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Benthic carbon mineralization in hadal trenches: Assessment by in situ O₂ microprofile measurements

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A B S T R A C T

Hadal trenches are considered to act as depo-centers for organic material at the trench axis and host unique and elevated biomasses of living organisms as compared to adjacent abyssal plains. To explore the diagenetic activity in hadal trench environments we quantified in situ benthic O₂ consumption rates and sediment characteristics from the trench axis of two contrasting trench systems in the Pacific Ocean; the Izu-Bonin Trench undergoing mesotrophic waters and the Tonga Trench underlying oligotrophic waters. In situ oxygen consumption at the Izu-Bonin Trench axis site (9200 m; 746 ± 103 μmol m⁻² d⁻¹; n = 27) was 3-times higher than at the Tonga Trench axis site (10800 m; 225 ± 50 μmol m⁻² d⁻¹; n = 7) presumably reflecting the higher surface water productivity in the Northern Pacific. Comparing benthic O₂ consumption rates measured in the central hadal Tonga Trench to that of nearby (60 km distance) abyssal settings (6250 m; 94 ± 44 μmol m⁻² d⁻¹; n = 16) revealed a 2.5 higher activity at the trench bottom. Onboard investigations on recovered sediment furthermore revealed that the prokaryotic abundance and concentrations of phytopigments followed this overall trend (i.e minimum values at the abyssal site followed by higher values from the Tonga and Izu-Bonin Trenches axis, respectively). Excess ²³⁴⁴Pb profiles suggested that mass-wasting events contributed to the deposition of material enhancing the concentration of organic matter in the central trench as compared to the abyssal settings. Our results complement recent findings from the Challenger deep in the Mariana Trench area, which also revealed elevated diageneric activity in the central trench underpinning the importance of hadal ecosystems for the deep sea carbon cycling.

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1. Introduction

Covering the depth range from 6500 to 11000 m, the 27 recognized hadal trenches represent some of the most remote and scarcely studied environments on Earth. Trenches are associated to oceanic faults formed during tectonic subductions and cover about 1–2% of the ocean bed, with the most prominent examples located in the West Pacific (Jamieson, 2015). Trench systems cover a large variety of surface production regimes, ranging from eutrophic (e.g. Atacama Trench) over mesotrophic (e.g. Japan and Izu-Bonin Trench) to oligotrophic areas (e.g. Mariana Trench and Tonga Trench). While temperature, salinity, O₂ availability and current regimes resemble conditions at the abyssal plain, hadal communities are exposed to extreme hydrostatic pressure and host many specialized piezophile organisms (Somero, 1992; Delong et al., 1997; Jamieson et al., 2010; Kato, 2011; Nunoura et al., 2015). Furthermore, the distinct bathymetry and isolation of the respective hadal basins facilitate endemism and the development of unique trench-associated benthic communities that tends to be of low diversity (Dansavaro et al., 2002; Todo et al., 2005; Blankenship et al., 2006; Kitahashi et al., 2013; Fujii et al., 2013; Leduc et al., 2016). However, in contrast to the general food scarcity of the deep sea, hadal trenches were early on recognized as potential depo-centers for organic material at the trench bottom accommodating relatively high abundance and biomass of macro- and meiofauna
Even though the mechanisms remain unclear, lateral transport of material from the surroundings and downslope focusing of labile organic material apparently sustain relatively high biological activity at the bottom of many trenches (Gooday et al., 2010; Danavaro et al., 2003; Turnewitsch et al., 2014; Ichino et al., 2015). In addition mass-wasting events often triggered by earthquakes provide large amounts of sedimentary material enriched by carrion-falls to the trench bottom (Nozaki and Ohta, 1993; Itou et al., 2000; Oguri et al., 2013). Trenches thus represent extreme environments and their axis may thereby act as quantitatively important hot spots for deposition and microbial mineralization of organic material in the deep sea.

Fig. 1. (A) Deployment sites of the two trench systems investigated; Izu-Bonin Trench in the Northern Pacific and Tonga Trench in the Southern Pacific. Close up bathymetry maps of the (B) northern part of the Izu-Bonin Trench and (C) Tonga Trench and abyssal plain sampling locations (Bathymetry maps provided by JAMSTEC).
Here we present in situ benthic O$_2$ consumption rates as measure of benthic carbon mineralization in trench axis sediments in two contrasting Pacific trench systems underlying water columns of different pelagic productivity: the Tonga Trench and the Izu-Bonin Trench – and for reference abyssal measurements conducted in the vicinity of the Tonga Trench. The in situ work is complemented by measurements of organic carbon content, excess $^{210}$Pb, microbial abundance and proxies for the liability of the organic material in recovered sediment cores. Data are used to discuss and elucidate the potential of stimulated deposition and diagenetic activity in hadal settings.

2. Material and methods

2.1. Study sites

The northern part of the Izu-Bonin Trench was visited in June 2012 with the RV Yokosuka (YK 12-09). The Izu-Bonin Trench comprises one of the largest hadal benthic habitats as the trench stretches for a length of 1100 km with a width between 5 and 16 km and has a maximum water depth of 9700 m (Jamieson, 2015; Renard et al., 1987). The targeted station of the trench axis was located in the northern section close to the triple junction between Japan Trench, Izu-Bonin Trench and Sagami Trough at a water depth of 9200 m (Ogawa et al., 2008; Fig. 1, Table 1 and Supplementary Table S1).

The ~10800 m deep, central Tonga Trench and a close-by abyssal reference site at ~6250 m were visited during October 2013 also using the RV Yokosuka (YK 13-10), (Fig. 1, Table 1 and Supplementary Table S1). The Tonga Trench axis extends from approx. 15 to 25 $^\circ$S stretching for a length of 1250 km (Jamieson, 2015). It host the second deepest spot on earth, the Horizon Deep (2013 with the RV Yokusuka (YK 12-09). The Izu-Bonin Trench site exhibited a relatively high NPP of $\text{g C m}^{-2}$ yr$^{-1}$ (Fisher, 1954; Belyaev, 1989).

The annual average Net Primary Production (NPP) in the two targeted Pacific trenches was assessed from 10 years (1998–2007) of remote sensing data (SeaWiFS; (http://dx.doi.org/10.5067/ORB VIEW-2/SEAWIFS_OC.2014.0) as derived by the Vertical Generalized Production Model of Behrenfeld and Falkowski (1997). The Izu-Bonin Trench site exhibited a relatively high NPP of $\text{g C m}^{-2}$ yr$^{-1}$ (Fisher, 1954; Belyaev, 1989).

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### Table 1

Station characteristics.

<table>
<thead>
<tr>
<th></th>
<th>Izu-Bonin Trench</th>
<th>Tonga Trench</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hadal Site</td>
<td>Abyssal Site</td>
</tr>
<tr>
<td><strong>Water depth (m)</strong></td>
<td>9200</td>
<td>~6250</td>
</tr>
<tr>
<td><strong>Bottom water</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>~ Temperature ($^\circ$C)</td>
<td>2.2</td>
<td>2.0</td>
</tr>
<tr>
<td>~ Salinity</td>
<td>34.7</td>
<td>34.7</td>
</tr>
<tr>
<td>~ Oxygen ($\mu$M)</td>
<td>164 ± 4</td>
<td>223 ± 3</td>
</tr>
<tr>
<td><strong>Sediment (0–5 cm)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>~ Porosity</td>
<td>0.87 ± 0.03</td>
<td>0.85 ± 0.04</td>
</tr>
<tr>
<td>~ Dry-sediment dens. (g cm$^{-3}$)</td>
<td>1.76 ± 0.23</td>
<td>1.32 ± 0.04</td>
</tr>
<tr>
<td><strong>Net Primary Production (NPP)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>mol $\text{C m}^{-2}$ yr$^{-1}$</td>
<td>16.7 (200)</td>
<td>8.8 (106)</td>
</tr>
</tbody>
</table>
2.3. Sediment sampling

For the recovery of intact sediment cores and to obtain video recordings of the seabed an autonomous sediment sampler lander system (Murashima et al., 2009) was deployed 3-times in the Izu-Bonin Trench and 2-times in the Tonga Trench (Supplementary Table S1). The lander system consisted of a floatation system similar to the one used by the profiling lander, a ballast release system and an instrumental payload. A HDTV camera provided continuous 3–8 h long video recordings of the seabed during each of the respective deployments while a conductivity, temperature and depth (CTD) instrument (SBE49, Sea-Bird Electronics, US) recorded basic physico-chemical conditions during the entire deployment. In addition one core liner (id 7.2 cm) was attached to each of the three legs of the tripod. The liners were inserted in the seabed just after landing and in concert with the ballast release the top and bottom of the liners were closed by a spring-loaded system (Murashima et al., 2009). Thus three intact sediment cores were recovered per deployment and divided for further onboard sampling and analyses. Here we report data as obtained from 4–5 sediment cores from each of the two trenches. At the abyssal reference site we obtained 4 push cores (id 4.2 cm) as collected during the dive #1370 by Shinkai6500. In all instances, the recovered sediment cores were sliced in 1 cm sections for the upper 10 cm and into 2 cm sections for the rest of the core length. The sediment was sub-sampled and preserved for subsequent analyses in our respective laboratories.

2.4. Quantification of phytopigment concentration

From each sediment section, samples for sediment-bound chlorophyll a (Chl a) and its degradation products, phaeopigments, were taken by small plastic liners (inner diameter 1.2 cm) and frozen at −18 °C until analysis. Here the sediment was ground and pigments were extracted in acetone (90%) for 24 h. Subsequently samples were centrifuged, and concentrations of Chl a and phaeopigments were determined in the supernatant using a Turner fluorometer (Shuman et al., 1975). The ratio of Chl a/(Chl a + phaeopigments) was used as an indicator for the freshness of the settling material (Pastor et al., 2011).

2.5. Quantification of prokaryotic abundance

For extraction of prokaryotes, 1 ml of homogenized sediment from selected depth intervals were transferred to 50 ml centrifuge tubes and fixed with 1 ml 1% glutaraldehyde. Then, 5 ml of 5 mM Na4P2O7 was added and the samples were sonicated for 20 s on ice (3 cycles at 20 kHz) (Danovaro and Middelboe, 2010). The samples were then further diluted with 40 ml Milli-Q water and sub-sampled. For extraction of prokaryotes, 1 mL of homogenized sediment was transferred to cryovials, snap frozen in liquid nitrogen and stored at −80 °C until analysis of prokaryote abundance. Here samples were 10-times diluted in TE buffer (10 mM Tris, 1 mM EDTA [pH 8.0]) and stained with SYBR green I (Molecular Probes, Invitrogen Inc., Life Technologies, NY). Cell abundance was quantified using flow cytometry (BD FACS Canto) equipped with an air-cooled argon laser (excitation wavelength, 488 nm) (Carreira et al., 2015).

2.6. Measurements of porosity, density and organic carbon content

For basic sediment characteristics 10–15 mL of sediment from the respective sections were stored frozen (−18 °C). In the home laboratory, the sediment was thawed and thoroughly homogenized. The sediment water content was determined as the relative weight loss after drying to constant weight at 105 °C and porosity was calculated accounting for the measured density. Homogenized samples were weighed into silver containers and pretreated with 6 M HCl to dissolve any carbonate. The organic carbon content was measured in CNS-analyzers (Izu-Bonin-Trench samples: Costech ECS4010; Tonga-Trench samples: Fisons NA 1500, Series 2) by flash combustion (Verado et al., 1990).

2.7. Measurements of 214pb + 137Cs and 210Pb

Methods for the determination of excess 210Pb (210Pbex) in sediments are described in Glud et al. (2013) and Turnewitsch et al. (2014). Sediment samples were first stored at +5 °C. For analyses, the samples then were dried at 80 °C for 48 h, milled and subsamples of 2 g were stored in hermetic sealed plastic tubes for 2 months. Total (i.e. sum of supported and excess) 210Pb, 214Pb and 137Cs concentrations were measured using a 12030 well-type germanium gamma ray detector (ORTEC, US) and an APV8002 multi-channel spectrum analyzer (Techno AP, Japan), with a background value of the detector of 0.0094 Bq g−1 for 210Pb. The results of the sediment cores occasionally expressed a higher but constant value of ~0.05 Bq g−1 in deeper sediment layers. We currently have no satisfactory explanation for these low apparent excess activities. However, as their influence on inventories and the interpretation of the main results is very small we thought it justified not to discuss them in this paper. The counting time for the measurements was 1–2 days. The respective peak areas of the raw data of 210Pb (T1/2 = 22.3 y; 465 keV) and 214Pb (351.9 keV) and 137Cs (T1/2 = 30 y; 661.6 keV) were calculated by Gaussian curve fitting using KaleidiaGraph 4.1. 210Pbex activities were obtained by subtracting 210Pb activities from the total 210Pb assuming secular equilibrium between 226Ra and the short-lived daughters, including 214Pb in the sediment. As reference material for 210Pb and 214Pb we applied DL-1a Uranium-Thorium ore (1.40 ± 0.02 Bq g−1) in 210Pb, Natural Resources, Canada) and for 137Cs, we applied IAEA 375 soil (5.280 ± 0.06 Bq g−1, determined on 31 Dec. 1991; IAEA).

3. Results

3.1. Video recordings

The sediment surface at the Izu-Bonin and Tonga Trench axis as well as the abyssal plain in the vicinity of the Tonga Trench appeared similar with little disturbance and conspicuous fauna at the sediment surface (not shown). However, lebensspuren were visible at the sediment surface (Supplementary Fig. S1), and at all sites scavenging amphipods (Hirondellea sp.) appeared abundant and several specimens were caught on lander-mounted traps. Amphipods appeared more abundant in the trench settings. The video recording showed that amphipods frequently emerged from and retreated to the sediment surface (Supplementary Fig. S1), and at all sites occasional expressed a high but constant value of ~0.05 Bq g−1 in deeper sediment layers. We currently have no satisfactory explanation for these low apparent excess activities. However, as their influence on inventories and the interpretation of the main results is very small we thought it justified not to discuss them in this paper. The counting time for the measurements was 1–2 days. The respective peak areas of the raw data of 210Pb (T1/2 = 22.3 y; 465 keV) and 214Pb (351.9 keV) and 137Cs (T1/2 = 30 y; 661.6 keV) were calculated by Gaussian curve fitting using KaleidiaGraph 4.1. 210Pbex activities were obtained by subtracting 210Pb activities from the total 210Pb assuming secular equilibrium between 226Ra and the short-lived daughters, including 214Pb in the sediment. As reference material for 210Pb and 214Pb we applied DL-1a Uranium-Thorium ore (1.40 ± 0.02 Bq g−1) in 210Pb, Natural Resources, Canada) and for 137Cs, we applied IAEA 375 soil (5.280 ± 0.06 Bq g−1, determined on 31 Dec. 1991; IAEA).

3.2. O2 microprofiles

In total we successfully obtained 50 O2 microprofiles and none of these reflected presence of infauna burrows or fauna induced irrigation. At all three locations the sediment surface was well oxygenated with an extensive O2 penetration depth (OPD) (Fig. 2). However, the abyssal site clearly exhibited the deepest OPD exceeding the maximum measuring depth of our microsensors (~13 cm). Applying a linear extrapolation of the concentration profiles at the abyssal Tonga Trench site provided a minimum OPD of ~50 cm. The OPDs at the two trench axis sites were
significantly shallower reflecting higher benthic O$_2$ consumption rates (Fig. 2). The sediment of the Tonga Trench bottom provided an intermediate OPD of 16.1 ± 1.0 cm (n=7), while the shallower and more eutrophic site in the Izu-Bonin Trench showed an OPD of 6.4 ± 0.3 cm (n=27) (Fig. 2, Table 2). The calculated benthic O$_2$ consumption rates reflected the differences in OPD, with the lowest metabolic activity of 92 ± 44 μmol m$^{-2}$ d$^{-1}$ (n=16) at the Tonga abyssal plain, 225 ± 50 μmol m$^{-2}$ d$^{-1}$ (n=7) within the Tonga Trench and the highest activity of 746 ± 103 μmol m$^{-2}$ d$^{-1}$ (n=27) at the Izu-Bonin Trench axis. (Fig. 2, Table 2). The scatter seen in the averaged profiles from the Tonga Trench axis (Fig. 2(B)) and abyssal (Fig. 2(C)) site most likely result from the small stones observed in these sediments.

3.3. Sediment parameters

3.3.1. Organic carbon and phytopigments

The total organic carbon content at the three sites was similar, with depth integrated values (0–15 cm) ranging around ~6.0–6.5 kg m$^{-2}$ (Table 2). At the Tonga area both the abyssal and hadal stations exhibited relatively constant organic carbon content throughout the sediment core indicating relatively well-mixed sediments (Fig. 3(B)). In contrast, the sediment surface at the Izu-Bonin Trench site appeared enriched in organic material, and relatively little variability was observed at sediment depths > 5 cm (Fig. 3(A)).

In contrast to the total organic material the concentrations of
phytopigments were distinctly different at the three stations. The depth-integrated values of phytopigments (0–15 cm) at the Izu-Bonin site were ~5-times higher than in the Tonga Trench which again were ~5-times higher than the values from the neighboring abyssal plain (Table 2). At the Tonga Trench sites no clear sediment–depth trend was visible, except for a potential minor peak of phaeopigments in the sediment at 5 cm depth (Fig. 3D)). The Chl a and phaeopigment concentrations in surface sediments at the Izu-Bonin Trench were higher than at the Tonga sites and the concentration decreased with depth over the first 7 cm, before sharply increasing within 2 cm and reaching an elevated value that remained relatively constant to the bottom of the core (Fig. 3C)).

3.3.2. Abundance of prokaryotic cells

The highest depth-integrated prokaryotic abundance was found at the Izu-Bonin Trench hadal site with 7.6 × 10⁸ cells cm⁻², followed by the hadal Tonga Trench site (1.2 × 10⁸ cells cm⁻²) and the abyssal Tonga site (7.2 × 10⁸ cells cm⁻²) (Table 2). As for the concentration of phytopigments and the organic carbon content, both Tonga sites exhibited a relatively constant abundance of prokaryotes from the surface to the bottom of the core (Fig. 3F)). At the Izu-Bonin site the prokaryotic abundance exhibited a distinct shift to elevated values at 7 cm depth (Fig. 3E)), mirroring the profile structure of the phytopigment concentration presented above (Fig. 3C)).

3.3.3. Sediment profiles of ²¹⁰Pbex and ¹³⁷Cs profiles

The excess ²¹⁰Pb (²¹⁰Pbex) activity near the sediment-water interface of the Izu-Bonin Trench axis was ~3-times higher than at the Tonga Trench axis (Fig. 3G) and (H)). But in contrast to the Tonga Trench the values in the Izu-Bonin Trench exhibited a strong monotonous decrease in activities from the sediment–water interface down to ~6–7 cm sediment depth (Fig. 3G)). This depth coincided also with distinct shifts in the sediment profiles of prokaryote abundance and phytopigment concentrations (Fig. 3C) and (E)). The depth-integrated inventory at the hadal Izu-Bonin Trench site (~40 kBq m⁻²) was ~5-times lower than at the hadal Tonga Trench site (~200 kBq m⁻²) (Table 2). The surface activity of ²¹⁰Pbex in the Tonga Trench hadal site was ~4-times higher than at the abyssal reference site (Fig. 3H)). This to a minor extend is due to the depth effect on specific ²¹⁰Pbex activities and inventories. The specifics of the profile shapes and the environmental settings, however, indicate that the difference in this particular case is mainly due to (1) a relatively recent turbiditic deposit in the trench axis and (2) moderate topographically (abyssal-hill) controlled reduction of deposition at the abyssal trench-rim site. Furthermore, while the activity at the abyssal site quickly reached an almost constant lower value, the values at the hadal trench site remained elevated down to the maximum measuring depth of 20 cm. The depth-integrated ²¹⁰Pbex inventory from the hadal Tonga Trench was extremely high and showed ~20-fold higher values (207 kBq m⁻²) than the abyssal site (~10 kBq m⁻²) (Table 2). The depth integrated ²¹⁰Pbex values at the hadal site would presumably have been even higher if it had been possible to obtain longer sediment cores as values remained elevated to the bottom of the core (Fig. 3H)).

No ¹³⁷Cs was detected in the Tonga Trench area, probably reflecting low flux of ¹³⁷Cs to the southern hemisphere during the nuclear weapons tests in 1945–1963 (Tsumane et al., 2011). However, at the Izu-Bonin Trench, ¹³⁷Cs penetrated to 4–5 cm sediment depth (Supplementary Fig. S2). No ¹³⁴Cs (T₁/₂ = 2.06 yr, 605 and 796 keV) was encountered in any of our samples; this contrasts with ¹³⁴Cs that was previously observed at 7261 m depth in Japan Trench and being ascribed to leakage during the 2011 Fukushima Dai-ichi nuclear power plant accident (Oguri et al., 2013).

4. Discussion

The diagenetic efficiency of marine sediments regulates the long-term regeneration and the preservation of organic material and therefore plays an important role for oceanic element cycling (e.g. Canfield, 1994; Wollast, 1998). One of the most robust and widely applied proxies for benthic carbon mineralization is to quantify the benthic O₂ consumption rate (Glud, 2008). In coastal settings, irrigation and respiration by fauna can contribute significantly to the degradation efficiency and activity (Kristensen, 1988; Aller 1994; Wenzhöfer and Glud, 2004). However, the relative importance of fauna attenuates with water depth, and at deep sea settings the diagenetic activity is almost exclusively mediated by the microorganisms (Glud et al., 1994; Wenzhöfer et al., 2016).
and Glud, 2002; Glud, 2008). Therefore, the diffusive mediated O₂ uptake (DOU) as derived from pore water microprofiles provides a good measure for the total turnover of organic material in abyssal and hadal sediments. Overall the benthic O₂ uptake gradually declines by ~3–4 orders of magnitude moving from coastal settings to abyssal water depths with O₂ fluxes decreasing from roughly 50 mmol m⁻² d⁻¹ down to 0.1–0.5 mmol m⁻² d⁻¹ (Andersson et al., 2004; Glud, 2008, Fig. 4). However, low biological activity with extremely low O₂ uptake rates of 0.1–0.3 mmol m⁻² d⁻¹ are encountered in sediments of the central ocean gyres, due to the extremely low flux of particulate organic matter from the photic zone to the seafloor (Fischer et al., 2009; Murray and Grundmanis, 1980). Despite the relatively low biogeochemical activity of deep sea sediments they are still estimated to be responsible for >50% of the global benthic carbon mineralization due to their vast extent (e.g. Jahnke, 1996; Andersson
4.1. Intensified diagenetic activity in hadal trench axis sediments

There only exist few in situ determinations of benthic O₂ consumption rates from the deep abyss. Available data for water depth between 4500 and 6500 m range from 50 to 575 μmol m⁻² d⁻¹ with an overall average value of 265 ± 169 μmol m⁻² d⁻¹ (n=20) while the corresponding values for the 5000–6500 m depth interval are 50–356 μmol m⁻² d⁻¹ with an average of 175 ± 128 μmol m⁻² d⁻¹ (n=9) (Reimers et al., 1986; Smith et al., 1978; Berelson et al., 1990; Halles et al., 1994; Glud et al., 1994, 2013; Wenzhöfer and Glud, 2002; this study). The three available data sets from hadal depths (> 6500 m) range from 154 ± 48 μmol m⁻² d⁻¹ in the Mariana Trench (~ 10900 m), 225 ± 50 μmol m⁻² d⁻¹ in the Tonga Trench (~ 10800 m) up to 746 ± 103 μmol m⁻² d⁻¹ in the Izu-Bonin Trench (~9200 m) (Table 2, Fig. 5). The ranking of the values mirrors the estimated pelagic productivity in the respective provinces equaling 4.2, 8.8 and 16.7 mol C m⁻² yr⁻¹ in the areas of the Mariana Trench, the Tonga Trench and the Izu-Bonin Trench, respectively (Table 2, Glud et al. (2013)). This suggests a direct link between the regional pelagic productivity and benthic diagenetic activity at the respective hadal trench bottoms. Overall the absolute values of the O₂ consumption of the investigated hadal sediments are similar or even exceed the available data from the deep abyss. Comparison of benthic consumption rates measured in central hadal trenches to those of nearby abyssal settings confirms intensified activities in trench settings that are 1.8–2.5-times higher in the trenches as compared to near-by abyssal sites (Table 2, Fig. 5). The elevated benthic diagenesis is reflected by relatively higher prokaryote (Table 2, Fig. 5, Glud et al. (2013)) and meiofauna abundance in hadal sediments (Danovaro et al., 2002; Leduc et al., 2016). The few available data on prokaryotic abundances in hadal sediments may even be considered to be minimum values given that cell lysis associated to recovery artifacts is expected to be more prominent in deeper settings (Hall et al., 2007). The higher microbial biomass and elevated diagenetic activity must be sustained by an elevated food supply to hadal sediments. But this is not necessarily reflected by higher total organic carbon content of hadal sediments (Fig. 5(B)), which for a large part presumably consist of relatively refractory material. Rather, it could be speculated that the enhanced activity is being sustained by a relatively efficient supply of more labile organic material that only makes up a small part of the sedimentary material.

Using the Chl a/(Chl a + phaeopigments) ratio as an indicator for the freshness of the settling organic material (Stephens et al., 1997; Pastor et al., 2011) indeed indicates that more labile material reaches the trench bottoms than the neighboring abyssal plains (Table 2). It is important to notice that the current investigation target the central basins of the respective trenches and cannot be extrapolated to the entire trench systems. Individual trenches exhibit a great downslope variety of habitats, with steep trench walls and rugged outcrops where sediments can accumulate (Blankenship-Williams and Levin, 2009). There are also places of tectonic activity sustaining biological hot spots based on chemosynthetic communities. While the importance of chemosynthetic organic material produced at seeps or vents in hadal settings remain an unquantified carbon source for hadal communities, the observation of elevated concentration of phytopigments in hadal sediments would still suggest a mechanism for focusing phyodetrital material along the trench axis sustaining elevated microbial activity with labile organic material in the central basins.

It has been suggested that increasing hydrostatic pressure may inhibit mineralization of sinking aggregates that mainly are colonized by microbes from surface waters and that relatively labile unprocessed phyodetrital material may reach great depth (Tamburini et al., 2013). This alone would, however, not explain higher concentration of phytopigments at hadal versus abyssal depths which would require a preferential down slope focusing of phyodetrital material towards the trench axis (Turnewitsch et al., 2014). This could potentially be maintained by frequent suspension and re-deposition of material along the trench slopes that would gradually lead to focusing of detrital material at the sediment surface in the central trench. Tidally driven hydrodynamic forcing and seismic activity could drive such a process. It is well established that earthquakes can trigger mass wasting, down slope transport of sedimentary material, but subsequent aftershocks and instability along the trench slopes can presumably maintain down slope material transport for extensive periods (Itoh et al., 2000; Oguri et al., 2013). Dense, 30–50 m thick nepheloid layers were observed in the central Japan Trench four months after the
Tohoku-Oki Earthquake (Oguri et al., 2013) and this would lead to preferential concentration of light detrital material in the upper sediment layers along the trench axis. Such events are also expected to lead to the deposition of large amounts of macrofauna carrion that will be focused at the trench bottom and sustaining microbial activity for extended periods (Oguri et al., 2013). Detailed investigation of radionuclide distribution in recovered sediment cores can provide some insight on deposition and particle dynamics in the targeted sediments.

4.2. Deposition dynamics as inferred from $^{210}$Pbex and $^{137}$Cs profiles

The radionuclide data together with the other sediment-compositional data suggest that the hadal surface sediments of the trench axis seafloor at both, the Izu-Bonin and the Tonga Trench system, had been affected by mass wasting events, potentially followed by subtle slower post-event processes that gradually smoothed the sediment surface. However, the data also suggest that the timing of the events differed between the two sites.

At the Izu-Bonin Trench the partially lumpy topography of the surface sediment and the distribution of organic carbon and phytopigments indicate the possible deposition of mass-wasted sediment. The sharp decrease in $^{210}$Pbex reaching low or near-zero levels at 5–6 cm depth (Fig. 3(G)), however, indicates that the most recent mass-wasting event (if any) occurred at least ~100 years ago ($5 	imes ^{210}$Pb half-lives) and that the topmost layer was also affected by a relatively recent gradual biological down mixing. This latter notion is also supported by the $^{137}$Cs results (Supplementary Fig. S2). At 5–6 cm depth the O$_2$ concentration approached zero, but prokaryotic abundance and phytopigments exhibited a distinct upward shift indicating a very pronounced change in sediment biogeochemistry and possibly sediment provenance. The absence of significant amounts of $^{210}$Pbex in this deeper layer (>6 cm; Fig. 3(G)) shows that this layer would also have resulted from a mass-wasting event older than ~100 yr.

The $^{210}$Pbex profile in the central hadal Tonga Trench exhibits three distinctive features, i) surface activities (~1.9 Bq g$^{-1}$) that are comparatively low for this water depth, ii) deep penetration and nearly constant values, but iii) an unusual high depth-integrated $^{210}$Pbex inventory (Fig. 3(H); Table 2) with all features
pointing towards a major sediment deposition event in relatively recent time. The surface value is in fact much lower than previously reported for hadal trench surface sediments, with the exception of sediments from the central Izu-Ogasawara Trench (Yamada et al., 1983; Swinbanks and Shirayama, 1986) that are thought to be influenced by very intense intertidal tides that propagate across the trench (Turnewitsch et al., 2014). Hadal trenches are often characterized by large earthquakes inducing turbidity currents and large submarine down slope landslides (Kawamura et al., 2012). These seismic events create thick distinct deposits at the hadal seafloor of the trench axis (Ito et al., 2000; Oguri et al., 2013). In the past five decades, 42 earthquakes over a magnitude of 6.0 were recorded in the investigated area of the Tonga Trench (21.6°S, 183.3°W to 24.71°S, 186.6°W; U.S. Geological Survey, http://earthquake.usgs.gov/earthquakes/search/). Thus the constant \(^{210}\text{Pb}_{\text{ex}}\) activities down to the bottom of the core (Fig. 3(H)) most likely resulted from an event of sudden, intense mass deposition. In the upper sediment layer amphipod behavior, as observed in video records (Supplementary Fig. S1), could have re-started biological sediment mixing after the mass-wasting event (Leduc et al., 2016).

The \(^{210}\text{Pb}_{\text{ex}}\) profile at the abyssal site near the Tonga Trench features low specific \(^{210}\text{Pb}_{\text{ex}}\) activities in the sediment, with slightly elevated values directly at the surface (Fig. 3(H)) and relatively low \(^{210}\text{Pb}_{\text{ex}}\) inventories (Table 2). Such features presumably reflect low vertical deposition of material rather than mass wasting as seen at the hadal trench site. Surprisingly, under similarly oligotrophic surface waters and at a similar water depth, specific activities of \(^{210}\text{Pb}_{\text{ex}}\) in surface sediments of the oceanward rim of the Mariana Trench were up to twice as high (1.79 Bq g\(^{-1}\)) and inventories were up to ~5-times as high than encountered at the Tonga Trench rim (Table 2) (Glud et al., 2013). The sampling site is located close to an abyssal hill and topographically accelerated near-seafloor waters may have led to comparatively low \(^{210}\text{Pb}_{\text{ex}}\) (and sediment) deposition at this particular trench-rim site.

5. Conclusion

The overall rates and the relative importance of the different diagenetic pathways at the bottom of hadal trench systems are controlled by the deposition rate of organic matter. The diagenetic activity of the three trenches investigated so far shows that benthic \(^{14}\text{C}\) consumption rates at the trench axis decrease from Izu-Bonin Trench > Tonga Trench > Mariana Trench according to the productivity of the mesotrophic and oligotrophic surface waters of their respective provinces. However, hadal deposition dynamics at the trench axes are highly variable and mass wasting may significantly affect the amount and the distribution of organic matter in the central trenches. This may induce a temporal dynamic in diagenetic activity at the trench bottoms showing elevated rates after mass wasting events and a subsequent decline in the activity. However, overall trench axes sediments seem to be enriched in food availability, prokaryotic abundance and metabolic activity as compared to adjacent abyssal sites. It can be speculated that even small scale and more frequent mass wasting events in combination with subtle bio-resuspension and tidal flow oscillations can maintain a relatively high diagenetic activity in hadal sediments of trench axes.

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Appendix A. Supporting information

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References