Presence of oxygen and aerobic communities from sea floor to basement in deep-sea sediments

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Abstract :

The depth of oxygen penetration into marine sediments differs considerably from one region to another. In areas with high rates of microbial respiration, O₂ penetrates only millimetres to centimetres into the sediments, but active anaerobic microbial communities are present in sediments hundreds of metres or more below the sea floor. In areas with low sedimentary respiration, O₂ penetrates much deeper but the depth to which microbial communities persist was previously unknown. The sediments underlying the South Pacific Gyre exhibit extremely low areal rates of respiration. Here we show that, in this region, microbial cells and aerobic respiration persist through the entire sediment sequence to depths of at least 75 metres below sea floor. Based on the Redfield stoichiometry of dissolved O₂ and nitrate, we suggest that net aerobic respiration in these sediments is coupled to oxidation of marine organic matter. We identify a relationship of O₂ penetration depth to sedimentation rate and sediment thickness. Extrapolating this relationship, we suggest that oxygen and aerobic communities may occur throughout the entire sediment sequence in 15–44% of the Pacific and 9–37% of the global sea floor. Subduction of the sediment and basalt from these regions is a source of oxidized material to the mantle.

Main

Morita and ZoBell nearly 60 years ago reported “the lower limits of the biosphere” at 3.9 to 7.5 meters below seafloor (mbsf) in abyssal clay of the oligotrophic North Pacific Gyre (NPG)¹⁷. Recent studies pushed the lower limit of the known sedimentary biosphere to slightly greater depths in abyssal clay of oligotrophic regions; microbial cells have been identified at 8 mbsf in the ultra-oligotrophic South Pacific Gyre (SPG)⁵ and 20 mbsf in the NPG⁶, and aerobic respiration has been inferred to nearly 30 mbsf in the NPG⁶. However, the existence, nature and consequences of life at greater sedimentary depths in the oligotrophic ocean have remained unknown.

To document the nature of life and habitability in the deepest abyssal sediment of a major low-productivity oceanic region, we undertook Integrated Ocean Drilling Program (IODP) Expedition 329 to the South Pacific Gyre (Oct-Dec 2010)⁷. The SPG is Earth's largest oligotrophic ocean region, covering ~10% of Earth's surface. Oxygen flux across the SPG seafloor is extremely low¹⁸. Mean sedimentation rate, surface chlorophyll concentrations and primary productivity are lower in the SPG than in any other oceanic region⁵. Shallow cores in abyssal sediment of the SPG exhibit the lowest seafloor cell concentrations and the lowest areal

rates of microbial activity ever previously encountered in marine sediment^{5, 19}.

Six of the seven Expedition 329 sites are located in the low-chlorophyll SPG (U1365-U1370), and one is located in the more biologically productive region south of the SPG (U1371) (Fig 1)⁷. These sites range in water depth from 3740 meters below sea level (mbsl) (U1368) to 5695 mbsl (U1365) (SI). Sediment temperature (1.1°-10.6° C) is habitable by psychrophiles at all sites⁷. Basement age ranges from 13.5 Ma (U1368) to 84-120 Ma (U1365 and U1366) (SI). Sediment thickness co-varies with basement age and is lower at the SPG sites (16 - 75 m) than at Site U1371 south of the SPG (131 m)⁷. Site U1370 migrated into the gyre from the southern biologically productive region between 20 and 30 myrs ago (Fig 1)⁷. The other sites have resided within the low-chlorophyll region for most or all of their history.

Microbial cells are present throughout the entire sediment sequence at all seven sites. At the six SPG sites (U1365-U1370), cell counts are extremely low and decrease with increasing sediment depth (Fig 2). They are one to seven orders of magnitude lower than counts at the same depths in previously drilled sites of ocean margins and upwelling regions¹⁹. They are up to two orders of magnitude lower than cell counts in piston-cored sediment of the oligotrophic NPG¹⁹. Site U1371, in the higher productivity region south of the gyre, is characterized by cell counts that are generally higher than at the SPG sites between 0 and 40 mbsf (Fig 2); at greater depths, they converge with the SPG counts.

At the six sites within the SPG, dissolved O₂ is present from the seafloor to the sediment-basement interface (Fig 2)⁷. Dissolved O₂ persists even in the deepest sediment at U1365 (62 to 75 mbsf) despite an intervening ~20-m layer of chert⁷. Persistence of dissolved O₂ throughout the SPG sediment sequence is consistent with the much earlier discovery that dissolved nitrate (NO₃⁻) is at or above deep-water concentrations throughout the entire sediment column of Deep

Sea Drilling Project Leg 92 sites elsewhere in the SPG²⁰ (NO_3^- reduction does not occur until most or all O_2 is depleted²¹). Because dissolved O_2 is present in the deepest sediment, it must also be present in the basement aquifer in diffusive contact with this sediment. This discovery⁷ greatly expands the subsurface envelope of the oxic realm to include the entire sedimentary sequence and the upper basaltic basement throughout the entire SPG.

In oceanic regions where dissolved O_2 penetrates only mm to decimeters into the sediment, the sediment is exposed to O_2 for a very short time (years to kyrs) before it enters a deep anoxic realm²². In contrast, SPG sediment is exposed to dissolved O_2 for an extraordinarily long time, and never becomes anoxic. Because O_2 penetrates the entire sedimentary sequence, O_2 exposure time for SPG sediment is formally equal to the age of the oldest sediment at each site, implying that SPG sediment is continuously exposed to O_2 for its entire history (up to 120 myrs at Site U1365) (SI).

In comparison, dissolved O_2 is absent from most of the sediment column at U1371, in the moderately productive subtropical convergence south of the SPG (Fig 1)⁷. At this site, O_2 diffusing down from the ocean decreases below detection within 0.9 mbsf and traces of O_2 penetrate ~15 meters upward into the sediment from the underlying basaltic aquifer. Oxygen exposure time for the shallow sediment at U1371 is only 35 kyrs (SI).

The presence of dissolved O_2 , nitrate (NO_3^-), phosphate (PO_4^-) and dissolved inorganic carbon ($\text{DIC} = \text{CO}_3^{2-} + \text{HCO}_3^- + \text{CO}_2$) throughout the sediment of SPG sites U1365-U1370 (Fig 2)⁷ indicates that cell abundance and metabolic activity are not limited by availability of electron acceptors or dissolved major inorganic nutrients (C, N, P) in the sediment or the upper basaltic basement. Concentration profiles of the dissolved metabolic products PO_4^- , DIC, and, at Site U1370, NO_3^- exhibit more complexity than dissolved O_2 profiles and the other NO_3^- profiles,

because DIC and, at U1370, NO_3^- are affected by loss to the basement and PO_4^- and DIC interact with sedimentary minerals.

Dissolved NO_3^- is produced in the sediment by aerobic degradation and subsequent nitrification of nitrogen from buried organic matter²¹. Downhole changes in dissolved NO_3^- and O_2 concentrations closely match the Redfield $\text{NO}_3^-:\text{O}_2$ ratio (16:-170)²³, suggesting that net O_2 reduction is almost solely due to oxidation of buried organic matter (SI).

Analysis of undisturbed coring intervals indicates that net O_2 reduction occurs throughout the entire sedimentary sequence at very low rates (Fig 3) (SI). Net O_2 consumption is highest in the first 1.1 to 2.3 mbsf of the SPG sites, ranging from 6.3×10^{-11} moles $\text{O}_2/\text{cm}^3/\text{yr}$ at U1366 to 5.3×10^{-10} moles $\text{O}_2/\text{cm}^3/\text{yr}$ at U1367 (Fig 3). These rates are considerably lower than rates reported from equivalent depths in sediment of the oligotrophic NPG (10^{-7} moles $\text{O}_2/\text{cm}^3/\text{yr}$)⁶. With increasing depth, the rate of net O_2 consumption rapidly decreases to even lower values. It is generally indistinguishable from zero in zones that span intervals of drilling disturbance (Fig 3). In the undisturbed sediment, net O_2 consumption rates are generally distinguishable from zero and range from 3.3×10^{-13} moles $\text{O}_2/\text{cm}^3/\text{yr}$ at U1370 (37.5 to 68 mbsf) to 1.5×10^{-11} moles $\text{O}_2/\text{cm}^3/\text{yr}$ at U1365 (4.9 to 8.8 mbsf) (Fig 3) (SI).

Within the SPG, depth-integrated subseafloor net O_2 reduction rates (from 1.5 mbsf to sediment-basalt interface) decrease from gyre edge to gyre center, in parallel with seasurface chlorophyll content (SI). Peak concentrations of dissolved PO_4^- , DIC and TOC are also consistent with organic-fueled subseafloor respiration declining from outside the gyre (U1371) to gyre center (U1368) (Fig 2).

Gross rates of O_2 consumption presumably exceed these organic-fueled rates of net O_2 reduction, because in situ water radiolysis generates both H_2 and O_2 in marine sediment²⁴ and

most H_2 produced in SPG sediment is quickly consumed (concentrations of dissolved H_2 at these sites are generally below 1 nM and never exceed 90 nM)⁷ (SI). The Redfield stoichiometry of O_2 reduction to NO_3^- production in SPG sediment suggests that radiolytic production of O_2 does not significantly contribute to the dissolved O_2 concentrations (perhaps because H_2 is kept at low concentrations by reactions that reverse radiolytic production of H_2 , O_2 and H_2O_2 , such as the microbially mediated Knallgas reaction).

Mean organic-fueled respiration per cell in the shallowest SPG sediment (1.6-2.3 mbsf) is in the range of 1.2×10^{-15} moles e^- /cell/year (U1365) to 1.1×10^{-14} moles e^- /cell/year (U1366). Mean organic-fueled per-cell respiration is generally even lower at greater depths; in intervals where the volumetric O_2 consumption rate is distinguishable from zero, mean organic-fueled per-cell respiration is between 3.2×10^{-17} moles e^- /cell/year and 6.8×10^{-14} moles e^- /cell/year. These rates at greater depths overlap with mean per-cell respiration rates reported for deep subseafloor aerobes in the North Pacific Gyre (1.5×10^{-15} moles e^- /cell/year)⁶. The rates from SPG depths where O_2 consumption is distinguishable from zero generally exceed mean per-cell rates of deep subseafloor anaerobes in eastern equatorial Pacific sediment [2.8×10^{-18} to 1.7×10^{-17} moles e^- /cell/year (SI)].

These per-cell rates of organic-fueled respiration are broadly consistent with the general interpretation that microbial respiration rates are extraordinarily low in subseafloor sediment^{25, 5, 6, 13, 16}. Nevertheless, estimates of per-cell rates must be treated with caution for the following reasons: (i) the ratio of active cells to dead or moribund cells in counted populations is not yet known, and (ii) the contribution of radiolytic H_2 oxidation to microbial respiration in SPG sediment is also unknown.

The primary driver of the reductions in cell abundance and net (organic-fueled) O_2 reduction

with increasing sediment depth at SPG sites (U1365-U1370) appears to be decreasing availability of organic matter with increasing sediment age. Total organic carbon (TOC) content decreases rapidly with sediment depth, from values between 0.08% (U1368) and 0.25% (U1370) in the first centimeters below seafloor to stable values of “below detection” (0.002%) to 0.03% at greater depths (Fig 2). This decrease in TOC with increasing depth is primarily due to consumption within the sediment; as the sediment ages, less TOC remains to be consumed²⁶.

Total organic carbon approaches our detection limit deep in the sediment at all six SPG sites, including U1370 (Fig 2), which migrated through the higher productivity region south of the SPG early in its history (Fig 1). In comparison, TOC is greater than 0.1% through the upper 100 mbsf at Site U1371 (south of the SPG) and greater than 1.0% for hundreds of mbsf at some ocean-margin sites²⁷.

Depth of O₂ penetration ultimately depends on the balance between supply of reduced oxidizable material (primarily organic matter) and supply of dissolved O₂¹. In near-seafloor sediment, organic flux to the seafloor exerts primary control²⁸. The situation becomes more complicated as sediment depth and age increase, because (i) the supply of organic matter at depth in sediment depends on both the initial flux of reduced material to the seafloor and the subsequent oxidation history of that material at successively greater sediment depths, and (ii) the timescale required for diffusion (e.g., of dissolved O₂) depends on the square of the distance penetrated²⁹.

Comparison of our SPG results to other sites indicate that dissolved O₂ penetrates the entire sediment column at sites with low mean sediment accumulation rates and relatively thin sediment thickness (Fig 4) (SI). This result is consistent with the complexities outlined above. Dependence of O₂ penetration depth on sediment accumulation rate is consistent with depth of

O₂ penetration depending on organic burial rate; organic flux to the seafloor broadly co-varies with sedimentation rate¹⁸ and at very low sediment accumulation rates, most organic matter is consumed at or near the seafloor and very little remains to be buried^{30, 6}. Dependence of O₂ penetration depth on sediment thickness is consistent with the exponential effect of diffusive distance on diffusive timescale; as sediment thickness increases, O₂ disappears faster than it can diffuse to the greatest depths.

Our results have significant implications for the nature and global distribution of subseafloor life. The persistence of microbial cells and aerobic respiration throughout the entire sediment sequence indicates that there is no depth limit to the biosphere within the sediment of the most oligotrophic ocean region. If active microbial communities and O₂ penetrate to basement throughout the regions shown in figure 4, an aerobic ecosystem is present throughout the sediment column and the upper basement over 15-44% of the Pacific seafloor and 9-37% of the entire ocean (Fig 4) (SI).

Throughout this vast area of O₂ penetration to basement, the predominant microbial activities are aerobic throughout the sediment column, subseafloor rates of organic-fueled respiration and cell abundances are extremely low, and sedimentary oxygen exposure time equals basement age.

This large-scale pattern of subseafloor oxidation may ultimately affect the chemical evolution of Earth's mantle and subduction-related volcanic systems. In subduction zones where deep sediment and basalt of the sinking slab became anoxic early in their history, the principal redox species in the upper portion of the sinking slab include reduced iron, reduced sulfur and reduced organic carbon³¹. In contrast, in subduction zones where dissolved O₂ penetrates (or long penetrated) the sediment sequence and the upper basement (e.g., the Tonga Trench and the Peru-Chile Trench), oxidized iron and manganese are abundant and reduced metal, reduced sulfur and

170 reduced organic matter are largely absent in the upper portion of the sinking slab (SI). The redox
171 state of subducted material influences the extent of mantle oxidation³², which in turn affects
172 magmatic evolution, mineral assemblage and gas speciation in volcanic systems, and the long-
173 term evolution of atmospheric oxygen content³¹.
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Figure Legends

Fig 1. Site locations and time-averaged seasurface chlorophyll-a concentrations [Global SeaWiFS Chlorophyll (mean of September 1997 - December 2004)]. Colored dots mark Expedition 329 site locations: U1365 (orange), U1368 (light blue), U1367 (pink), U1368 (green), U1369 (red)), U1370 (dark blue), and U1371 (black). Colored lines mark site paleopositions with tiny dots marking site locations at 20-myr increments. Sites U1365-U1370 are located within the SPG oligotrophic region and U1371 is located south of the SPG oligotrophic region. White dots mark drill-sites where life in deep subseafloor sediment has previously been examined.

Fig 2. Sedimentary profiles of cell abundance and chemical concentrations⁷, keyed to site location colors in Fig 1: (A) cell concentration (logarithmic scales), (B) dissolved O₂, (C) dissolved NO₃⁻, (D) dissolved PO₄⁻, (E) dissolved inorganic carbon, (F) total organic carbon. Profiles span the sediment column, from seafloor to basement. Because optode-based O₂ measurements are less noisy than electrode-based measurements, the O₂ profiles in (A) are limited to optode data except where sedimentary fabric prevented optode deployment (the lowermost portion of U1367, as well as most of U1368 and U1371). Vertical line in (B) marks the minimum quantification limit (MQL). Open circles in (B) mark data below the MQL.

Fig. 3. Net O₂ reaction rates calculated from O₂ optode data at SPG Sites U1365, U1366, U1367, U1369 and U1370 (SI). Vertical dark blue lines represent mean net O₂ reduction rates, light blue boxes represent the first standard deviation of the mean reaction rate, and vertical lines of open dots with blue margins (ooo) mark intervals where the net O₂ reduction rate appears to be negative, but is indistinguishable from zero (SI). The net

reaction rate is also statistically indistinguishable from zero at sites and depths where the O_2 reduction rate is positive and the light blue boxes intersect the left side of the panel (at these depths the first standard deviation of the rate overlaps with zero). Dissolved O_2 is present throughout the sediment column at all six SPG sites. We did not calculate reaction rates for intervals that lack optode data (the lowermost sediment of U1367 and all of U1368) and intervals disturbed by drilling (cross-hatched intervals). Basaltic basement is marked by dark gray intervals.

Fig 4. Regions where we predict dissolved O_2 and aerobic activity to persist from seafloor to igneous basement, based on mean sediment accumulation rates and mean sediment thicknesses (**SI**). Red dots indicate coring sites where dissolved O_2 diffusively penetrates the entire sediment column (up to 75 mbsf)^{5, 7, 20}. At these sites, sediment thickness was determined by drilling or piston-coring the entire sediment column. Black dots indicate sites where dissolved O_2 disappears in cm to meters below the seafloor^{6, 12}. Yellow dots indicate sites where dissolved O_2 penetrates more than 7 to 34 mbsf and may penetrate to basement but O_2 content is not fully characterized throughout the entire sediment column^{5, 6, 8, 20}. The dark blue area represents the minimum area over which dissolved O_2 permeates the entire sediment sequence and the upper basement; it is defined by combinations of mean sediment thicknesses from standard global maps^{33, 34} (averaged over five-minute grids) and mean sediment accumulation rates comparable to the single-site sediment thicknesses and sedimentation rates where O_2 is known from direct measurements to penetrate the entire sediment sequence. Some sites where O_2 is known to penetrate the entire sediment column are outside this region; this discrepancy results from regionally interpolated estimates of mean sediment thickness^{33, 34} being greater than

the sites' local sediment thicknesses determined by drilling to basement. The light blue area represents the maximum area over which dissolved O₂ permeates the entire sediment sequence from the overlying seafloor; it is defined by combinations where (i) dissolved chemical data indicate that O₂ may penetrate the entire column but chemical data resolution is too low to be certain or (ii) O₂ penetrates the entire sediment column at individual sites, but the regionally interpolated estimate of mean sediment thickness is greater than direct measurements of sediment thickness at the drilled sites. Dissolved O₂ may be present in the igneous basement over an even greater area, due to seawater advection through the basement.

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Supplementary Information

Chemical, physical and geological data

All Expedition 329 chemical, physical and geological data and their measurement protocols are described in reference 1. We present site details and summary results in Table 1. All samples were taken by piston coring in advance of the drill bit¹.

Cell enumeration procedures

We provide the cell-count data for this manuscript in Table 2. These are not the shipboard data in reference 1; the minimum quantification limit (MQL) for the shipboard cell counts ($\sim 10^3$ cells/cm³)¹ was too high to conclusively test the presence or absence of microbial cells in the deepest, oldest sediment of our sites. Consequently, we greatly refined the cell-counting protocols and undertook new counts for this manuscript after the expedition.

For cell enumeration, we routinely took 2-cm³ samples from the center of cut core ends using a 3-cm³ syringe. Each 2-cm³ sediment plug was extruded into a sterile 15-ml centrifuge tube containing 8 ml of 2.5% (w/v) NaCl solution with 2 % (v/v) formalin as a fixative, and then thoroughly shaken to form a homogenous suspension. We performed cell counts by a fluorescence color-based cell enumeration technique using SYBR Green I fluorescent dye². To evaluate low-density populations (below 10^4 cells cm⁻³), we detached cells from sediment by using a multi-layer density gradient technique³. For

blank samples, we replaced the sediment slurry with sterile-filtered TE Buffer. We then counted cell numbers by either manual or computer-based microscopic observations^{2,4}. We defined the MQL as the mean of the blank counts plus three times their standard deviation. As shown in manuscript Fig 2, the MQL for these counts is 130 cells/cm³. We carried out all filter preparation steps, including sonication of sediment and SYBR Green I staining, in an ultra-clean bench placed in a HEPA-filtered clean booth at the Kochi Institute for Core Sample Research, JAMSTEC.

We confirmed the presence of dissolved O₂ throughout the sediment column at all six SPG sites by independently undertaking parallel O₂ measurements for each site using fiber-optic O₂ microsensors (optodes)⁵ and amperometric Clark-type O₂ sensors (microelectrodes)⁶. For consistency, we used optode data for all O₂ calculations and illustration, except for Sites U1368 and U1371, where optode data are limited to small fractions of the sediment column; at those sites, electrode-based measurements are used for illustration.

Calculation of O₂ exposure times

We calculated O₂ exposure times⁷ by dividing O₂ penetration depth by sediment age at the depth of O₂ penetration. For Sites U1365 to U1370, O₂ penetration depth equals total sediment thickness and sediment age at the depth of O₂ penetration equals basement age¹. For Site U1371, we used mean sediment accumulation rate calculated from sediment thickness and basement age to estimate sediment age at depth of O₂ penetration.

Comparison of dissolved O₂ to dissolved NO₃⁻

Because O_2 measurements and NO_3^- measurements were made at different sediment depths and (often) in different holes, we interpolated O_2 concentrations for comparison to NO_3^- in SI Fig 1. Because the diffusion coefficient of dissolved O_2 is about 10% higher than that of NO_3^- at *in situ* temperatures⁸, O_2 diffuses into the sediment slightly faster than NO_3^- diffuses out. This difference is consistent with the slight excess of NO_3^- relative to the Redfield O_2/NO_3^- respiration ratio in at the sites with greatest sediment thickness (U1365 and U1370). To account for the slight difference in diffusion coefficients of O_2 and NO_3^- , the relationship of O_2 and NO_3^- profiles to the Redfield ratio in subseafloor SPG sediment has been quantitatively tested by use of a diffusion-reaction model for the O_2 and NO_3^- data of Site U1370⁹; this test demonstrated that the best-fit NO_3^-/O_2 respiration ratio is indistinguishable from the Redfield ratio throughout the sediment column.

Reaction rate calculations

We quantified vertical distributions of O_2 reaction (aerobic respiration) rates (Table 3) using the MatLab program and numerical procedures of reference 10, with dissolved O_2 concentrations, physical properties (*in situ* temperature, porosity, formation factor) and sediment burial rates from reference 1. For our calculations, we assumed fluid advection rates to be below detection. We derived our diffusion coefficients from *in situ* temperature data¹ and diffusion coefficients of O_2 in seawater at standard temperatures⁸.

The algorithm for calculating reaction rates uses iterative numerical procedures to identify the maximum number of depth intervals with statistically different reaction rates at a prescribed significance level ($\alpha = 0.05$). It explicitly accounts for downhole variation

in physical properties and measurement spacing.

A key variable in this approach is the user-defined minimum number of data points required to define a reaction zone. We used a minimum of either 5 data points (for Sites U1365, U1367, U1369, U1370)) or 7 data points (for Site U1366) to define the minimum reaction zones for our calculations after testing a range of values from 3-21 data points. Our selection of these minimum reaction zones was based on the fit of an algorithm-derived best-fit line to the actual O₂ measurements and the complexity or variability of the defined reaction rate zones. For example, reaction zones defined by fewer than 5 points exhibited nice fits to the actual O₂ data, but the resulting reactions rates were very erratic and unrealistic as the values often alternated rapidly between positive and negative values. This erratic character resulted from rapid changes in slope of the best-fit line used to derive reaction rates. For reaction zones defined by more than 7 points, the best-fit line departed significantly from the actual O₂ measurements, and the reaction zones are typically too broad and underestimated the characteristic reaction rate. Our selection of the 5- or 7-point minimum reaction zone iteration depended on which number of points per minimum zone yielded a lower uncertainty.

We used a Monte Carlo technique to estimate uncertainties in the calculated reaction rates¹⁰. The key variables for the uncertainty estimate are the precision of the O₂ measurement and the number of reaction rate iterations. For our results, we used a 1% measurement precision with 50 iterations.

At Sites U1365, U1369 and U1370, the program calculated brief intervals of net O₂ production for the second reaction zone below the seafloor. These results are essentially indistinguishable from zero (see Table 3 and manuscript Fig 3) and disappear if we

calculate the mean rates over longer data intervals. Their cause is unclear, but their consistent occurrence in the second reaction interval at each site suggests that they may be an artifact of the rapid change in O₂ gradient at this depth and the very small number of data points in this reaction subzone (five).

We calculated per-cell respiration rates from these reaction rates and the cell counts in manuscript Fig 2a. These rates were converted to electron transport rates assuming transfer of 4 electrons per O₂ molecule reduced. We calculated per-cell respiration rates for equatorial Pacific ODP Site 1226 using sulfate reduction rates from reference 10, cell counts from reference 11, and assuming transfer of 8 electrons via reduction of each sulfate ion.

Predicting the global distribution of O₂ and aerobic communities from seafloor to basement

To map where oxygen may be present in the sediment from seafloor to basement, we examined the relationship between O₂ penetration to basement and several relevant variables for which there are globally extrapolated maps; these variables included estimates of mean annual seasurface chlorophyll content¹², particulate organic carbon flux at 2 km waterdepth¹³, seafloor carbon deposition flux¹⁴, organic carbon burial rate¹⁵,¹⁶, seafloor oxygen flux^{15, 16}, oxygen-equivalent carbon flux¹⁶, sediment thickness^{17, 18}, and mean sedimentation rate (calculated as described below). Global extrapolations of seafloor carbon deposition flux, seafloor oxygen flux and sedimentation rate are generally correlated because seafloor carbon deposition flux and seafloor oxygen flux are typically calculated from estimates of sedimentation rate^{e.g., 15, 16}.

Of these variables, we found the combination of mean sediment accumulation rates and sediment thickness best explained the distribution of sites where dissolved O₂ does or does not penetrate from seafloor to basement. Consequently, we used sediment thickness and mean sediment accumulation rates to create a map that predicts where oxygen is likely to be present throughout the entire sediment column. We created the global sediment accumulation rate map by merging sediment thickness grids^{17, 18} and dividing by the basement age grid¹⁹. For these maps, we resampled the original grids¹⁷⁻¹⁹ at a 5-minute grid interval. We used Generic Mapping Tools software²⁰ for grid manipulations and calculations.

To define combinations of sediment thickness and sediment accumulation rate for regions with oxic sediment to basement, we used dissolved O₂ measurements^{1, 21-23} or measurements of dissolved NO₃⁻ concentrations that approximate or exceed local bottom-water values²⁴. At sites where dissolved O₂ measurements approach zero²³, we detrended the data, discarded measurements that lie outside the second standard deviation of the data profile and then determined if zero fell within the second standard deviation of the remaining measurements. To define combinations of sediment thickness and sediment accumulation rate for regions with anoxic sediment at depth, we used profiles of dissolved O₂, NO₃⁻, dissolved manganese, dissolved iron, dissolved SO₄²⁻ and dissolved CH₄ from Deep Sea Drilling Project, Ocean Drilling Program and Integrated Ocean Drilling Program sites²⁵ and profiles of dissolved O₂ from deep piston coring sites^{21, 22}. We examined dissolved chemical profiles from 401 open-ocean DSDP, ODP and IODP drill sites and 24 long-coring sites that geographically bound the regions of possible O₂ penetration to basement (425 total sites). To prevent our results from being affected by

small numbers of bad measurements at individual sites, we limited this analysis to the 149 sites (of the 425) that exhibit smoothly varying concentration profiles for measurements of one or more of these dissolved chemicals. At eight sites, we used dissolved manganese as evidence of O₂ absence, following the standard assumptions that (i) manganese is not reduced in oxic environments^{26, 8} and (ii) dissolved manganese is predominantly reduced [Mn(II) and MnCl⁺²⁷ or ligand-stabilized Mn(III)²⁸]. However, recent studies have recorded dissolved manganese concentrations of a few micromolar in subseafloor sediment with abundant dissolved O₂ in the South Pacific Gyre¹ and the North Pacific Gyre (R.W. Murray, pers. comm. 8/14); whether these concentrations are sampling artifacts or (meta)stable concentrations of dissolved manganese in strongly oxic sediment remains to be determined.

Assessment of influence on subducting sediment

To assess effects of O₂ penetration depth on the chemistry of subducting sediment, we examined published records of sediment composition at DSDP/ODP/IODP sites seaward of subduction zones. In some regions, sediment sequences that we infer to be fully penetrated by O₂ directly enter a subduction zone (e.g., the Tonga Trench and the central and southern portions of the Peru-Chile Trench) (see manuscript Fig 4). In other regions, sedimentation rate and sediment thickness increase as the trench is approached. Despite anoxia in the upper sediment column of the latter regions, a great deal of oxidized material is present deeper in the sediment. For example, porewater chemical profiles indicate that manganese reduction is dominant in the upper sedimentary column of DSDP Site Sites 1149 and 1231, which respectively approach the Izu-Bonin Trench and the

northern Peru-Chile Trench^{29, 11}. In such sequences, dissolved O₂ is not present in the upper sediment column at the time of subduction, but oxidized iron and oxidized manganese may remain abundant in solid phases at greater depth (e.g., DSDP Sites 303, 426, 578 and 581)³⁰⁻³² and dissolved O₂ and NO₃⁻ may be present in the deepest sediment and the upper basement¹¹.

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Table 1. Site properties¹ and depth-integrated O₂ reduction rates below 1.5 mbsf. n.d. = not determinable (no optode data). n.a. = not applicable (O₂ does not penetrate to 1.5 mbsf at U1371).

Site	Latitude	Longitude	Water depth (m)	Seasurface chl-a concentration (mg Chl-a/m ³)	Total sediment thickness (m)	O ₂ exposure time (Ma)	O ₂ consumption in sediment >1.5 mbsf (mol/cm ² /yr)
<i>Within gyre</i>							
U1365	-23°51'	-165°39'	5695	0.057	75	84 - 120	-2.20E-08
U1366	-26°03'	-156°54'	5127	0.054	30	84 - 120	-6.28E-09
U1367	-26°29'	-137°56'	4289	0.035	27	33.5	-2.03E-09
U1368	-27°55'	-123°10'	3740	0.030	16	13.5	n.d.
U1369	-39°19'	-139°48'	5277	0.110	16	58	-3.24E-09
U1370	-41°51'	-153°06'	5075	0.138	68	75	-1.77E-08
<i>Outside gyre</i>							
U1371	-45°58'	-163°11'	5305	0.199	131	0.035	n.a.

Table 2. Post-expedition cell counts for Expedition 329 sites. The cell counts shown in manuscript Fig 2a and used for our per-cell reaction rate calculations (Table 3) were limited to counts from sedimentary intervals described by shipboard scientists as characterized by no visible sediment disturbance or only slight disturbance¹. Counts from sediment described by shipboard scientists¹ as heavily disturbed, moderately disturbed or affected by flow-in were excluded from manuscript Fig 2a and our per-cell calculations. Define disturbance notes of fourth column. The extent of sediment disturbance at each sampling depth is identified in the Disturbance intensity column as follows: H (heavily disturbed), M (moderately disturbed, S (slightly disturbed), F (flow-in). Intervals free of visible disturbance are left blank in the Disturbance intensity column.

Site	Hole	core	section	cm interval	Depth (mbsf)	Cell abundance (cells / cm ³)	Disturbance intensity
U1365	B	1	1	40-50	0.5	5.14×10 ⁵	H
U1365	B	1	2	40-50	2.0	5.29×10 ⁴	M
U1365	B	1	3	40-50	3.5	3.02×10 ⁴	M
U1365	B	2	1	75-85	4.9	1.69×10 ⁴	
U1365	B	2	2	140-150	7.1	2.27×10 ⁴	
U1365	B	2	3	75-85	7.9	2.19×10 ⁴	
U1365	B	2	4	75-85	9.4	1.44×10 ⁴	
U1365	B	2	5	75-85	10.9	1.00×10 ⁴	
U1365	B	2	6	75-85	12.4	1.06×10 ⁴	
U1365	B	2	7	58-68	13.7	8.41×10 ³	
U1365	B	3	1	75-85	14.4	1.31×10 ⁴	S
U1365	B	3	2	75-85	15.9	1.18×10 ⁴	
U1365	B	3	3	75-85	17.4	8.00×10 ³	
U1365	B	3	4	75-85	18.9	1.17×10 ⁴	
U1365	B	3	5	75-85	20.4	1.33×10 ⁴	
U1365	B	3	6	75-85	21.9	4.43×10 ³	
U1365	B	3	7	40-50	23.1	5.22×10 ³	

U1365	B	4	1	75-85	23.9	6.91×10^2	
U1365	B	4	2	75-85	25.4	1.71×10^3	
U1365	B	4	3	75-85	26.9	1.69×10^3	
U1365	B	4	4	75-85	28.4	4.96×10^2	
U1365	B	4	5	75-85	29.9	2.04×10^3	
U1365	B	4	6	75-85	31.4	4.96×10^2	
U1365	B	4	7	25-30	32.4	3.34×10^2	
U1365	B	5	1	75-85	33.4	2.26×10^2	
U1365	B	5	2	75-85	34.9	3.08×10^3	
U1365	B	5	3	75-85	36.4	1.03×10^3	
U1365	B	5	4	75-85	37.9	6.84×10^2	
U1365	B	5	5	65-75	39.3	1.43×10^3	S
U1365	B	5	6	75-85	40.9	6.64×10^2	H
U1365	B	5	7	63-73	42.3	6.67×10^2	H
U1365	B	8	2	40-50	65.5	1.33×10^4	
U1365	B	8	3	55-65	66.6	8.70×10^1	
U1365	B	9	1	140-149	68.4	5.17×10^3	
U1365	B	9	2	40-50	69.0	1.01×10^4	
U1365	B	9	3	40-50	70.5	3.86×10^2	
U1365	B	9	4	40-50	72.0	2.76×10^3	
U1365	B	9	5	40-50	73.5	3.60×10^3	
U1365	B	9	6	50-60	74.7	4.99×10^3	
U1365	B	9	6	50-60	75.1	2.10×10^3	
U1365	B	9	6	50-60	75.6	4.55×10^3	
<hr/>							
U1366	D	1	2	40-50	2.0	2.27×10^4	
U1366	D	1	3	40-50	3.5	1.05×10^4	
U1366	D	1	4	50-60	5.1	5.23×10^4	
U1366	D	1	5	40-50	6.5	5.10×10^4	
U1366	D	1	6	40-50	8.0	1.43×10^5	
U1366	D	1	7	20-30	9.0	1.71×10^4	
U1366	D	2	1	40-50	9.9	3.36×10^4	
U1366	D	2	2	40-50	11.4	8.32×10^3	
U1366	D	2	3	40-50	12.9	1.11×10^4	
U1366	D	2	4	40-50	14.4	5.56×10^2	
U1366	D	2	6	40-50	17.2	2.75×10^3	
U1366	F	2	2	60-70	7.7	9.15×10^2	
U1366	F	2	4	60-70	10.7	1.44×10^4	
U1366	F	3	1	40-50	14.5	5.44×10^3	H
U1366	F	3	2	40-50	16.0	6.67×10^3	
U1366	F	3	3	40-50	17.5	4.99×10^3	
U1366	F	3	4	40-50	19.0	8.74×10^3	
U1366	F	3	5	40-50	20.5	5.75×10^3	
U1366	F	3	6	40-50	22.0	3.55×10^3	
U1366	F	3	7	30-41	23.4	2.48×10^2	

U1366	F	4	1	40-50	24.0	5.61×10 ³	H
U1366	F	4	2	40-50	25.3	5.67×10 ³	
U1366	F	4	2	40-50	25.5	9.81×10 ³	
U1366	F	4	3	40-50	27.0	5.49×10 ³	
U1366	F	4	4	0-10	28.1	7.18×10 ³	
U1366	F	4	5	50-59	29.5	8.84×10 ³	H
U1366	F	4	5	40-50	30.1	7.47×10 ⁵	H
U1367	C	1	1	10-20	0.2	2.31×10 ⁵	S
U1367	C	1	2	60-70	2.2	1.91×10 ⁵	
U1367	C	1	3	60-70	3.7	3.84×10 ⁴	
U1367	C	1	4	60-70	5.2	9.56×10 ⁵	
U1367	C	1	5	60-70	6.7	1.06×10 ³	
U1367	C	2	1	60-70	7.9	2.82×10 ³	S
U1367	C	2	2	60-70	9.4	1.89×10 ³	
U1367	C	2	3	60-70	10.9	5.90×10 ³	
U1367	C	2	4	60-70	12.4	1.70×10 ³	
U1367	C	2	5	60-70	13.9	1.43×10 ³	
U1367	C	2	6	60-70	15.4	4.90×10 ³	F
U1367	C	2	7	50-60	16.8	4.79×10 ³	
U1367	C	3	1	50-60	17.3	1.82×10 ⁴	
U1367	C	3	2	0-5	18.2	5.00×10 ³	
U1367	C	3	3	60-70	20.4	4.38×10 ³	
U1367	C	3	4	60-70	21.9	2.23×10 ³	S
U1367	C	3	6	0-5	23.6	6.04×10 ³	
U1367	D	2	4	50-60	12.5	4.31×10 ⁵	
U1367	D	3	1	80-90	17.8	2.42×10 ⁴	
U1367	D	3	2	10-20	18.6	1.28×10 ⁶	
U1367	D	3	3	10-20	20.1	7.45×10 ⁴	S
U1367	D	3	4	80-90	22.3	2.23×10 ³	S
U1367	D	3	5	80-90	23.8	3.34×10 ²	
U1367	D	3	6	10-20	24.6	2.85×10 ³	
U1368	C	1	1	10-15	0.1	1.13×10 ⁶	
U1368	C	1	2	60-70	2.2	4.04×10 ⁶	
U1368	C	1	3	60-70	3.7	5.45×10 ⁶	
U1368	C	1	4	60-70	5.2	1.05×10 ⁵	
U1368	C	1	5	40-50	6.5	1.85×10 ⁵	
U1368	C	1	6	10-20	7.7	1.04×10 ⁵	
U1368	C	2	1	50-60	8.6	3.43×10 ³	S
U1368	C	2	2	60-70	10.2	5.07×10 ³	S
U1368	C	2	3	60-70	11.7	2.40×10 ³	S
U1368	C	2	4	60-70	13.2	7.85×10 ³	S
U1368	C	2	5	60-70	14.7	2.19×10 ³	

U1368	C	2	6	10-20	15.6	1.31×10^5	H
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U1369	C	1	1	15-20	0.2	4.83×10^5	H
U1369	C	1	2	50-60	2.1	6.18×10^3	H
U1369	C	1	3	50-60	3.6	9.93×10^2	
U1369	C	1	4	50-60	5.1	2.85×10^3	
U1369	C	2	1	50-60	6.6	2.41×10^3	
U1369	C	2	2	50-60	8.1	1.71×10^3	
U1369	C	2	3	50-60	9.6	2.16×10^3	
U1369	C	2	4	50-60	11.1	9.99×10^2	
U1369	C	2	5	50-60	12.6	5.34×10^3	
U1369	C	2	6	50-60	14.1	1.24×10^2	
U1369	C	2	7	45-54	15.5	1.09×10^4	
U1369	E	2	6	90-100	15.3	1.38×10^4	
<hr/>							
U1370	E	1	1	35-42.5	0.4	9.55×10^5	S
U1370	E	1	2	30-40	1.9	1.88×10^5	
U1370	E	1	3	30-40	3.4	1.07×10^5	
U1370	E	1	4	147-152	6.0	8.67×10^4	
U1370	E	2	1	135-140	7.6	2.62×10^3	
U1370	E	2	2	135-140	9.1	8.31×10^3	
U1370	E	2	3	135-140	10.6	2.19×10^3	
U1370	E	2	4	125-130	12.0	7.58×10^3	
U1370	E	2	5	135-140	13.6	1.81×10^4	
U1370	E	2	6	118-123	14.9	4.53×10^3	
U1370	E	3	1	135-140	17.1	8.19×10^3	
U1370	E	3	2	135-140	18.6	6.78×10^3	
U1370	E	3	3	135-140	20.1	2.11×10^3	
U1370	E	3	4	125-130	21.5	5.11×10^3	
U1370	E	3	5	135-140	23.1	2.12×10^3	
U1370	E	3	6	53-58	23.8	2.76×10^3	
U1370	E	4	1	135-140	26.6	3.79×10^3	
U1370	E	4	2	135-140	28.1	1.43×10^3	
U1370	E	4	3	135-140	29.6	1.03×10^3	
U1370	E	4	4	125-130	31.0	2.78×10^3	
U1370	E	4	5	135-140	32.6	6.91×10^2	
U1370	E	5	1	135-140	36.1	8.61×10^3	
U1370	E	5	2	129-134	37.5	5.67×10^3	
U1370	E	5	3	135-140	39.0	6.05×10^3	
U1370	E	5	4	125-130	40.4	7.71×10^3	
U1370	E	5	5	135-140	42.0	8.93×10^3	
U1370	E	5	6	55-60	42.7	5.97×10^3	
U1370	E	6	1	135-140	45.6	2.48×10^3	
U1370	E	6	2	124-134	47.0	3.91×10^3	

U1370	E	6	3	135-140	48.5	1.85×10^3	
U1370	E	6	4	135-140	50.0	1.47×10^3	
U1370	E	6	5	95-100	51.1	7.23×10^3	
U1370	E	8	2	135-140	58.3	2.06×10^3	H
U1370	E	8	3	135-140	59.8	5.08×10^3	F
U1370	E	8	4	125-130	61.2	7.13×10^3	F
U1370	E	8	5	135-140	62.8	3.74×10^3	F
U1370	E	9	1	135-140	63.5	6.57×10^3	F
U1370	E	8	6	135-140	64.3	6.57×10^3	F
U1370	E	9	2	135-140	65.0	4.43×10^3	F
U1370	F	5	3	135-140	39.6	4.87×10^3	
U1370	F	5	4	135-140	41.1	4.06×10^3	
U1370	F	5	5	135-140	42.6	3.90×10^3	
U1370	F	6	2	135-140	47.6	5.50×10^3	
U1370	F	6	3	135-140	49.1	5.68×10^3	
U1370	F	6	4	135-140	50.6	4.41×10^3	
U1370	F	6	5	135-140	52.1	6.17×10^3	
U1370	F	7	1	135-140	55.6	3.65×10^3	
U1370	F	7	2	135-140	57.1	1.45×10^3	
U1370	F	7	3	135-140	58.6	2.29×10^3	
U1370	F	7	4	125-130	60.0	3.94×10^3	
U1370	F	7	5	135-140	61.6	7.09×10^3	
U1370	F	7	6	135-140	63.1	2.19×10^3	

U1371	E	1	1	30-40	0.4	4.91×10^5	H
U1371	E	1	2	30-40	1.9	2.37×10^5	
U1371	E	1	3	30-40	3.4	4.65×10^5	
U1371	E	1	4	135-140	5.9	1.29×10^6	
U1371	E	1	5	135-140	7.4	1.48×10^5	
U1371	E	1	6	52-57	8.0	2.33×10^5	
U1371	E	2	1	135-140	9.6	1.25×10^5	
U1371	E	2	2	135-140	11.1	9.06×10^4	
U1371	E	2	3	135-140	12.6	1.24×10^5	
U1371	E	2	4	135-140	14.1	5.41×10^4	
U1371	E	2	5	90-95	15.1	1.07×10^5	
U1371	E	3	2	135-140	20.6	1.05×10^5	
U1371	E	3	3	125-130	22.0	1.38×10^5	
U1371	E	3	4	135-140	23.6	1.27×10^5	
U1371	E	3	5	115-120	24.9	6.93×10^4	
U1371	E	3	6	41-46	25.4	9.82×10^4	
U1371	E	4	1	135-140	28.6	3.45×10^5	
U1371	E	4	2	135-140	30.1	4.05×10^3	
U1371	E	4	3	135-140	31.6	2.85×10^4	
U1371	E	4	4	135-140	33.1	2.38×10^4	
U1371	E	4	5	115-120	34.4	1.34×10^4	

U1371	E	5	1	135-140	38.1	6.20×10^3	
U1371	E	5	2	135-140	39.6	2.85×10^3	
U1371	E	5	3	135-140	41.1	4.07×10^3	
U1371	E	5	4	135-140	42.6	8.15×10^3	
U1371	E	5	5	60-65	43.3	1.53×10^4	
U1371	E	6	3	135-140	50.6	7.95×10^3	H
U1371	E	6	5	135-140	53.6	5.16×10^3	
U1371	E	7	1	135-140	57.1	5.11×10^3	H
U1371	E	7	2	135-140	58.6	3.61×10^3	
U1371	E	7	3	125-130	60.0	5.20×10^3	H
U1371	E	7	5	135-140	63.1	2.84×10^3	
U1371	E	8	1	135-140	66.6	2.81×10^3	H
U1371	E	8	3	135-140	69.6	5.76×10^3	
U1371	E	8	5	135-140	72.6	6.91×10^3	
U1371	E	9	2	135-140	76.5	1.33×10^4	
U1371	E	9	4	135-140	79.5	2.17×10^3	
U1371	E	9	6	135-140	82.5	2.25×10^3	
U1371	E	10	1	135-140	85.6	2.79×10^3	
U1371	E	10	3	135-140	88.6	6.97×10^3	
U1371	E	10	5	135-140	91.6	1.13×10^4	
U1371	E	11	1	135-140	95.1	2.35×10^4	
U1371	E	11	3	125-130	98.0	2.32×10^3	
U1371	E	11	5	135-140	101.1	9.46×10^3	
U1371	E	12	2	135-140	106.1	6.86×10^2	
U1371	E	12	3	125-130	107.5	4.30×10^3	
U1371	E	12	4	108-118	108.8	6.66×10^3	
U1371	E	13	1	135-140	114.1	3.10×10^3	
U1371	E	13	2	135-140	115.6	6.89×10^3	
U1371	E	13	3	125-130	117.0	3.02×10^3	
U1371	E	13	4	135-140	118.6	7.68×10^3	
U1371	E	13	5	135-140	120.1	1.99×10^3	
U1371	E	13	6	135-140	121.6	1.43×10^4	
U1371	E	13	7	24-29	122.0	5.19×10^3	
U1371	E	14	1	135-140	123.6	1.08×10^4	
U1371	E	14	2	135-140	125.1	3.79×10^3	
U1371	E	14	3	30-40	125.6	4.78×10^3	
U1371	E	14	5	30-40	128.6	3.32×10^2	
U1371	E	14	6	51-56	130.2	1.57×10^4	F

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277 **Table 3.** Vertical distribution of O₂ reaction rates (net respiration) at Expedition 329
278 sites.

Interval	# data points in each zone	Depth (mbsf)	Reaction rate $\pm 1*\sigma$ (mol O ₂ /cm ³ /yr)	Net respiration rate per cell $\pm 1*\sigma$ (mol O ₂ /cell/yr)
Site U1365				
1	4	0.25 - 2.18	-8.68E-11 $\pm$ 3.68E-11	-3.06E-16 $\pm$ 3.76E-16
2	5	2.38 - 4.69	4.63E-12 $\pm$ 1.86E-11	1.97E-16 $\pm$ 7.95E-16
3	6	4.89 - 8.76	-1.52E-11 $\pm$ 8.49E-12	-6.83E-16 $\pm$ 3.82E-16
4	25	8.95 - 12.81	-9.28E-13 $\pm$ 6.13E-12	-9.98E-17 $\pm$ 6.60E-16
		24.95 - 27.20	-9.28E-13 $\pm$ 1.27E-12	-5.46E-16 $\pm$ 7.45E-16
		27.95 - 30.95	-9.28E-13 $\pm$ 3.84E-12	-7.33E-16 $\pm$ 3.10E-16
		31.18 - 37.95	-9.28E-13 $\pm$ 1.95E-12	-8.99E-16 $\pm$ 2.15E-16
5	13	64.45 - 65.95	-8.45E-12 $\pm$ 2.52E-12	-1.26E-15 $\pm$ 1.80E-15
		69.04 - 71.05	-8.45E-12 $\pm$ 1.96E-12	-1.52E-15 $\pm$ 1.13E-15
		74.45 - 75.05	-8.45E-12 $\pm$ 1.96E-12	-2.96E-15 $\pm$ 1.30E-15
Site U1366				
1	7	0.25 - 2.26	-6.27E-11 $\pm$ 2.22E-11	-2.77E-15 $\pm$ 1.44E-15
2	22	2.41 - 2.87	-2.67E-12 $\pm$ 1.25E-11	-8.49E-17 $\pm$ 4.04E-17
		3.03 - 8.27	-2.67E-12 $\pm$ 2.36E-12	-3.93E-17 $\pm$ 5.29E-17
		8.43 - 11.82	-2.67E-12 $\pm$ 2.88E-12	-1.45E-16 $\pm$ 1.79E-16
		11.98 - 14.29	-2.67E-12 $\pm$ 9.78E-12	-2.75E-16 $\pm$ 1.01E-16
		14.45 - 14.76	-2.67E-12 $\pm$ 9.84E-12	-8.90E-16 $\pm$ 3.44E-16
Site U1367				
1	8	0.05 - 0.5	-5.34E-10 $\pm$ 1.70E-10	-2.13E-15 $\pm$ 7.89E-16
		0.65 - 1.10	-5.34E-10 $\pm$ 1.28E-10	-2.79E-15 $\pm$ 1.71E-15
2	19	1.70 - 3.35	-1.55E-12 $\pm$ 1.73E-11	-8.11E-18 $\pm$ 3.11E-18
		3.50 - 3.80	-1.55E-12 $\pm$ 1.65E-11	-3.12E-18 $\pm$ 3.34E-18
		3.95 - 5.75	-1.55E-12 $\pm$ 5.36E-12	-3.24E-18 $\pm$ 1.27E-18
		5.90 - 18.8	-1.55E-12 $\pm$ 9.67E-13	-1.04E-17 $\pm$ 2.72E-17
Site U1369				
1	6	0.3 - 1.32	-1.72E-10 $\pm$ 6.35E-12	-3.56E-16 $\pm$ 2.49E-16
2	5	1.44 - 4.98	4.43E-12 $\pm$ 6.35E-13	1.33E-15 $\pm$ 1.06E-15
3	14	5.10 - 14.00	-3.59E-12 $\pm$ 1.51E-13	-1.69E-15 $\pm$ 1.42E-15
Site U1370				
1	15	0.05 - 1.64	-3.38E-10 $\pm$ 2.45E-12	-5.19E-16 $\pm$ 5.61E-16
2	12	1.81 - 6.23	7.64E-13 $\pm$ 7.42E-13	7.88E-18 $\pm$ 7.74E-18
3	12	6.40 - 15.22	-5.04E-12 $\pm$ 5.32E-13	-6.98E-16 $\pm$ 5.74E-16
4	13	15.40 - 37.29	-2.39E-12 $\pm$ 1.22E-13	-6.08E-16 $\pm$ 4.18E-16
5	37	37.46 - 68.00	-3.28E-13 $\pm$ 3.92E-14	-6.98E-17 $\pm$ 3.14E-17

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280 Fig 1. Dissolved O_2 concentrations vs. dissolved NO_3^- concentrations at Sites U1365-
 281 U1370. Symbol colors as in manuscript Fig 1. Most data closely match the
 282 Redfield ratio [black line³³]. Data from the two sites with thinnest sediment
 283 (youngest) basement (U1367 and U1368) fall below the Redfield line because
 284 their O_2 concentrations are primarily controlled by O_2 loss to the underlying
 285 basement. Data from below 30 mbsf at U1370 fall below Redfield at low O_2
 286 concentrations because NO_3^- concentrations at greater depth are affected by loss
 287 to the underlying basement. These non-Redfield losses (of O_2 to the basement at
 288 U1367 and U1368, and of NO_3^- to basement at U1370) are consistent with non-
 289 heterotrophic (lithotrophic) microbial processes in the basement.

290 Fig 2. Regions where we predict dissolved O_2 and aerobic activity to persist from
 291 seafloor to igneous basement, based on sediment thickness and mean sediment
 292 accumulation rates. (A) Sediment accumulation rate and sediment thickness at
 293 sites where O_2 does or does not penetrate to basement. Sediment thicknesses at
 294 these sites were determined by direct measurement (drilling or piston-coring to
 295 basement). Red dots indicate sites where dissolved O_2 diffusively penetrates the
 296 entire sediment column (up to 75 mbsf)^{1, 21, 24}. Black dots indicate sites where
 297 dissolved O_2 disappears in cm to meters below the seafloor^{1, 11, 21-24}. Yellow dots
 298 indicate sites where dissolved O_2 penetrates more than 7 to 34 mbsf and may
 299 penetrate to basement but O_2 content is not fully characterized throughout the
 300 entire sediment column^{21, 22, 24}. (B) Global map predicted from relationships in
 301 (A), combined with mean sediment thicknesses and mean sediment accumulation
 302 rates defined by standard global maps of sediment thickness^{17, 18} and seafloor

age¹⁹ averaged over fine-minute grids.

The blue areas in 2A and 2B are defined by combinations of sediment thickness and mean sediment accumulation where O₂ is known to penetrate the entire sediment sequence; they represent a minimum estimate of the area over which dissolved O₂ permeates the entire sediment sequence and the upper basement (9% of global seafloor in 2B). The green areas are defined by combinations where O₂ may penetrate the entire column but chemical data resolution is too low to be certain (13% of seafloor in 2B). The orange areas mark combinations of mean sediment accumulation and sediment thickness for which O₂ may penetrate to basement but there are no O₂ or NO₃⁻ data (3% of seafloor in 2B). Because estimated mean sediment thicknesses in five-minute grids throughout the ocean^{17, 18} often differ from local sediment thicknesses determined by drilling or piston-coring to basement, not all sites where O₂ penetrates to basement in 2A are located in the blue areas in 2B. The combined yellow, green and blue areas in both 2A and 2B are defined by the combinations of mean sedimentation rates and sediment thicknesses from the standard sediment-thickness maps^{17, 18} that include all locations where dissolved O₂ is known to locally penetrate the entire sediment column (34% of seafloor in 2B). The sum of the blue, green, yellow and orange regions represents a maximum estimate of the area over which dissolved O₂ permeates the entire sediment sequence from the seafloor (37% of total seafloor in 2B). These collective regions broadly include all areas of abyssal clay and slowly accumulating carbonate ooze in the world ocean.

326 Fig 1.

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329 Fig 2A.

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332 Fig 2B.

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