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Hadal trenches are dynamic hotspots for early diagenesis in the deep sea

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The deepest part of the global ocean, hadal trenches, are considered to act as depocenters for organic material. Relatively high microbial activity has been demonstrated in the deepest sections of some hadal trenches, but the deposition dynamics are thought to be spatially and temporally variable. Here, we explore sediment characteristics and in-situ benthic oxygen uptake along two trenches with contrasting surface primary productivity: the Kermadec and Atacama trenches. We find that benthic oxygen consumption varies by a factor of about 10 between hadal sites but is in all cases intensified relative to adjacent abyssal plains. The benthic oxygen uptake of the two trench regions reflects the difference in surface production, whereas variations within each trench are modulated by local deposition dynamics. Respiratory activity correlates with the sedimentary inventories of organic carbon and phytodetrital material. We argue that hadal trenches represent deep sea hotspots for early diagenesis and are more diverse and dynamic environments than previously recognized.
The 27 hadal trenches encompassing the depth range of 6000 to 11,000 m stretch along the tectonic subduction zones and represent the deepest parts of the global ocean. Temperature, O2 availability, and current velocities in hadal settings resemble conditions in other deep sea environments, but the extreme hydrostatic pressure and geographic isolation favor lower diversity and endemism among piezophilic communities. Seismic-driven mass-wasting, downslope funneling, and fluid dynamics appear to enhance local deposition, and hadal trenches have been argued to represent important depocenters for organic matter. Reports on elevated abundance of prokarocytes, infauna, and scavenging fauna in the deepest parts of trenches relative to the adjacent abyssal plains also suggest that enhanced deposition of organic matter potentially sustains a higher biological activity despite the extreme settings. However, sampling at hadal depths is technically challenging and the few existing studies mainly target the deepest sedimentary basins of trenches. Furthermore, reliable sample recovery from great depth can be confounded by severe artefacts related to shifts in hydrostatic pressure and transient heating, which may compromise the assessment of biological activity and early diagenesis in recovered sediments. Conversely, in situ quantification of the benthic O2 consumption rate is considered a robust proxy of biological activity and benthic carbon mineralization in deep sea settings.

In situ measurements of benthic O2 uptake have demonstrated that rates of benthic mineralization of organic material gradually decrease by 2–3 orders of magnitude from the coastal oceans to 6000 m water depth on abyssal plains. Yet recent in situ measurements in the deepest sedimentary basins of trenches suggest that this pattern might be reversed in the hadal realm, and that intensified deposition of organic matter could enhance biological activity and benthic carbon mineralization at these sites. While these studies together only covered the deepest points in each of five hadal trenches, there is increasing evidence that varied hadal seascapes and local dynamics may result in highly variable seafloor conditions across the depths of a trench as well as along the trench axis and that the very deepest point may not reflect the conditions of the trench as a whole. Thus, investigations of within-trench variability are key for understanding element cycling and early diagenesis in these unique environments.

To explore availability and mineralization of organic carbon along two contrasting hadal systems, we visited the Kermadec and Atacama trenches during 21–27 November 2017 and 2–6 March 2018, respectively (Fig. 1a). Five hadal sites were targeted along a 483 km transect in the Kermadec Trench (depth range 9300–10,010 m) together with one abyssal reference site (depth 6080 m), while six hadal sites along a 445 km transect (depth range 7720–8085 m) and two abyssal reference sites (depths 4050 m and 5500 m) were investigated in the Atacama Trench region (Table 1, Fig. 1b, c). The estimated surface primary production in the Kermadec Trench region is ~400 mg C m$^{-2}$ d$^{-1}$, while the value for the Atacama trench region amounts to ~900 mg C m$^{-2}$ d$^{-1}$ (Table 1).

**Results and discussion**

At each site, we deployed two autonomous instruments; a “Reiver” for probing and imaging the sediment surface and a “Hadal-Profiler Lander” for measuring the benthic O2 distribution. The initial sediment probing with the Reiver enabled us to assess whether the seafloor was appropriate for subsequent lander deployments and sediment sampling (Supplementary Fig. S1). The Hadal–Profiler Lander was equipped with a transecting array of O2 microsensors which enabled measurements of multiple sets of O2 microprofiles during the 15–24-h long deployments. The O2 microprofiles were used to calculate the diffusion-mediated O2 uptake (DOU) and the depth distribution of the volume specific O2 consumption rate (see “Methods summary”). While the DOU only represent about 50% of the total O2 uptake in fauna-rich coastal sediments, parallel measurements down to 4000 m depth have shown that the total and the diffusive mediated O2 consumption rates converge with increasing water depth as macrofauna biomass attenuates, and thus rates of these two measures become statistically indifferent at deep sea settings.

Therefore, DOU calculated from microprofiles generally provide a robust rate measurement of sediment community respiration in deep sea environments. Intact sediment cores were recovered by a multi-corer, by an autonomous coring lander, or sub-sampled from a box-corer as indicated in Table 1. It is not trivial to recover intact sediment from hadal depths, and here we only report on sediment cores that were recovered with an apparently intact sediment surface and clear overlying water. The sediment cores were sectioned and preserved for a wide range of geological, biogeochemical, biological, and microbial investigations. Here we report on the sediment porosity, total organic carbon (TOC %), and pythodetrital pigment concentrations (see “Method summary”).

We obtained a total of 206 microprofiles in the two trench regions, ranging from 6 to 39 microprofiles per site depending on breakage or malfunctions of the applied microelectrodes. The average and the median of the profile numbers per site were 14.7 and 11, respectively. Some O2 microprofiles were clearly disturbed by obstacles; infauna, pumice, nodules or small stones that were encountered sporadically in the recovered sediment. Such encounters resulted in noisy and disturbed O2 signals, and a few occasional subsurface O2 concentration peaks that could imply bioirrigation. Such “disturbed” profiles were not included in the quantification of the benthic O2 consumption rates (Table 2).

In the Kermadec Trench region, measurements at the abyssal site K7 off the trench axis, exhibited an O2 penetration depth (OPD), that exceeded the maximum measuring depth of ~20 cm, and the derived averaged DOU (152 ± 22 µmol m$^{-2}$ d$^{-1}$) was the lowest rate encountered at any of the 14 sites visited in the two trench regions (Fig. 2 and Table 2). All sites along the Kermadec Trench axis exhibited steeper O2 attenuation, shallower OPD and a higher DOU than encountered at abyssal site K7. There was, however, considerable difference in activity levels along the trench axis with values ranging from of 193 ± 21 µmol m$^{-2}$ d$^{-1}$ at K4 to 668 ± 83 µmol m$^{-2}$ d$^{-1}$ at K2 (Table 2). The volume specific O2 consumption rate was generally intensified close to the sediment surface and to a lesser extent at theoxic-anoxic interface. This pattern is typically ascribed to elevated lability of organic carbon at the sediment surface and intensified oxidation of reduced inorganic constituents (Fe$^{2+}$, Mn$^{2+}$, NH$_4^+$, H$_2$S, FeS) close to the oxic-anoxic interface —solutes and solids being produced by deeper anaerobic mineralization processes. The intensified activity at the sediment surface could imply that the organic material is a key-driver for the overall aerobic activity in these settings. The relative amount of O2 consumed in the sediment layers close to the oxic-anoxic interface in the Kermadec Trench region ranged between 5% and 23% (Table 2).

In the Atacama Trench region, we visited two abyssal reference sites one at either side of the trench axis. Site A7, at the oceanward side of the trench, had an OPD > 20.0 cm and a DOU of 355 ± 31 µmol m$^{-2}$ d$^{-1}$, while A9 at the landward side of the trench had an O2 penetration of 6.2 ± 0.5 cm and a DOU of 687 ± 101 µmol m$^{-2}$ d$^{-1}$ (Fig. 2 and Table 2). Thus, the landward reference site being closer to the continent and the productive coastal ocean had – as expected – higher benthic O2 consumption...
rates. Still, as in the Kermadec Trench, all hadal sites along the Atacama trench expressed markedly higher activity than the abyssal reference sites (Fig. 2 and Table 2) and the volume specific activity attenuated steeply below the surface and typically exhibited a secondary peak close to the oxic-anoxic interface. The O$_2$ concentration in the bottom water of the Atacama Trench region was somewhat lower (~160 μmol L$^{-1}$) compared to that of the Kermadec Trench region (~210 μmol L$^{-1}$), but the Atacama Trench DOU rates clearly exceeded the values from the latter (Table 2). In fact, the resolved OPD and DOU in the ~8000 m deep Atacama Trench aligned with values encountered previously in sediments from continental shelves and slopes$^{18}$ (Supplementary Fig. S2). The empirical relationship between the resolved DOU and OPD aligned with observations from other ocean realms, and the relation was used to assess the OPD for the least active sites (Table 2 and Supplementary Fig. S2).

Thus, for both study regions, the benthic O$_2$ consumption rates observed at all hadal sites exceed the values encountered at neighboring abyssal plain sites, and our results demonstrate that hadal trenches represent sites of intensified early diagenesis in the deep sea. However, the DOU along both trench axes also exhibited a high degree of variability (Fig. 2, Table 2).

Fig. 1 Study areas in the Kermadec Trench and the Atacama Trench regions in the Pacific Ocean. Detailed bathymetries with specific sampling sites in the two respective trenches; Kermadec Trench (b) and Atacama Trench (c). The sites were visited during two cruises with RV Tangaroa (TAN1711, 2017) and RV Sonne (SO261, 2018), respectively. Bathymetry data were obtained from the Global Multi-Resolution Topography Synthesis (Ryan et al.$^{41}$; see also supplementary references). Black line in b and c indicates the 6000 m depth contour. Figure; Copyright British Geological Survey© UKRI 2020.
investigations in other oceanic realms have shown a general correlation between TOC availability at the sediment surface and benthic O$_2$ consumption rates. Unfortunately, we did not recover high quality sediment cores from all targeted sites, but for the available data the DOU correlated well to the TOC content of the sediment (Fig. 3a). This finding implies (i) that intensified organic matter deposition and benthic metabolism are general phenomena in hadal trench sediments relative to adjacent abyssal plains, and (ii) that spatial-temporal deposition dynamics above the sedimentary content of Chlorophyll a (Fig. 3b), which is often biologically processed material, but the DOU correlated well to the available data the DOU correlated well to the TOC content of the sediment (Fig. 3a). This finding implies (i) that intensified organic matter deposition and benthic metabolism are general phenomena in hadal trench sediments relative to adjacent abyssal plains, and (ii) that spatial-temporal deposition dynamics above and within the hadal environment induce a large variation in biological and diagenetic activity along trench axes, and (iii) the intercept with the abscissa indicate a fraction of refractory organic material along trench axes, and fresh phytodetrital material has been suggested to mediate focusing (and winnowing) of fresh material that could sustain elevated biological activity in trench sediments. The variation in DOU observed along the Kermadec and Atacama trench axes presumably reflect variable time since the last mass-wasting event or variations in recent material focusing and winnowing, respectively, that seismic activity and tsunamis can translocate material including labile organic carbon from coastal oceans to the interiors of hadal trenches. Furthermore, mass mortality of faunal communities along trenches and on the trench slopes during mass wasting presumably led to intensified deposition of labile organic material along the trench axis. Finally, tidal near-inertial fluid dynamics and complex bathymetry within trenches have been suggested to mediate focusing (and winnowing) of fresh material along trench axes, and fresh phytodetrital material has been observed at great depth in hadal regions. Thus, there are several potential pathways for deposition of labile organic material that could sustain elevated biological activity in trench sediments. The variation in DOU observed along the Kermadec and Atacama trench axes presumably reflects variable time since the last mass-wasting event or variations in recent material focusing along the axes. We have no direct way to quantify the lability of biologically processed material, but the DOU correlated well to the sedimentary content of Chlorophyll a (Fig. 3b), which is often shortly after the Tohoku-Oki Earthquake revealed hadal deposition of $^{134}$Cs from the Fukushima nuclear powerplant and high loading of fresh organic material. These observations suggest that seismic activity and tsunamis can translocate material including labile organic carbon from coastal oceans to the interiors of hadal trenches. Furthermore, mass mortality of faunal communities along trenches and on the trench slopes during mass wasting presumably led to intensified deposition of labile organic material along the trench axis. Finally, tidal near-inertial fluid dynamics and complex bathymetry within trenches have been suggested to mediate focusing (and winnowing) of fresh material along trench axes, and fresh phytodetrital material has been observed at great depth in hadal regions. Thus, there are several potential pathways for deposition of labile organic material that could sustain elevated biological activity in trench sediments. The variation in DOU observed along the Kermadec and Atacama trench axes presumably reflects variable time since the last mass-wasting event or variations in recent material focusing along the axes. We have no direct way to quantify the lability of biologically processed material, but the DOU correlated well to the sedimentary content of Chlorophyll a (Fig. 3b), which is often

Table 1 Positions and water depths at the investigated sites in the Kermadec (K) and the Atacama (A) trench regions.

| Site | Latitude | Longitude | Depth (m) | NPP (mg C m$^{-2}$ d$^{-1}$) | Coring |
|------|----------|-----------|-----------|------------------------------|--------|
| K2   | 29° 13.70'S | 176° 07.00' W | 9700      | 340                          | -      |
| K3   | 30° 22.84' S | 176° 38.48' W | 9540      | 369                          | -      |
| K4   | 31° 08.41' S | 176° 48.48' W | 9300      | 393                          | Lander |
| K5   | 31° 56.14' S | 177° 17.48' W | 10,010    | 414                          | -      |
| K6   | 32° 08.93' S | 177° 23.91' W | 9555      | 416                          | MUC    |
| K7   | 32° 11.22' S | 176° 33.66' W | 6080      | 405                          | BC     |
| A2   | 21° 46.86' S | 71° 12.48' W  | 7955      | 838                          | MUC    |
| A3   | 23° 02.94' S | 71° 18.12' W  | 7915      | 933                          | MUC    |
| A4   | 23° 21.78' S | 71° 20.60' W  | 8085      | 917                          | MUC    |
| A5   | 23° 49.02' S | 71° 22.32' W  | 7770      | 935                          | MUC    |
| A6   | 24° 15.96' S | 71° 25.38' W  | 7720      | 846                          | MUC    |
| A7   | 22° 56.22' S | 71° 37.08' W  | 5500      | 843                          | MUC    |
| A9   | 20° 19.97' S | 70° 58.70' W  | 4050      | 938                          | MUC    |
| A10  | 20° 19.14' S | 71° 17.46' W  | 7770      | 838                          | MUC    |

The average net primary production (NPP) was derived from the model of Behrenfeld and Falkowski using remote sensing data from the period 2009-2018 at the respective sites. The last column indicates the procedure that was applied for recovering sediment cores with intact sediment surfaces at the respective sites: autonomous lander (Lander), multi-corer (MUC), sub-sampling from box-corer (BC).

Table 2 Oxygen penetrations depth (OPD), diffusive O$_2$ uptake (DOU), the relative amount of volume specific O$_2$ consumption rate estimated to be associated with inorganic oxidation processes ($R_{ox}$), and the fraction of O$_2$ microprofiles that were visually disturbed during the measurements.

| Site | Depth (m) | OPD (cm) | DOU ($\mu$mol m$^{-2}$ d$^{-1}$) | $R_{ox}$ (%) | Disturbed (%) |
|------|-----------|----------|---------------------------------|--------------|---------------|
| K2   | 9700      | 6.1 ± 0.4| 668 ± 83 (5)                    | 23 ± 5 (4)   | 17            |
| K3   | 9540      | 8.6 ± 0.5| 538 ± 91 (7)                    | 13 ± 8 (6)   | 13            |
| K4   | 9300      | 20.7*    | 193 ± 21 (11)                   | 19 ± 4 (9)   | 0             |
| K5   | 10010     | 8.9 ± 0.1| 452 ± 14 (9)                    | 14 ± 1 (5)   | 52            |
| K6   | 9555      | 11.5 ± 0.3| 306 ± 20 (5)                   | 11 ± 1 (5)   | 0             |
| K7   | 6080      | 26.4*    | 152 ± 22 (8)                    | 5 ± 3 (5)    | 0             |
| A2   | 7995      | 3.2 ± 0.1| 1236 ± 56 (35)                  | 5 ± 1 (16)   | 10            |
| A3   | 7915      | 2.6 ± 0.1| 1793 ± 77 (29)                  | 4 ± 1 (13)   | 6             |
| A4   | 8085      | 3.4 ± 0.4| 1490 ± 81 (18)                  | 4 ± 1 (9)    | 5             |
| A5   | 7770      | 4.0 ± 0.2| 992 ± 50 (12)                   | 9 ± 1 (10)   | 8             |
| A6   | 7720      | 4.1 ± 0.3| 1035 ± 143 (8)                  | 6 ± 1 (8)    | 0             |
| A7   | 5500      | 21.7**   | 355 ± 31 (7)                    | 0 ± 0 (7)    | 11            |
| A9   | 4050      | 6.2 ± 0.5| 687 ± 101 (8)                   | 5 ± 1 (8)    | 27            |
| A10  | 7770      | 3.1 ± 0.3| 1634 ± 71 (19)                  | 8 ± 1 (12)   | 5             |

Range indicates Standard Error and values in brackets indicate the number of observations. The * indicate values estimated from an empirical relation between DOU and OPD (Supplementary Fig. S2), while ** imply that the value is based on only one observation, the remaining profiles at this site did not reach anoxia.
Fig. 2 Selected oxygen microprofiles measured in the Kermadec Trench (K) and Atacama Trench (A) regions. The sites and water depth where the respective microprofiles were measured are indicated in each panel (see also Table 1). The depth distribution of the calculated volume specific O₂ consumptions rates for each profile are depicted by blue lined boxes – note the different scale for profiles obtained in the two trenches. The estimated depth of the sediment surface is assigned to 0 mm and highlighted by a horizontal black line.

Fig. 3 The diffusive oxygen uptake (DOU) derived from in situ microprofiles. The profiles were measured by an autonomous benthic lander and plotted as a function of the total organic carbon content (TOC) (a), and chlorophyll a content (Chl a) (b), both inventories were quantified in surface sediments (0-5 cm) of recovered intact sediment cores. Red and blue symbols depict values from the Atacama and Kermadec trench regions, respectively, where circles are values from the hadal depth range and squares represent values from abyssal reference sites (See Table 1), and error bars indicate standard error (Table 2). Data were approximated by linear regressions that provided the following equations DOU = 8.87TOC - 432 (R = 0.81) and DOU = 63.7 (Chl a) + 118 (R = 0.81) for a and b, respectively. In some instances, the error bars are smaller than the symbol size.
used as an indicator of the availability of labile phytodetrital material. This suggests that fluid dynamics and/or sorting during down-slope material transport might further amplify the delivery of relatively labile material to surface sediments at the trench axis.

A previous data compilation has suggested a close coupling between surface ocean productivity and hadal benthic O$_2$ uptake rates<sup>20</sup> (Fig. 4). Indeed, measurements in the Atacama Trench that underlies a region of high ocean productivity, represent the highest recorded hadal DOU values to date, and these exceed on average the values from the Kermadec Trench by a factor of 3 (Fig. 4). However, the sites within the Kermadec Trench, which underlie a region of relatively low and evenly distributed ocean productivity (Table 1), show DOU levels that span the entire range of values recorded from previous studies compiled from five different Pacific trenches (Fig. 4). Thus, even though there is a connection between surface ocean productivity and benthic O$_2$ consumption in hadal sediments, this linkage appears to be modulated by complex depositional processes.

Assuming a Respiratory Quotient of 1.0 (i.e., that O$_2$ consumed via benthic diagenesis is balanced by a corresponding molar production of CO$_2$), our compilation implies that—on average—benthic mineralization of organic material in hadal settings corresponds to 1.6% of the estimated overlying surface production (Fig. 4). This estimate of benthic mineralization is about 1.5–2.0 times higher than the estimated total depositional flux of organic material at these depths as derived from empirical relations between surface production and material collected by sediment traps<sup>31-33</sup>. As this vertical depositional flux will include a considerable fraction of highly refractory material with little or no nutritional value, this calculation further underscores that hadal trenches in general act as deep sea depocenters, where lateral inputs of reactive organic matter enhance benthic metabolic and diageneric processes to such an extent that these environments stand out as hotspots in the deep sea.

Benthic O$_2$ consumption is generally accepted as a robust proxy for the total benthic mineralization of organic carbon<sup>34,35</sup>. However, the basic underlying assumption of efficient oxygenic reoxidation of reduced equivalents from anaerobic mineralization might be compromised in the unique depositional environments of hadal trenches. Lack of efficient bioturbation at hadal depths and deposition of labile material in anoxic sediment layers during recurring mass wasting events may lead to burial of reduced equivalents from anaerobic degradation. While the 30 cm long sediment cores recovered from the Kermadec trench axis were relatively oxidized with low content of iron-sulfides, the sediment from the Atacama trench appeared highly reduced (Thamdrup et al. in prog). Onboard incubations with $35S$O$_2$ documented active sulfate reduction below the nitorgenous horizon and the deeper sediment had variable but generally increasing levels of ferrous iron and iron sulfides. On average, the total reducible inorganic sulfur content amounted to 11 ± 9 μmol cm$^{-3}$, while the average HCl extractable Fe(II) content was 70 ± 17 μmol cm$^{-3}$ at sediment depths from 20–30 cm (Assuming aerobic oxidation stoichiometry this corresponds to 39 ± 16 μmol cm$^{-3}$ of O$_2$ equivalents buried in these largely non-bioturbated sediments. Thus, even though our O$_2$ microprofiles indicate some degree of inorganic reoxidation at the oxic-anoxic interface (Fig. 2 and Table 2), the benthic O$_2$ consumption may underestimate the total benthic carbon mineralization in hadal settings. In addition, although it should be minor, a contribution from macrofauna is not included in our current assessment. Therefore, our estimates of ~3–5 times higher carbon mineralization rates in hadal settings as compared to adjacent abyssal sites should be regarded as conservative minimum values—and hadal carbon mineralization might be even more important than our assessment suggests. Future work on anaerobic processing of organic material in hadal sediments is required to resolve this issue.

This study documents that the biogeochemical function of hadal trenches cannot be understood by extrapolating findings from other oceanic realms. The trenches generally act as depocenters for organic material and express intensified early diageneric activity. However, we also demonstrate extensive variations in benthic activity both between and along the axis of the two studied trenches. Hadal benthic activity is linked to the regional surface production, but activity levels are strongly modulated by complex local deposition dynamics. Hadal trench environments therefore appear to be much more dynamic and biogeochemically diverse than previously recognized. This spatial and temporal variation needs to be fully appreciated for understanding and quantifying the biogeochemical function and importance of hadal trench environments, and to resolve linkages to small and large scale hadal biogeographic patterns.

**Methods summary**

Before initiating work at each site, one of two free-fall camera lander systems, “Reivers”, was used to inspect sediment conditions. When deployed, these vehicles descended to the seafloor at 47 m min$^{-1}$ and filmed the penetration of a vertical 7.5 cm diameter × 100 cm steel bar in the sediment upon landing. The bar had markings at 10 cm intervals and was part of a two-part ballast system (the other being a 56 kg stack of steel plates), that was jettisoned by acoustic command from the ship shortly after landing. Ballast release was actuated by a single Oceano 2500 Ultimate Depth Acoustic Release (IXSEA Blue, France) via a shipside telecommand unit (TT801, IXSEA Blue France). Bespoke HDTV video cameras (GZ-V950, JVC Kenwood) were mounted in stainless steel pressure housings, with sapphire viewports and...
subsamples using a Turner fluorometer. Both TOC and Chl a were converted to sediment inventories by depth integrating to a sediment depth of 5.0 cm.

Data availability
The datasets generated and/or analysed during the current study are available from the corresponding author (R.N.G.) on request and will be made available in the PANGAEA repository under the project title “HADES-ERC” (www.pangaea.de).

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Author contributions

R.G. wrote the manuscript with contributions from all co-authors. R.N.G., P.B., F.W., A.G., B.T., H.A.S., A.J.J., K.O., and H.S. carried out the measurements, performed the analytical work and the theoretical analyses. F.W., A.R., R.N.G. M.L., and A.G. organized the expeditions and logistics, and assisted in the sampling. All authors discussed the results, their implications and commented on the manuscript as it progressed.

Competing interests

The authors declare no competing interests.

Additional information

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