 6120 m current-meter depth (118 mab)
3 current-meter deployment N1: oceanward rim; 38°N, 144°31'E; 5870 m current-meter depth
4 current meter deployment C4: western axis, 34°0.1'N, 141°50.7'E; 8930 m water depth, 8900 m current-meter depth (30 mab)
5 current meter deployment I5: western axis, 34°1.3'N, 141°52.1'E; 9170 m water depth, 9140 m current-meter depth (30 mab)
6 current meter deployment J3: eastern axis, 34°1.3'N, 141°52.1'E; 9230 m water depth, 9200 m current-meter depth (30 mab)
7 landward rim: G1: 34°0.4'N, 141°10.5'E; 4270 m water depth, 4240 m current-meter depth (30 mab); H2: 34°1.1'N, 141°19.7'E; 6330 m water depth, 6300 m current-meter depth (30 mab); K2: 34°1.9'N, 141°19.1'E; 6070 m water depth, 6040 m current-meter depth (30 mab); M2: 33°58.1'N, 141°20.4'E; 5600 m water depth, 5570 m current-meter depth (30 mab); N2: 33°57.8'N, 141°21.1'E; 5990 m water depth, 5960 m current-meter depth (30 mab)
8 oceanward rim: B2: 33°59.9'N, 142°32.8'E; 5920 m water depth, 5890 m current-meter depth (30 mab); O3: 33°56.9'N, 142°31.5'E; 6130 m water depth, 6100 m current-meter depth (30 mab)
9 C12: 11°36'N, 142°34'E; 7009 m water depth, 7034 m current-meter depth (25 mab); C23: 11°22’N, 142°35’E; 10890 m water depth, 10915 m current-meter depth (25 mab); C32: 11°00’N, 142°36’E; 6615 m water depth, 6640 m current-meter depth (25 mab)
abyssal Northwest Pacific (NWP):
- central NWP, low POC export
- NWP, low-intermediate POC export
- NWP, Kuroshio Current, intermediate-high POC export
- NWP West Caroline Basin, controversial information on POC export

hadal trenches in NWP:
- Mariana Trench, low POC export
- Izu-Ogasawara Trench, low-intermediate POC export
- northern Japan Trench, intermediate-high POC export
- northernmost Japan Trench, intermediate-high POC export

Porcupine Abyssal Plain (PAP), Northeast Atlantic:
- PAP, intermediate-high POC export, topographically influenced
- PAP, intermediate-high POC export, not topographically influenced
approx. POC flux to the seafloor at water depths between 3.5 km and 6.5 km (g m⁻² yr⁻¹)

ratio of measured and expected \(^{210}\text{Pb}\) inventory in trench-axis or near-trench-axis sediments

- MT
- J/IO
- NJ
- NMJ

min.
max.
I at oceanward trench-rim stations

mean \( I_p \)
median \( I_p \)
\( V_{max} \), landward mid slope
\( V_{max} \), oceanward rim

no field data for IO inventory ratio of 0.7

\( l_f \) at oceanward trench-rim stations
(a) Horizontal distance from seamount centre (arbitrary unit)

(b) Horizontal distance from trench centre (arbitrary unit)

(c) Vertical distance from seafloor in the far field (arbitrary unit)

(d) Vertical distance from seafloor in the far field (arbitrary unit)
maximum baroclinic tidal velocity (m s$^{-1}$)

(a) water depth at seafloor (km)

(b) latitude (° N)
approx. depth-integrated kinetic energy of $M_2$ internal tide ($J m^{-2}$)

approx. sea surface amplitude of the $M_2$ internal tide (mm)

ratio of measured and expected $^{206}$Pb$_{207}$ inventory in trench-axis or near-trench-axis sediments
Online Supplement

1. Analyses of $^{210}\text{Pb}_{\text{xs}}$

To ensure an internal quality control of $^{210}\text{Pb}_{\text{xs}}$ data, one set of sediment sub-samples was analysed at SAMS and another subset was analysed at JAMSTEC for both the Mariana-Trench and Japan / Izu-Ogasawara Triple Junction trench samples. First, the method used at SAMS is described. Wet sediment subsamples were freeze-dried and ground in an agate mill. Porewater salt was not removed but the salt content of the sediment samples (assumed to equal the measured bottom-water salinity) was taken into consideration when calculating dry bulk densities (DBDs) and specific $^{210}\text{Pb}_{\text{xs}}$ (see below). Approximately 5 g (for sediments with higher expected activities) or, where possible, 10 g (for sediments with lower expected activities) of the dried and ground sediment were pressed into 47 mm-diameter discs using 20 tonnes of pressure and placed in clear unvented polystyrene petri dishes. The lids of the dishes were sealed onto the dishes using epoxy adhesive. The sealed samples were allowed to sit for at least 1 month prior to analysis to allow for the establishment of secular equilibrium between the gaseous $^{222}\text{Rn}$ (half life: 3.82 days) and its parent $^{226}\text{Ra}$, which is also the effective parent nuclide of $^{210}\text{Pb}$ and therefore required to calculate $^{210}\text{Pb}_{\text{xs}}$. The gamma-ray spectra of the samples were determined using planar germanium detectors (Canberra) and the instruments’ respective software. To measure $^{210}\text{Pb}$ activities and $^{226}\text{Ra}$ activities (through its short-lived daughter $^{214}\text{Bi}$), counts were registered at gamma-ray energies of 46.5 keV and 610 keV, respectively. Samples were counted for 90000 seconds (~ 1.04 days). Counts were corrected for backgrounds and counting efficiencies. Counting efficiencies of the detectors were determined using standard sediment pellets. These pellets have the same geometry as the sample pellets and were prepared from Arabian-Sea sediments that are assumed to represent typical deep-sea sediments. These sediments are known to have the natural $^{210}\text{Pb}$ and $^{226}\text{Ra}$ in radioactive equilibrium (they were collected from sediment depths > 20 cm) and were spiked with known activities of $^{210}\text{Pb}$ and $^{226}\text{Ra}$ from standard solutions.

Basic calculations, corrections and conversions of the JAMSTEC measurements were the same as described above. Here we only specify differences between the procedures at the two labs. The
respective sediments were placed in plastic cubes and dried at 80°C for 48 hours. The dried sediments were milled and 2 g were packed into a plastic vessel and left for 2 months to ensure equilibrium between 226Ra and 222Rn. The 210Pb\textsubscript{xs} concentrations were measured using an ORTEC 12030 well-type gamma ray detector and a SEIKO EG&G MCA7800 spectrum analyser. The respective peak areas of the raw data of 210Pb (46.5keV) and 214Pb (351.9keV; also a short-lived 226Ra daughter) were calculated by Gaussian curve fitting using KareidGraph 4.1. Both 210Pb and 214Pb concentrations were referenced against a CANMET DL-1a uranium-thorium standard. Total counting times for the samples ranged from 1 to 3 days.

To be able to calculate sedimentary inventories of excess 210Pb, radioactivities in disintegrations per second per gram of dry sediment (Bq g\textsuperscript{-1}) were translated into disintegrations per second per cubic centimetre of wet sediment (Bq cm\textsuperscript{-3}) by using measured DBD corrected for salinity. Because of the high similarity of the SAMS- and JAMSTEC-derived Mariana-Trench 210Pb\textsubscript{xs} profiles given in Bq g\textsuperscript{-1} and because of the fact that the SAMS- and JAMSTEC-derived 210Pb\textsubscript{xs} profiles originated from subsamples of the same sediment core, the SAMS-derived DBD profile was applied to both the SAMS- and the JAMSTEC-derived 210Pb\textsubscript{xs} profile to convert concentrations given in Bq g\textsuperscript{-1} into concentrations given in Bq cm\textsuperscript{-3}. And because of the high similarity of DBD profiles from different cores and lander deployments in the trench of the Japan / Izu-Ogasawara Triple Junction an average DBD profile was used for both the SAMS and JAMSTEC data to convert 210Pb\textsubscript{xs} concentrations given in Bq g\textsuperscript{-1} of dry sediment into 210Pb\textsubscript{xs} concentrations given in Bq cm\textsuperscript{-3} of wet sediment.

Sedimentary 210Pb\textsubscript{xs} profiles of the new data as well as 210Pb\textsubscript{xs} profiles from previous studies are shown in Figure S1.
Figure S1. Sedimentary excess $^{210}\text{Pb}$ ($^{210}\text{Pb}_{\text{ex}}$) profiles from different hadal-trench environments in the Northwest Pacific. The plots are arranged from the southernmost (a) to the northernmost (e) region. (a) Mariana Trench (Glud et al., 2013; uncertainties of JAMSTEC data: 1SD of counting statistics; uncertainties of SAMS data: propagated 1SD). Station locations are indicated in Figure S2. (b) Izu-Ogasawara Trench (note that data from Yamada et al. (1983) are given as total $^{210}\text{Pb}$; data from Swinbanks and Shirayama et al. (1986) have been read from their Figure 3a and are therefore only approximate); Yamada et al. (1983) gave 2SD uncertainties based on counting statistics, but they were not plotted here for clarity; Swinbanks and Shirayama et al. (1986) did not show uncertainties in their $^{210}\text{Pb}_{\text{ex}}$ plot. Swinbanks and Shirayama et al. (1986) calculated their excess values by assuming a constant $^{226}\text{Ra}$ content of 0.087 Bq g$^{-1}$ which was estimated from sediments deeper than 7 cm sediment depth in the study of Yamada et al. (1983). For station locations, see Figure 7 of the main text. (c) Japan / Izu-Ogasawara Triple Junction (previously unpublished data; uncertainties of JAMSTEC data: 1SD of counting statistics; uncertainties of SAMS data: propagated 1SD). The sampling location is indicated by ‘L’ in Figure S6. (d) Northern Japan Trench (Oguri et al. (2013). Uncertainties: 1SD of counting statistics. For sampling locations see Figure S12. (e) Northernmost Japan Trench (data recalculated from Mohamed et al., 1996; for details of the recalculation see Section 6.1; according to Mohamed et al. (1996), the 1SD uncertainties are based on counting statistics and uncertainties of background determinations). For sampling locations, see Figure S12.
2. Mariana Trench

2.1 Sediments

The $^{210}$Pb$_{xs}$ profiles from the Mariana Trench were already shown and the inventories given by Glud et al. (2013). Here we revisit these data and describe and interpret them in some more detail. The sampling locations are indicated as red circles in the detailed bathymetry of Figure S2. When expressed in Bq g$^{-1}$ the $^{210}$Pb$_{xs}$ profiles from both our sites show the highest activities within the topmost 1 cm of the sediment (Fig. S2). Both profiles also have a pronounced subsurface maximum: at the 6035 m site it occurred around 4.5 cm whereas at the 10850 m site it occurred around 2.5 cm in the JAMSTEC analyses and around 3.5 cm in the SAMS analyses (the reason for this difference in sediment depth of the subsurface maximum at the 10850 m site is not known). [It is worth noting that sedimentary $^{210}$Pb profiles from the Izu-Ogasawara Trench (8260 m water depth; Yamada et al. (1983) and Figure S1b) and the northern Japan Trench (7261 m water depth; Oguri et al. (2013) and Figure S1d in the Online Supplement) also show subsurface maxima (Yamada et al. (1983): subsurface maximum at 2.5 cm sediment depth; Oguri et al. (2013): subsurface maximum at 2-4 cm sediment depth]. When expressed in Bq cm$^{-3}$ the $^{210}$Pb$_{xs}$ profiles look qualitatively similar to the profiles expressed in Bq g$^{-1}$, but for the 10850 m site the subsurface maximum is of almost the same magnitude as the surface maximum (not shown). At both the 6035 m and the 10850 m site, the vast majority of $^{210}$Pb$_{xs}$ occurs within the topmost 5 cm of the investigated sediment columns.

The transition between the deepest sediment layer still containing larger amounts of $^{210}$Pb$_{xs}$ (4-5 cm) and the first layer with small or undetectable amounts of $^{210}$Pb$_{xs}$ (5-6 cm) is more abrupt than in most abyssal sediments. Interestingly, a similarly abrupt transition was observed at 7 cm sediment depth in the aforementioned $^{210}$Pb profile from the Izu-Ogasawara Trench (Yamada et al., 1983). These abrupt transitions suggest sudden deposition of larger amounts of sedimentary material (Nozaki and Ohta, 1993; Oguri et al., 2013) and / or a form of particle transport within the surface sediments that is strongly confined to a certain layer of surface sediment and without much $^{210}$Pb$_{xs}$ ‘leaking’ into deeper sediments. The $^{210}$Pb$_{xs}$ inventories at the 10850 m site are much higher than the peak activities...
at the 6035 m site: at the 6035 m site the inventory was 1.72 ± 0.16 Bq cm⁻² (mean ± 1 propagated standard deviation) according to the SAMS measurements and 1.85 ± 0.05 Bq cm⁻² according to the JAMSTEC measurements; by contrast, at the 10850 m site the inventory was 5.50 ± 0.23 Bq cm⁻² according to the SAMS measurements and 4.55 ± 0.07 Bq cm⁻² according to the JAMSTEC measurements.

The present study is relevant for seafloor covered by sediments. Hadal trenches are known to have very varied smaller-scale seafloor topographies, reaching from smooth sediment covers of varying thickness to rock outcrops devoid of any noteworthy sediment cover. To judge how representative the sampling sites of this study may be, available information on sediment-related aspects have been collated for each trench site.

Relatively little is known about the sediment distribution across the southern Mariana Trench. The Challenger Deep sensu Fujioka et al. (2002) consists of three shallow en echelon basins with water depths greater than 10850 m: a western, central and eastern one (see also Nakanishi and Hashimoto, 2011). On 30 May 2009, footage and seafloor cores obtained during Dive 011 of the Nereus Hybrid Underwater Robotic Vehicle (HROV) in the eastern basin revealed a sediment-covered basin floor and rock outcrops at the southern boundary of the basin floor, with the rocks believed to be part of the subducting plate; on 01 June 2009 footage and seafloor cores obtained during Dive 012 of the Nereus HROV in the western basin also revealed a sediment-covered basin floor (Bowen et al., 2009). Footage and sediment cores obtained during Nov/Dec 2010 by free-falling benthic landers have also shown that the central basin is covered with sediments (Glud et al., 2013). These studies confirm earlier evidence from coring work and footage for a sediment cover in the deepest basins (coring by the ABISMO mud core sampler: Yoshida et al., 2009; studies and surveys involving the ROV Kaiko: Akimoto et al., 2001; Todo et al., 2005; Gooday et al., 2008, 2010; Barry and Hashimoto, 2009; Kitazato et al., 2009). Time lapse photos obtained in 1977 from the northeastern basin slope of the western basin at 11°21.3'N, 142°13.8'E and a depth of ~ 10600 m also show a seafloor covered by sediments (Yayanos, 2009).
The footage of Glud et al. (2013) from the central basin shows some evidence for subtle patchiness of the sediment surface on horizontal scales of O(1-10 cm): mostly gentle depressions with somewhat rougher microtopography alternate with areas with smoother surfaces. This horizontal variability may be partly due to amphipods (probably Hirondellea gigas) swimming into and out of the sediment as observed on the video recordings of Glud et al. (2013). However, in comparison to many other deep-sea settings (e.g., Heezen and Hollister, 1971; Turnewitsch et al., 2000; Howe et al., 2004; Glud et al., 2013) the sediment surface looks smoother, with less microtopography in the form of lebensspuren. This reduced horizontal patchiness increases the likeliness that the single sediment core from the Challenger Deep analysed for $^{210}$Pb$_{xs}$ is in fact representative.
There is early evidence for (at least patchy) sediment cover on the northern trench slopes. Wiseman and Hendey (1953), who report on the first sediment sample collected from the Challenger Deep between the western and central basins (11°20.0'N, 142°19.0'E) at a depth of ~ 10505 m, note that on “23 March 1875 a sample of the deep-sea floor was taken [by H.M.S. Challenger] at 11°24.0'N 143°16.0'E from a depth of 4475 fms. (8185 m), that is, about 60 nautical miles east of the 1951 [Challenger Deep] station. Microscopical examination of this earlier material … showed that it was similar, but not the same as, that collected in October 1951. The material was similar in colour, and about the same proportion of it was organically produced silica. The chief difference was, however, in the proportions of the organisms represented. The earlier material was almost entirely composed of radiolarians with very few diatom fragments.” This 8185 m station is on the lower northern slope of the Mariana Trench to the east-northeast of the Challenger Deep; here the maximum depth of the trench is > 9200 m. Despite the relative steepness of the northern slope it seems that at least pockets of sediments do accumulate here. Regarding the shallowest depths to the north, however, Fryer et al. (2003) state that the “southern forearc is virtually devoid of sediment.”

Bathymetric studies of the region around the Challenger Deep show that the deep (> 8 km water depth) southern (subducting) slope of the trench is structured by elongated topographic features that strike nearly parallel to the main trench axis and are a few kilometres wide and up to ~ 400 m high (Fujioka et al., 2002; Fryer et al., 2003; Nakanishi and Hashimoto, 2011). These features are typically interpreted as reflecting “tectonically controlled topography rather than the secondary effect of erosion or sedimentation” (Fujioka et al., 2002). More specifically, both Fujioka et al. (2002) and Fryer et al. (2003) view these features as fault-related graben and horst structures. Nakanishi and Hashimoto (2011), however, conclude that the “topographic expression of the elongated structures is a half graben with ridge and escarpment rather than full graben”.

In their Figure 3, Fryer et al. (2003) show sidescan imagery of the Challenger Deep region. These data include kilometer-scale “patches” of high acoustic backscatter that are mainly associated with graben structures. On the southern slope the size of these patches seems to increase towards the trench axis, with some of these patches reaching the seafloor at the trench axis. Fryer et al. (2003) interpret
these features as debris flows of material from the fault scarps, with the material flowing into adjacent graben. Fryer et al. (2003) suggest the high backscatter may indicate that the debris flow events are relatively recent and have not been buried by pelagic sedimentation yet. It would also seem that debris-flow sediments do not entirely fill in the graben prior to subduction. This interpretation of the sidescan data would suggest that a significant fraction of the southern slope is covered with sediments. Footage and/or coring have shown that there is also a sediment cover at the southern rim of the Challenger Deep (e.g.: Todo et al. (2005): Station 40, 11° 3.93’N, 142° 29.79’E, 7123 m water depth; Glud et al. (2013): the station at 6035 m water depth).

Gooday et al. (2010) conducted a detailed study of benthic foraminifera from the Challenger Deep and suggested “that some agglutinated foraminifera living at extreme hadal depths construct a test from biogenic and detrital particles, which subsequently dissolve. The incorporation of … coccoliths and fragments of planktonic foraminiferal shells into two tests indicates that these delicate calcareous particles reach this extreme hadal site intact. Presumably, they are conveyed by rapidly sinking particles, such as phytodetritus aggregates or faecal pellets.” Gooday et al. (2010) also mention that the “floor of the Challenger Deep lies well below the carbonate compensation depth, which is situated between 4000 and 4600 m in the Pacific Ocean”. And they refer to a study in which planktonic foraminiferan shells were placed in a nylon bag attached to a sediment trap moored at 8688 m depth in the Japan Trench: on trap recovery after 387 days these shells were found to have completely dissolved (Nozaki and Oba, 1995). This gives a maximum estimate for the time it takes for the calcareous particles to settle from the surface ocean to the deepest depths of the Challenger Deep.

Another potentially important finding of Gooday et al. (2010) is that the “discoidal structures in the test of Trochamminacean sp. C may represent the distal shields of Hayaster perplexus, a rather thin and fragile coccolith that must have required rapid transport to reach a depth of almost 11000m intact. The delicate nature of these coccoliths, and their probable presence at or near the sediment surface, precludes transport by turbidity currents, which have been reported to carry shallow-water foraminiferan tests to extreme depths in the Philippine Trench (Fisher and Hess, 1963).”
Given the above information, it would seem safe to conclude that (1) the trench axis and significant parts of the southern (and possibly northern) trench slope are covered by sediments, (2) mass wasting (turbidity currents?) may occur on the southern (and possibly northern) trench slope, and (3) comparatively fresh and bioavailable material from the surface ocean reaches the deepest depths of the ocean as primary flux (rather than through secondary particle transport in the form of turbidity currents).

2.2 Currents

In Section 3.1.4 of the main text of this paper the probable importance of downslope bedload transport and / resuspension for sediment dynamics within the trench is mentioned. This type of transport would be intimately linked to local and regional currents and fluid dynamics (Section 3.2 of the main text). For the southern Mariana Trench there is some early anecdotal evidence (e.g., Walsh, 2009; Yayanos, 2009) and also information from deep current measurements (Taira et al., 2004). Don Walsh, one of the two men diving to the seafloor of the Challenger Deep on 23 January 1960, described the effect of the touch-down of their bathyscaphe Trieste as follows: the resuspended sediment “was a “diatomaceous ooze”, very fine and light coloured. As we landed, a cloud of sediment was stirred. This happened with all of our dives and usually after a few minutes it would drift away. Not this time. The cloud remained for the entire time on the bottom [20 minutes] and showed no signs of moving away” (Walsh, 2009). [The use of the term “diatomaceous” probably originates from the description of the very first sediment sample collected from the Challenger Deep: “The deposit is brown when wet. About 4 per cent, consisting essentially of diatoms and minor amounts of radiolaria, is coarser than 63[μm]. A little volcanic debris, as well as a few ovoid bodies suggestive of faecal pellets are present” (Wiseman and Hendey, 1953).] Time lapse photos from 1977 presented by Yayanos (2009) show that sediment resuspended by the touch-down of the camera system had left the site within less than 40 minutes. The resuspension plume of this camera system would have been much smaller than the plume caused by the Trieste submersible. This early observational evidence suggests
currents near the seafloor of the Challenger Deep can be slow and possibly even almost stagnant, at least temporarily.

Taira et al. (2004) report on a unique data set of current velocities across the eastern basin of the Challenger Deep, including data from 25 meters above the seafloor (mab) (deployment locations are indicated in Figure S2). To investigate the possible influence of currents near the seafloor on sediment dynamics we revisit this dataset (access to the current-meter data was granted by the Japan Oceanographic Data Center (JODC)). Here we use the unfiltered data, i.e., data from which higher-frequency variability due to tides and (near-)inertial fluctuations has not been removed.

Current speed has been known for a long time to be an important scalar fluid-dynamical parameter in controlling sediment deposition, erosion and resuspension. Phytodetrital particulate-matter aggregates constitute a major component of the primary sedimenting flux from the surface oceans, forming pelagic and contributing to hemipelagic sediments. Field and laboratory studies indicate that current speeds of approximately \( \geq 6-8 \text{ cm s}^{-1} \) at \( O(1\text{m}) \) above the seafloor can be sufficient to resuspend such phytodetrital aggregates (Lampitt, 1985; Beaulieu, 2002). Older, more compacted and more cohesive sedimentary material tends to be characterised by higher threshold current speeds for erosion and resuspension (possibly at least \( \sim 10-15 \text{ cm s}^{-1} \); e.g., McCave and Hall, 2006).

Another potentially important fluid-dynamical parameter for sediment dynamics is the intensity of the variability of current velocity, i.e., the intensity of the combined variability of current speed and current direction. This potential importance can be expected to result from (a) the statistical nature of benthic boundary layer turbulence and increased probabilities of relatively rare but very high bed shear stresses in flows that have a significant oscillating (tidally- and/or inertially-influenced) and rotating (Coriolis-influenced) component; and (b) the decreased probability of the statistical sediment-grains ‘landscape’ that constitutes the sediment/water interface to reach a self-stabilising quasi-steady state under a boundary layer with a significant oscillating and rotating flow component (Turnewitsch et al., in prep.).

We therefore investigated the current-meter data of Taira et al. (2004) in terms of current speed as well as higher-frequency directional variability. The focus is on the time series at 25 mab at sites on
the northern slope (meter CD12: 7035 m total water depth; 11°36’N, 142°34’E), the southern rim (meter CD32: 6640 m total water depth; 11°00’N, 142°36’E) and the Challenger Deep (meter CD23: 10915 m total water depth; 11°22’N, 142°35’E).

All three stations are characterised by a large fraction of very low current velocities, in many cases indistinguishable from 0 cm s\(^{-1}\) (see the frequency distributions of unfiltered and not-averaged current speeds at 25 mab in Figure S3). These intervals of near-stagnant near-seafloor waters typically last for several hours but can occasionally be up to ~ 1-2 days in duration. It may well be that the landing of the Bathyscaphe Trieste in the Challenger Deep took place during one of these intervals of near-stagnant waters, which would explain why the plume of sediment resuspended at touch-down did not disappear during the 20 minutes the submersible stayed at the seafloor (Walsh, 2009).

In terms of the frequency distributions the northern slope station and the Challenger-Deep station are almost identical. There are usually many months between very short events (time scale of a few hours) during which the typical critical near-seafloor current speed of ~ 7 cm s\(^{-1}\) for the resuspension of freshly deposited aggregated sedimentary material is exceeded. By contrast, the southern rim station has a somewhat higher fraction of higher current speeds, with ~ 1% of the data above the typical critical near-seafloor current speed of ~ 7 cm s\(^{-1}\) (Fig. S3): during the first 8 months of the record these events occur at least once per month; during the last ~ 6.5 months of the record, however, such events are much more sporadic (approximately every 2-3 months).

The longer-term flow (time scale of > 1 year) near the seafloor on the northern slope and southern rim is directed towards southwesterly directions (Fig. S4a,c). By contrast, in the Challenger Deep a net-flow towards an east-northeasterly direction was observed (Fig. S4b). However, the more important difference might be between the northern-slope and the Challenger-Deep stations on the one hand and the southern-rim station on the other hand: in terms of higher-frequency directional variability (time scales of hours up to several days) the southern-rim station is much more dynamic than the other two stations, including many complete 360° current rotations which may at least partly be (near-)inertial oscillations (Fig. S4; and examples of more highly resolved flow patterns in Figure S5). The northern and central sites also have occasional intervals of enhanced directional variability.
(Fig. S5a-d); but these events are comparatively rare and less intense. At the southern rim they are much more common and more intense (Fig. S5e,f). It is worth noting that in many cases very slow or near-stagnant currents precede and/or occur during a significant directional change of the flow. The reduced directional variability on the northern slope and in the Challenger Deep may be due to the more pronounced topographic restriction of the flow compared to the southern-rim station.

Because of the increased proportion of higher current speeds and enhanced higher-frequency variability of current directions at the southern-rim site it would seem that unconsolidated sediment particles at the sediment/water interface could be affected by the ambient fluid dynamics near the seafloor, including (transient) non-deposition, erosion or resuspension. Sediments at the northern mid-slope site and in the Challenger Deep seem less likely to be influenced by these processes.
Figure S3. Frequency distributions of current speeds across the southern Mariana Trench as recorded by the three near-seafloor (25 mab) current meters CD12 (northern mid slope), CD23 (Challenger Deep) and CD32 (southern trench rim) of Taira et al. (2004). Geographical coordinates, water depths at the seafloor and the number of measurements are given in the figure legend. Deployment locations are indicated in Figure S2.
Figure S4. Progressive vector diagrammes for the near-seafloor (25 mab) Mariana Trench current-meter records (a) CD12 (northern mid slope), (b) CD23 (Challenger Deep) and (c) CD32 (southern trench rim) of Taira et al. (2004). Water depths at the seafloor and start and end dates/times of the records are given. Individual months are indicated by alternating grey and black lines. Arrows and associated lower-case letters in brackets indicate parts of the progressive vector diagrammes that are shown in more detail in Figure S5.
Figure S5. Examples of near-seafloor (25 mab) flow patterns (progressive vector diagrams) in the Mariana Trench from stations (a,b) CD12 (northern mid slope), (c,d) CD23 (Challenger Deep) and (e,f) CD32 (southern trench rim). The data are from Taira et al. (2004). Arrows indicate progression in time. Data points on the graphs are plotted at hourly intervals. Dates/times of the plotted time intervals are given. Boxes in the upper diagrams of (e) and (f) mark the flow patterns that are shown in more detail in the lower diagrams of (e) and (f).
3. Izu-Ogasawara Trench

3.1 Sediments

Sedimentary $^{210}$Pb$_{ss}$ data were reported by Yamada et al. (1983) for three sites in the Izu-Ogasawara Trench (sampling locations are shown in Figure 7 of the main text). Samples were collected with a box corer between 1 and 4 March 1980. The deepest sampling site (8260 m; Station 9) was “on a small plain” slightly east of the trench axis (whose maximum water depth is > 9000 m). The sediment was described as “brown clay” without “appreciable calcium carbonate”. Sediment from this box corer deployment was also subsampled for $^{210}$Pb$_{ss}$ by Swinbanks and Shirayama (1986). Tendal et al. (1982) who also sampled the same box-corer sediment for infaunal xenophyophores described the sediments as “distal turbidite facies”. Four turbiditic sequences were identified with thicknesses of ~ 4-7 cm. The turbidite identity increased with increasing sediment depth whereas the intensity of disturbance of the typical turbidite sequence (presumably due to bioturbation) increased towards the sediment/water interface, i.e., in the younger deposits. Four subcores of 100 cm$^2$ surface area each were investigated. With the exception of one echiurid worm the tube-building xenophyophore Occultammina profunda was the only macrofaunal species observed. Fragments of live $O$. profunda occurred at a density of 3600 ± 3100 fragments per square meter, with the high uncertainty reflecting significant horizontal decimeter-scale patchiness in their distribution. It was estimated that individuals were at least ~ 2.5 cm in size.

It is very interesting to note that the vertical distribution of fragments of live $O$. profunda resembled the vertical distribution of $^{210}$Pb$_{ss}$ (in the unit Bq g$^{-1}$) (compare Figure 3 of Tendal et al. (1982) and Figure 7 of Yamada et al. (1983), and see Figure 1 of Swinbanks and Shirayama (1986)): in both cases a pronounced subsurface maximum occurs at 2-3 cm sediment depth and almost all $O$. profunda fragments and $^{210}$Pb$_{ss}$ were found within the topmost ~ 6-7 cm of the sediment (Fig. S1b). The two subcores investigated by Swinbanks and Shirayama (1986) yielded similar results (Fig. S1b): weaker but detectable subsurface peaks in $^{210}$Pb$_{ss}$ activity occurred at 1-2 cm sediment depth, the depth at which the $O$. profunda stercomare numbers also peaked (see Figure 3a,b of Swinbanks and
Shirayama (1986)). These distributional patterns strongly suggest that at the 8260 m site the $^{210}$Pb$_{xs}$ originated from pelagic (rather than turbiditic) sedimentation and has been transported into the surface sediments by the activity of the infaunal xenophyophore *O. profunda* (Swinbanks, 1982; Swinbanks and Shirayama, 1986). Sedimentary inventories of $^{210}$Pb$_{xs}$ in the subcores of Yamada et al. (1983) and Swinbanks and Shirayama (1986) were reported as 10.0 and 12.8 kBq m$^{-2}$, respectively.

Two further $^{210}$Pb$_{xs}$ profiles were obtained by Yamada et al. (1983), one from “reddish brown nannofossil silty clay” sediments at 4310 m water depth on the trench slope (Station 5) to the south of the deep station, and another one from “nanno-foram sandy mud” at 2970 m water depth on the upper western slope of the trench (Station 4). The data from the southern slope station suggest maximum $^{210}$Pb$_{xs}$ activities occurred near the sediment/water interface and there was no evidence for subsurface maxima (Fig. S1b). At the western upper slope station $^{210}$Pb$_{xs}$ activities were generally very low (Fig. S1b). In both cases $^{210}$Pb$_{xs}$ was confined to the topmost ~7 cm of the sediment column. The $^{210}$Pb$_{xs}$ inventory at the slope Station 5 was reported to be 6.3 kBq m$^{-2}$ (Yamada et al., 1983). For the upper western slope station, no inventory was given.

### 3.2 Currents

The only deep current-meter record from this part of the Izu-Ogasawara Trench seems to be an unpublished one mentioned by Owens and Warren (2001a,b). This record was obtained by M. Fukusawa in 1987 on the western mid slope (28°52’N, 142°40’E) to the north of the study sites of Yamada et al. (1983) and at a water depth of 4150 m (see deployment location indicated by a white diamond in Figure 7 of the main text). The record is 300 days long. We were unable to get access to the original dataset, but Owens and Warren (2001a,b) report the following statistics for the overall data set: mean current speed: 3.92 cm s$^{-1}$; mean current direction: 152° (i.e., approximately to the south-southeast); major half-axis of the standard error ellipse: 1.79 cm s$^{-1}$; minor half-axis of the standard error ellipse: 0.36 cm s$^{-1}$; standard error of the current direction: 153°. These statistics would suggest that the current speeds are not particularly high but that the directional variability is very intense. This significant directional variability may be related to the intense internal tides that are generated along
parts of the Izu-Ogasawara Arc to the west of the trench (Figure 7b in the main text) and propagate across the trench to the east (Figure 8a in the main text).

3.3 Radionuclides in the water column

Approximately 4.5 years after Yamada et al. (1983) collected their sediment samples in the Izu-Ogasawara trench, Nozaki et al. (1998) retrieved water samples throughout the whole water column of the Izu-Ogasawara trench at a site (29°5.4’N, 142°50.8’E: white triangle in Figure 7 of the main text) ~ 70 km northwest of the trench-axis sampling site of Yamada et al. (1983). The water depth at the seafloor of the site of Nozaki et al. (1998) was 9750 m and the site was located in the trench axis. The surface ocean in this region is oligotrophic. Numerous radionuclides were measured in unfiltered water samples, with the ones relevant to this study being particle-reactive $^{210}$Pb, $^{228}$Th, $^{230}$Th, $^{232}$Th and $^{231}$Pa, non-particle-reactive $^{227}$Ac, and to some degree also particle-reactive $^{239,240}$Pu.

It is important to note that inside the trench waters both $^{228}$Th and $^{230}$Th activities scatter but do not show an obvious trend with depth; this contrasts with their distributions within the water column above the trench that are in good agreement with vertical distributions in other bathyal and abyssal regions of the ocean ($^{228}$Th: higher activities towards the surface and seafloor, governed by the distribution of the parent nuclide $^{228}$Ra; $^{230}$Th: near-monotonous increase from the surface towards the seafloor, governed by continuous $^{230}$Th production from the parent nuclide $^{234}$U throughout the water column and reversible scavenging of $^{230}$Th by settling particulate matter). This suggests particulate-matter and associated particle-reactive radionuclide dynamics might differ markedly between bathyal and abyssal water columns on the one hand and hadal-trench water columns on the other hand, at least in parts of the Izu-Ogasawara Trench.

In the water column above the trench the activities of particle-reactive $^{231}$Pa and its non-particle-reactive daughter $^{227}$Ac also increase from the surface ocean towards abyssal depths. The downward increase of $^{227}$Ac activities is stronger, leading to a significant excess of $^{227}$Ac over $^{21}$Pa in the deeper abyssal water column. The excess is believed to be due to release of $^{227}$Ac from sediments. As for $^{228}$Th and $^{230}$Th there is no clear overall trend with depth for $^{231}$Pa and $^{227}$Ac within the trench water.
column. Activities of $^{228}$Th, $^{230}$Th, $^{231}$Pa and $^{227}$Ac within the trench water column seem to be similar to their respective activities in abyssal waters just above the trench. As shown in Figure 2b of the main text, this also holds for $^{210}$Pb.

Nozaki et al. (1998) conclude that the “uniformity of each nuclide in the trench water is presumably due to rapid vertical mixing of water within the trench” and that the trench water “communicates freely by [diapycnal] mixing with the bottom water overlying the abyssal plain of the western North Pacific”. This would mean that the near-complete vertical mixing over a vertical space scale of several kilometers would have to occur on a time scale of only a few years (half life of $^{228}$Th, the most short-lived radionuclide measured in the study of Nozaki et al. (1998): 1.913 years) or even faster. Even though the vertical density stratification within hadal trenches tends to be very weak (e.g., Taira et al., 2005; Taira, 2006), such fast mixing over such long vertical distances would require a very effective mixing mechanism, occurring over much of the trench water column. As outlined in the main text and as mentioned in Section 3.2 above, internal tides that are generated along parts of the Izu-Ogasawara Arc to the west of the trench and propagate across the trench to the east might be a main driver of this mixing.
4. Japan / Izu-Ogasawara Triple Junction

4.1 Sediments

The sediment-sampling location is shown in Figure S6, indicated by ‘L’. The composite $^{210}\text{Pb}_{xs}$ profile determined at SAMS and the $^{210}\text{Pb}_{xs}$ profile determined at JAMSTEC are very similar (Fig. S1c). If the $^{210}\text{Pb}_{xs}$ concentrations are expressed in Bq g$^{-1}$ a monotonous decrease of activities is found from the sediment / water interface down to ~ 6-7 cm sediment depth, with some evidence for very small amounts of $^{210}\text{Pb}_{xs}$ down to ~ 10-11 cm. The vast majority of $^{210}\text{Pb}_{xs}$ is located within the topmost ~ 6 cm of the sediment column. This is similar to the Mariana Trench, but the transition between sediment layers with significant and negligible $^{210}\text{Pb}_{xs}$ concentrations is less abrupt in the Japan/Izu-Ogasawara Triple Junction sediments. Maximum concentrations in the Mariana- and Japan/Izu-Ogasawara Triple Junction axis sediments are very similar (~ 5-6 Bq g$^{-1}$). If $^{210}\text{Pb}_{xs}$ concentrations are expressed in Bq g$^{-1}$ there are no subsurface maxima in the Japan/Izu-Ogasawara Triple Junction sediments (Fig. S1c). This is in contrast to the Mariana-Trench sediments. If $^{210}\text{Pb}_{xs}$ concentrations in the Japan/Izu-Ogasawara Triple Junction sediments are expressed in Bq cm$^{-3}$ maximum concentrations are found around ~ 1.5 cm sediment depth and there is no surface maximum (not shown). This is also in contrast to the Mariana-Trench sediments. The $^{210}\text{Pb}_{xs}$ inventories of the Japan/Izu-Ogasawara Triple Junction sediments as determined by SAMS and JAMSTEC are 4.05 ± 0.43 Bq cm$^{-2}$ (average ± 1SD) and 4.28 Bq cm$^{-2}$, respectively.

The sediment surfaces at the sampling sites were fairly smooth but not nearly as smooth as in the Mariana Trench and structured by numerous lebensspuren. A large holothurian was observed on the sediment surface and amphipods were swimming near the seafloor. Macrosopic particles (amongst them also large filamentous ones) were drifting in the near-seafloor waters. In contrast to the Mariana and southern Izu-Ogasawara Trench the overlying surface ocean is characterised by moderately high primary productivity. This site is also close to the Japanese mainland (Fig. S6) whereas there are no major terrestrial land masses near the study sites in the Mariana and southern Izu-Ogasawara Trenches.
Figure S6. Bathymetric map (Mercator projection) of the hadal trench at the Japan/Izu-Ogasawara Triple Junction. Grid spacing: 500 m; contour interval: 200 m. White cross: sediment-sampling site of this study; red crosses: deployment sites of the current meters of Fujio et al. (2000), including current meters at 30 m above the seafloor.
4.2 Currents

Between November 1987 and November 1996 a number of current meters were deployed on the western slope, the eastern rim and in the trench axis of the Japan/Izu-Ogasawara Triple Junction (Fujio et al., 2000). The deployment sites are shown in Figure S6. These deployments included 11 current meters at 30 mab. They are the ones we refer to in this study. The minimum deployment duration was 265 days and the maximum 535 days. Current direction and speed were recorded every 0.5 or 1.0 hours. Fujio et al. (2000) focussed on lower-frequency flow components to deduce regional mean flow patterns and therefore removed higher-frequency components (tidal, near-inertial) by applying a 24-hours (half width) Gaussian filter. For sediment dynamics, all flow components are of potential importance and we therefore revisited the unfiltered near-seafloor datasets.

At around ~ 4000-6500 m depth there tends to be a moderately strong net southward flow above the western (landward) side of the trench and a strong net northward flow on the eastern (oceanward) side of the trench (see Figure 7 of Fujio et al., 2000; and Figure S7). Interestingly, this also holds for the near-seafloor flow in the trench axis (Fig. S7).

The records from the western (landward) slope generally show moderately high current speeds (Table 2 in the main text and Figure S8a) and increased higher-frequency variability of current directions. Interestingly, the variability of current directions is noticeably higher at the shallowest western slope site (4270 m water depth at the seafloor) compared to the deeper western slope sites (5600-6330  water depth at the seafloor). Records from the eastern (oceanward) rim of the trench show high current speeds (Table 2 in the main text and Figure S8a) but decreased higher-frequency variability of current directions. Examples of typical temporal flow patterns in the form of progressive vector diagrams for the western mid slope and eastern trench rim are given in Figures S9 and S10, respectively.

The near-seafloor records from the trench axis are very interesting as the two western ones differ significantly from the eastern one. Current speeds on the western side of the trench axis were extremely low and most of the time (82-83%) below the nominal detection limit of 1.5 cm s⁻¹ (Table 2 in the main text and Figure S8a). By contrast, current speeds on the eastern side of the trench axis were
moderately high (Table 2 in the main text and Figure S8a) and displayed an increased higher-frequency variability of current directions. Examples of typical temporal flow patterns in the form of progressive vector diagrams for the western and eastern trench axis are given in Figure S11. This difference is particularly interesting as the seafloor of the trench axis is plain around the deployment sites and the western and eastern deployment sites are only ~ 15 km apart. The difference can certainly be viewed as a spatial (rather than a temporal) one because one of the western current meters (I5) was deployed for the same time interval as the eastern current meter (J5).

As outlined in the main text, it is also very interesting to see that the frequency distributions of current-speed records from the western (landward) mid slope resembled the one for the flow above the seafloor of the eastern trench axis (Figure S8a). It could therefore be speculated that the western (landward) mid-slope stations and the eastern trench-axis station constitute two seafloor reflection areas of the same internal-tide beam that emanates from the upper western (landward) slopes.

Our sediment sampling was conducted only ~ 2.5 km to the west-northwest of the eastern trench-axis current-meter deployment site (Figure S6). The more dynamic flow regime of the eastern trench axis is therefore more likely to be of relevance to the sampled sediments than the much less dynamic flow regime of the western trench axis. The aforementioned observation of horizontally drifting macroscopic particles in the near-seafloor waters of the sediment-sampling site is consistent with this notion.
Figure S7. Progressive vector diagrams for near-seafloor current-meter records in the hadal trench of the Japan/Izu-Ogasawara Triple Junction. (a) All stations; (b) same as (a) but without the eastern rim stations. Locations of current-meter deployments are shown in Figure S6. For the western side of the trench (mid slope and western trench axis), the net flow is towards southerly or southeasterly directions; by contrast, for the eastern side (rim and eastern trench axis) the flow is always towards northerly or northwesterly directions.
Figure S8. Frequency distributions of near-seafloor current speeds (a) at the Japan/Izu-Ogasawara Triple Junction and (b) at the northern and northernmost Japan Trench. Respective locations of current-meter deployments are shown in Figures S6 and S12. The grey area indicates the approximate range of near-seafloor current speeds above which freshly introduced phytodetrital material from the primary flux tends to be eroded and resuspended (Lampitt, 1985; Beaulieu, 2002). At the northern and northernmost Japan Trench, frequency distributions on the western (landward) mid slope and on the eastern (oceanward) rim are similar. By contrast, at the Japan/Izu-Ogasawara Triple Junction, frequency distributions on the western (landward) mid slope and on the eastern (oceanward) rim differ markedly, with the frequency distribution on the eastern rim being flatter and including a higher proportion of very high current speeds. It is also important to note that on the western side of the trench axis the near-seafloor waters are nearly stagnant whereas on the eastern side of the trench axis they are significant, with their frequency distribution resembling the one of the western (landward) mid slope stations.
Figure S9. Examples of typical flow patterns near the seafloor (30 mab) on the western (landward) mid slope of the trench at the Japan/Izu-Ogasawara Triple Junction. The patterns are depicted in the form of progressive vector diagrammes which implicitly assume that for every point in time the flow is horizontally isotropic. Arrows indicate the direction of progressing time. Water depths at the seafloor are given for each deployment site. Locations of current-meter deployments are shown in Figure S6. The space scale is the same for all plots. The plotted time intervals differ between plots and are as follows: G1: 01/03/1992 15:00 – 16/03/1992 15:00; H2: 24/10/1991 01:30 – 05/11/1991 11:00; K2: 17/07/1992 00:00 – 31/07/1992 10:30; M2: 19/03/1995 15:00 – 16/04/1995 12:00; N2: 11/10/1995 06:00 – 31/10/1995 09:00. The measurement intervals are as follows: G1, H2, K2: 0.5 hr; M2, N2: 1.0 hr.
Figure S10. Examples of typical flow patterns near the seafloor (30 mab) on the eastern (oceanward) rim of the trench at the Japan/Izu-Ogasawara Triple Junction. The patterns are depicted in the form of progressive vector diagrammes which implicitly assume that for every point in time the flow is horizontally isotropic. Arrows indicate the direction of progressing time. Water depths at the seafloor are given for each deployment site. Locations of current-meter deployments are shown in Figure S6. The space scale is the same for both plots. The plotted time intervals differ between plots and are as follows: B2: 04/03/1988 03:30 – 18/03/1988 08:00; O3: 13/07/1995 01:00 – 02/08/1995 11:00. The measurement intervals are as follows: B2: 0.5 hr; O3: 1.0 hr.
Figure S11. Examples of typical flow patterns near the seafloor (30 mab) in the western (landward: C4, I5) and eastern (oceanward: J3) axis of the trench at the Japan/Izu-Ogasawara Triple Junction. The patterns are depicted in the form of progressive vector diagrams which implicitly assume that for every point in time the flow is horizontally isotropic. Arrows indicate the direction of progressing time. Water depths at the seafloor are given for each deployment site. Locations of current-meter deployments are shown in Figure S6. The space scale is the same for all plots. The plotted time intervals differ between plots and are as follows: C4: 18/09/1989 00:00 – 26/10/1989 05:30; I5: 20/12/1991 10:30 – 22/02/1992 10:00; 21/12/1991 11:00 – 26/01/1992 04:30. The measurement intervals are 0.5 hr.
5. Northern Japan Trench

5.1 Sediments

This region is near the Japanese mainland and characterised by a highly productive surface ocean. The sedimentary $^{210}\text{Pb}$ data were obtained from samples collected by the free-falling camera system also used by Glud et al. (2013) in the Mariana Trench and to retrieve sediment cores from the axis of the hadal trench at the Japan/Izu-Ogasawara Triple Junction. Two stations were sampled, one in the trench axis (DC1: 7553 m, 38°5.160’N, 143°59.455’E) and another one a few miles east (oceanward) of the trench axis at a slightly shallower depth (DC2: 7261 m, 38°5.119’N, 144°2.617’E). The sediment sampling sites are shown in Figures S12.

The complete $^{210}\text{Pb}_{xs}$ profiles from the northern Japan Trench were shown by Oguri et al. (2013). It is important to note that these cores were collected approximately 4 months after the Tohoku-Oki earthquake in 2011. There is strong evidence suggesting that the trench-axis sediments at station DC1 were influenced by recently deposited turbidite sediments: down to 26 cm sediment depth $^{210}\text{Pb}_{xs}$ was high and increased slightly from ~ 1 Bq g$^{-1}$ at the sediment/water interface to ~ 1.6 Bq g$^{-1}$ at 25 cm sediment depth. Several layers within the topmost 26 cm of the sediment also contained clearly detectable $^{137}\text{Cs}$ activities and almost the whole topmost 26 cm were characterised by low sediment densities in an X-ray computer-tomographic (CT) scan. Below 26 cm sediment depth, however, the $^{210}\text{Pb}_{xs}$ profile showed some resemblance to an undisturbed and ‘normal’ profile more typical of deep-sea conditions: between 26 cm and 29 cm sediment depth $^{210}\text{Pb}_{xs}$ activities were ~ 2.3 Bq g$^{-1}$, resembling a strongly bioturbated surface sediment; between 29 cm and 34 cm there was an abrupt drop in $^{210}\text{Pb}_{xs}$ activity and below 34 cm there was a more gradual decline down to 48 cm, with the deepest measured activity between 48 and 50 cm being near the detection limit. $^{137}\text{Cs}$ was detected between 26 and 32 cm and the X-ray CT scan showed generally higher sediment density at sediment depths > 26 cm. Oguri et al. (2013) conclude that, collectively, all this information suggests that a recent turbidite of 26 cm thickness is overlying an original, largely hemipelagic and bioturbated sediment.
By contrast, sediments from the somewhat shallower site seemed to be only minimally or even negligibly affected by the most likely Tohoku-Oki earthquake-related turbidity current(s): the topmost 6 cm of the sediment column contained clearly detectable $^{210}\text{Pb}_{\text{xs}}$, and $^{210}\text{Pb}_{\text{xs}}$ between 7 cm and 9 cm was near the detection limit; between 2 cm and 4 cm there was a distinct subsurface maximum, resembling the one observed by Yamada et al. (1983) and Swinbanks and Shirayama (1986) in their $^{210}\text{Pb}$ profiles from the trench site in the Izu-Ogasawara Trench; the topmost 5 cm of the sediment column also contained detectable $^{137}\text{Cs}$ and the topmost 4 cm showed low sediment density on the X-ray CT scan. These characteristics suggest the surface sediments down to a sediment depth of ~ 9 cm at the slightly shallower trench site are virtually ‘normal’ bioturbated hemipelagic deep-sea sediments. It may well be that the $^{210}\text{Pb}_{\text{xs}}$ subsurface maximum at the somewhat shallower station DC2 is also related to infaunal xenophyophores as they were found by Swinbanks (1982) on the upper oceanward trench slope (water depth of ~ 6440 m) approximately 30 nautical miles to the north of the study area of Oguri et al. (2013) (Figure S12: station indicated by ‘S’).

It was therefore decided to view the $^{210}\text{Pb}_{\text{xs}}$ profile from the somewhat shallower and oceanward DC2 site as undisturbed by the Tohoku-Oki turbidite. Using DBDs determined for these sediments, a $^{210}\text{Pb}_{\text{xs}}$ inventory of 38.9 kBq m$^{-2}$ was calculated for station DC2 (Table 1 in main text). If only $^{210}\text{Pb}_{\text{xs}}$ data and accompanying DBDs from non-turbiditic sediment depths > 26 cm are considered for the trench-axis site DC1, a $^{210}\text{Pb}_{\text{xs}}$ inventory of 29.3 kBq m$^{-2}$ is calculated. However, as the turbidity current triggered by the Tohoku-Oki earthquake / tsunami is very likely to have disturbed the surface of the original and largely hemiplegic sediment, this value for the inventory should be viewed with caution and as a probable underestimate (see arrows in Figures 2a, 3, 4 and 8b,c in main text). The $^{210}\text{Pb}_{\text{xs}}$ profiles used to calculate these inventories are shown in Figure S1d.
Figure S12. Bathymetric overview map (Mercator projection) of the northern and northernmost Japan Trench. Grid spacing: 500 m; contour interval: 200 m. Yellow circles with red rim: sediment-sampling sites of Oguri et al. (2013); red circles: sediment-sampling sites of Mohamed et al. (1996); white circles: deployment sites of the current meters of Ando et al. (2013).
5.2 Currents

For this part of the Japan Trench, only one near-seafloor current-meter record is available. This record (N1) is from the eastern (oceanward) rim at 38°N, 144°31’E and a water depth of 5870 m (water depth at seafloor: 5920 m) (Ando et al., 2013; Figures S12 and S13). Current-speed and -direction measurements were conducted hourly over 507 days between May 2007 and October 2008. Ando et al. (2013) removed higher-frequency (tidal, near-inertial) oscillations with a 24-hours Gaussian filter to be able to investigate the regional net flow patterns. The results of their work are consistent with the results of Fujio et al. (2000) in that they find a significant net northward flow on the eastern (oceanward) rim of the Japan Trench (Figure S14).

As for the Japan/Izu-Ogasawara Triple Junction we revisited this dataset in its unfiltered form. Current speeds were moderately high (Table 2 in the main text) and certainly high enough to have a transient influence on non-deposition, erosion or resuspension of phytodetrital material freshly deposited from the surface ocean. The frequency distribution of current speeds resembled the one of the near-seafloor currents on the western mid slope in the Japan/Izu-Ogasawara Triple Junction (Figure S8a and b). The flow was comparatively steady, but every few months an interval of somewhat lower-frequency variability of current directions occurred, including several complete 360° rotations. An example of such an interval is shown in Figure S14.
Figure S13. Progressive vector diagrammes for near-seafloor current-meter records at the northern (N1: oceanward rim) and northernmost (W1: landward mid slope; W2: oceanward rim) Japan Trench. Locations of current-meter deployments are shown in Figure S12. For comparison, the progressive vector diagrammes for the current-meter records of the Japan/Izu-Ogasawara Triple Junction are also shown (all in black; see Figure S7). As for the Japan/Izu-Ogasawara Triple Junction, there is southwestward flow on the western (landward) side and flow towards northerly directions on the eastern (oceanward) side of the trench. However, for the northern Japan Trench the northward flow on the oceanward rim is not as strong as for the Japan/Izu-Ogasawara Triple Junction.
Figure S14. Examples of typical flow patterns near the seafloor on the western (landward) mid slope (W1: 32 mab) and eastern (oceanward) rim (N1: 50 mab; W2: 118 mab) of the northern and northernmost Japan Trench. The patterns are depicted in the form of progressive vector diagrams which implicitly assume that for every point in time the flow is horizontally isotropic. Arrows indicate the direction of progressing time. Water depths at the seafloor are given for each deployment site. Locations of current-meter deployments are shown in Figure S12. The space scale is the same for all plots. The plotted time intervals differ between plots and are as follows: N1: 14/05/2008 04:00 – 12/09/2008 17:00; W1: 14/07/2008 14:00 – 08/09/2008 06:00; W2: 25/04/2008 21:00 – 06/06/2008 16:00. The measurement intervals are 1.0 hr.
6 Northernmost Japan Trench

6.1 Sediments

Mohamed et al. (1996) analysed sediments from cores that were collected in 1991 from six stations across the northernmost (~ 39°N) Japan Trench: station 12 (most landward, westernmost: 1860 m), station 13 (3700 m), 14 (5600 m), 16 (trench axis: 7540 m), 17 (6140 m) and 18 (most oceanward, easternmost: 5560 m) (Fig. S12). This part of the Japan Trench is overlain by productive surface waters, with significant fluxes of particulate organic carbon reaching the seafloor (Lutz et al., 2007). Mohamed et al. (1996) do not give information on how the cores were collected. Total $^{210}$Pb was measured and supported $^{210}$Pb was assumed to be negligible throughout the cores. Based on this assumption sediment accumulation rates ($S$) were calculated, using only parts of the total-$^{210}$Pb profiles that were assumed not to be influenced by any bioturbation. These estimated sediment accumulation rates were then used to calculate inventories of $^{210}$Pb$_{xs}$, $I$, according to $I = A_0 \rho S / \lambda$, where $A_0$ is the $^{210}$Pb$_{xs}$ activity at the sediment / water interface, $\rho$ is the dry bulk density assumed to be constant at 0.75 g cm$^{-3}$, and $\lambda$ is the radioactive decay constant of $^{210}$Pb. This approach led to extremely high estimated $^{210}$Pb$_{xs}$ inventories.

We think that, in this particular case, two aspects of the chosen approach to calculate the inventories are problematic: (1) The estimated $S$ values were based on total-$^{210}$Pb activities from deeper sediment layers in which very little or no $^{210}$Pb$_{xs}$ must have occurred. Interpreting total-$^{210}$Pb activities in terms of $^{210}$Pb$_{xs}$ activities to estimate $S$ in these deeper sediment layers must therefore be associated with large (and in this case unquantified) uncertainties and a high likeliness of significantly overestimating true $S$ values. (2) The assumption that $\rho$ is constant at 0.75 g cm$^{-3}$ is introducing a large error in the inventory estimates. First, $\rho$ profiles in deep-sea sediments tend to cover a broad range of values, starting with low values near the sediment / water interface and increasing values towards deeper sediment depths. Second, even for sediment depths of O(10 cm), a value of $\rho = 0.75$ g cm$^{-3}$ may well be an overestimate.
We therefore decided to apply a different approach to the total-\(^{210}\)Pb data of Mohamed et al. (1996) to try and estimate \(^{210}\)Pb\(_{xs}\) inventories for their six stations across the northernmost Japan Trench. It was assumed that the total-\(^{210}\)Pb activities in deeper sediments reflect supported \(^{210}\)Pb and for each core an average of supported \(^{210}\)Pb was calculated which was subtracted from all the other total-\(^{210}\)Pb values of the respective core. For sediment layers where no total-\(^{210}\)Pb was measured by Mohamed et al. (1996) and for which \(^{210}\)Pb\(_{xs}\) would be expected, \(^{210}\)Pb\(_{xs}\) was estimated through linear interpolation between the two neighbouring data points. These steps give an estimate for the vertical distribution of \(^{210}\)Pb\(_{xs}\) in the sediment in the unit Bq g\(^{-1}\) of dry sediment. To calculate the inventory, Bq g\(^{-1}\) of dry sediment need to be converted into Bq cm\(^{-3}\) of wet sediment. For this conversion a profile of dry bulk density (DBD, g dry sediment per cm\(^{3}\) of wet sediment) was assumed. Here we used an average DBD profile obtained from sediments from the Japan/Izu-Ogasawara Triple Junction site. This was applied to all six \(^{210}\)Pb profiles of Mohamed et al. (1996). This approach is likely to introduce a significant and unquantified uncertainty in the calculated \(^{210}\)Pb\(_{xs}\) inventories, especially for non-trench-axis sediments. However, the depth dependence of the DBD profile and its range of values in combination with the consideration of supported \(^{210}\)Pb levels should still lead to more realistic inventory estimates than Mohamed et al.’s use of a single, high DBD value for all sediment layers in all sediment cores and negligence of supported \(^{210}\)Pb. The recalculated \(^{210}\)Pb\(_{xs}\) profiles are shown in Figure S1e and the recalculated inventories are 19.1, 15.1, 16.5, 66.9, 16.3 and 21.0 kBq m\(^{-2}\) for stations 12, 13, 14, 16, 17 and 18, respectively (Table 1 and 2 of the main text).

6.2 Currents

There are no current-meter data from 39°N. However, from 40°N near-seafloor current-meter data are available for both the western (landward) slope (station W1) and the eastern (oceanward) trench rim (station W2) (Ando et al., 2013) (Figure S12), and in combination with the oceanward rim results from 38°N (see Section 5.2) it is possible to visualise an approximate ‘interpolated’ picture for 39°N where the sediment samples of Mohamed et al. (1996) were collected. Mooring W1 was deployed at 40°N, 144°6’E at a water depth of 5040 m (32 mab); the deployment took place between May 2007
and October 2008 and lasted for 520 days. Mooring W2 was deployed at 40°N, 144°40’E at a water depth of 6120 m (118 mab); the deployment also took place between May 2007 and October 2008 and lasted for 517 days. Current speeds and directions were recorded hourly and Ando et al. (2013) removed higher-frequency (tidal, near-inertial) oscillations with a 24-hours Gaussian filter to be able to investigate the regional net flow patterns. And again, the results of their work are consistent with the results for the N1 site and the results of Fujio et al. (2000) in that they find a significant net northward flow on the eastern (oceanward) rim of the Japan Trench and a (somewhat weaker) net southward flow on the western slope (see Figure 12 of Ando et al., 2013; and Figure S13).

As for the Japan/Izu-Ogasawara Triple Junction and the N1 site, we revisited the W1 and W2 data sets in their unfiltered form. Similarly to the oceanward rim site N1, current speeds on both sides of the trench at 40°N are moderately high (Table 2 in the main text) and comprise time intervals during which near-seafloor flow would be sufficiently strong to have an influence on non-deposition, erosion or resuspension of phytodetrital material freshly deposited from the surface ocean. The flow was comparatively steady but, as at the oceanward rim station N1 at 38°N, every few months an interval of somewhat lower-frequency variability of current directions occurred, including several complete 360° rotations (Fig. S14). Superimposed on the comparatively steady background flow are intervals of high-frequency (near-tidal) current direction changes that cover partial up to complete rotations and tend to be associated with low current speeds (Fig. S14). On the oceanward rim, directional variability was very low, with very few abrupt ~ 90° turns and very few and short 360° rotations (Fig. S14). It can be concluded that, in terms of near-seafloor fluid dynamics, the northern and northernmost Japan-Trench rim is less dynamic than the southern trench region of the Japan/Izu-Ogasawara Triple Junction and possibly also the oceanward rim of the Mariana Trench.
Online Supplement: References


