

# IODP Expedition 329: Life and Habitability Beneath the Seafloor of the South Pacific Gyre

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## Abstract

Integrated Ocean Drilling Program (IODP) Expedition 329 made major strides toward fulfilling its objectives. Shipboard studies documented (1) fundamental aspects of habitability and life in this very low activity subseafloor sedimentary ecosystem and (2) first-order patterns of habitability within the igneous basement. A broad range of post-expedition studies will complete the expedition objectives.

Throughout the South Pacific Gyre (SPG; Sites U1365–U1370), dissolved oxygen and nitrate are present throughout the entire sediment sequence, and sedimentary microbial cell counts are lower than at all previously drilled IODP/Ocean Drilling Program (ODP)/Deep Sea Drilling Program (DSDP) sites. In contrast, at Site U1371 in the upwelling zone just south of the gyre, detectable oxygen and nitrate are limited to the top and bottom of the sediment column, manganese reduction is a prominent electron-accepting process, and cell concentrations are higher than at the same depths in the SPG sites throughout the sediment column.

Geographic variation in subseafloor profiles of dissolved and solid-phase chemicals are consistent with the magnitude

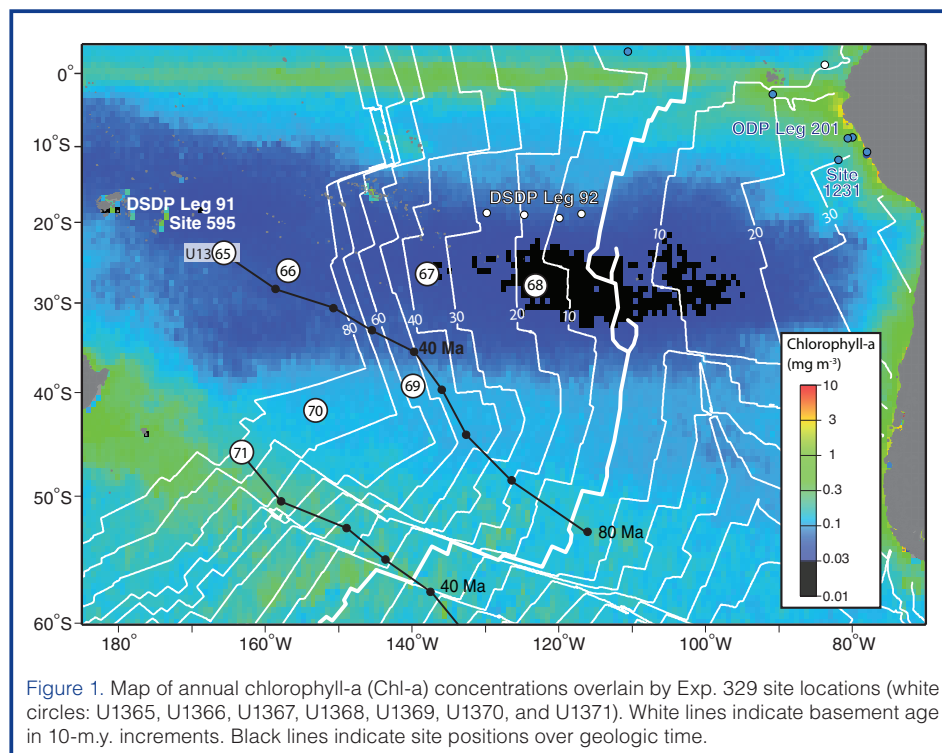
of organic-fueled subseafloor respiration declining from outside the gyre to the gyre center.

Chemical profiles in the sedimentary pore water and secondary mineral distributions in the basaltic basement indicate that basement alteration continues on the timescale of formation fluid replacement, even at the sites with the oldest basement (84–120 Ma at Sites U1365 and U1366).

## Introduction

The nature of life in the sediment beneath mid-ocean gyres is poorly known. Almost all sites where subseafloor sedimentary life has been studied are on ocean margins (ODP Legs 112, 180, 201, and 204 and IODP Expeditions 301, 307, and 323) or in the equatorial ocean (ODP Legs 138 and 201). Despite those studies, the extent and character of subseafloor life throughout most of the ocean remains unknown (National Research Council of the National Academies, 2003). This absence of knowledge is largely due to ignorance of subseafloor life in the major ocean gyres, which collectively cover most of the area of the open ocean.

The SPG is the ideal region for exploring the nature of subseafloor sedimentary communities and habitats in the low-activity heart of an open-ocean gyre. It is the largest of the ocean gyres, and its center is farther from continents than the center of any other gyre. Surface chlorophyll concentrations and primary photosynthetic productivity in the seawater are lower in this gyre than in other regions of the world ocean (Fig. 1; Behrenfeld and Falkowski, 1997). Its surface water is the clearest in the world (Morel et al., 2007). The sediment of this region has some of the lowest organic burial rates in the ocean (Jahnke, 1996). Sediment of this region contains the lowest cell concentrations and lowest rates of microbial activity ever encountered in shallow marine sediment (D'Hondt et al., 2009).



(1–100 m) sedimentary cover that spans thousands of kilometers and >100 m.y. of seafloor age. It is therefore ideal for testing hypotheses of the factors that limit hydrothermal circulation and chemical habitability in aging oceanic crust (sedimentary overburden, basement permeability, and decreasing basal heat flow).

The SPG contains the largest portion of the seafloor that has never been explored with scientific ocean drilling. Consequently, Exp. 329 will advance scientific understanding across a broad front, will help to constrain the nature of crustal inputs to the subduction factory, and will constrain the origin of the Cretaceous Normal Superchron (CNS) and tectonic history of a region as large as Australia. Recovery of sedimentary interstitial waters at several of the proposed sites will provide novel constraints on glacial-interglacial  $p\text{CO}_2$  models.

## Geological Setting

Exp. 329 drill sites span nearly the entire width of the Pacific plate in the Southern Hemisphere between 20°S and 45°S (Fig. 1; D'Hondt et al., 2011a). This oceanic crust was accreted along at least four different plate boundaries (Pacific/Phoenix, Pacific/Antarctic, Pacific/Farallon, and Pacific/Nazca). Crustal ages range from ~100 Ma (Chron 34n) at Site U1365 to ~13 Ma (Chron 5ABn) at Site U1368 (Gradstein et al., 2004). Based on crust age and regional tectonic histories (Larson et al., 2002; Tebbens and Cande, 1997), spreading rates range from slow-intermediate (<20 km m.y.<sup>-1</sup>, half-rate) to ultrafast (>80 km m.y.<sup>-1</sup>, half-rate).

The site locations cover a relatively wide range of crustal ages, spreading rates, and tectonic/volcanic environments. The depth and crustal age of each site correlates well with the predicted depth versus age curve (Stein and Stein, 1994), which suggests the sites are located on representative ocean crust. Calculated spreading rates at each site are somewhat biased toward fast and ultrafast spreading rates (28–95 km m.y.<sup>-1</sup>, half-rate). Surprisingly, the 95 km m.y.<sup>-1</sup> value is one of the fastest spreading half-rates measured globally. The abyssal hill fabric is relatively well defined for most coring sites. However, off-axis volcanism at Site U1368 masked the original seafloor fabric. Sediment thickness ranges from <3 m to 122–130 m and generally increases west and south of our survey area. This sediment thickness trend is consistent with greater sediment cover on older crust and on crust located farther away from the center of the gyre. Sediment at each of the Exp. 329 sites generally appears as pelagic drape, with some localized mass wasting deposits.

## Microbiological Setting

The sedimentary communities and activities of shallow (0–8 meters below seafloor [mbsf]) SPG sediment are unlike those in any sediment of equal depth previously explored by scientific ocean drilling (D'Hondt et al., 2009). A shallow coring survey prior to IODP drilling demonstrated that cell concentrations and organic-fueled respiration in the shallow

sediment of Sites U1365–U1370 are orders of magnitude lower than concentrations in previously examined sediment of equivalent depth (D'Hondt et al., 2009). Dissolved oxygen penetrates extremely deeply (D'Hondt et al., 2009; Fischer et al., 2009).

These pilot results demonstrated that, at least in the shallow sediment, (1) net metabolic activities are low and oxygen is the principal net terminal electron acceptor and (2) biomass is substantially different than in any previously examined deep-sea sediment. In contrast, on the southern edge of the gyre, where sea-surface chlorophyll content is much higher, cell concentrations and dissolved chemical concentrations in the shallow (0–4 mbsf) sediment (D'Hondt et al., 2009) resemble those of ODP Site 1231 (on the northeastern edge of the gyre), where most of the subseafloor interstitial water is anoxic. At these sites the microbial community may be principally supported by oxidation of organic matter coupled to reduction of Mn(IV), Fe(II), and  $\text{NO}_3^-$  migrating up from the underlying basaltic aquifer (D'Hondt et al., 2004; Shipboard Scientific Party, 2003). These results suggested that biomass and microbial activity in subseafloor sediment may vary predictably with sea-surface chlorophyll content.

## Scientific Objectives

The fundamental objectives of Exp. 329 are

- To document the habitats, metabolic activities, genetic composition, and biomass of microbial communities in subseafloor sediment with very low total activity;
- To test how oceanographic factors (such as surface ocean productivity) control variation in sedimentary habitats, activities, and communities from gyre center to gyre margin;
- To quantify the extent to which subseafloor microbial communities of this region may be supplied with electron donors by water radiolysis, a process independent of the surface photosynthetic world; and
- To determine how basaltic basement habitats, potential activities and, if measurable, microbial communities vary with crust age and hydrologic regime (from ridge crest to abyssal plain).

Exp. 329 provided key data and the samples necessary to meet these objectives (D'Hondt et al., 2011a). However, fully meeting these objectives requires post-expedition studies across a very broad front, including but not limited to studies that rely on environmental nucleic acids, microbial cultivations, biogeochemistry, and mineralogy. In combination, the shipboard and post-expedition studies will address several significant questions. Are communities in mid-gyre subseafloor sediment uniquely structured? Do they contain previously unknown organisms? What are their principal sources of metabolic energy? Do their principal metabolic activities and composition vary with properties of the surface world, such as sea-surface chlorophyll concentrations or

organic flux to the seafloor? Is microbial activity sustainable in subsurface basalt by mineral oxidation (e.g., oxidation of iron and sulfur species in the basaltic minerals) for tens of millions of years after basalt formation? Post-expedition studies are building on expedition results to definitively answer these questions (D'Hondt et al., 2011b; Reese et al., 2012; Sauvage et al., 2012; Steele et al., 2012; Ziebis et al., 2012).

The results of Exp. 329 and subsequent shore-based studies are also testing (i) the factors that control evolution of geothermal circulation and chemical alteration in oceanic crust, (ii) models of regional tectonic history (Zhang et al., 2012), (iii) South Pacific paleoceanographic history (Alvarez Zarikian et al., 2012; Amaya et al., 2012; Berger et al., 2012; Dubois et al., 2012; Dunlea et al., 2012; Huang et al., 2012), and (iv) models of glacial-interglacial ocean-climate change (Lado Insua et al., 2011).

### Coring-Drilling Strategy

The general coring strategy was to sample the entire sediment column multiple times at seven sites and to core the upper basement at three sites. The sites (Fig. 1) collectively underlie the full range of surface-ocean productivity conditions present in the SPG, ranging from the extremely low productivity conditions of the gyre center (Site U1368) to the moderately high (for open ocean) productivity at the southern edge of the gyre (Site U1371, at the northern edge of the Antarctic Convergence). This series of sites is composed of two transects, with the first transect centered at ~26°S, beneath the heart of the SPG, and the second transect centered at ~42°S in the southern portion of the gyre (Fig. 1).

The sites in the northern sequence have been continuously far from shore and beneath the low-productivity gyre waters for many tens of millions of years. They provide an ideal opportunity to document the nature of life in subsurface sediment with very low biomass and very low rates of activity. In combination with the southern transect, the northern transect also will allow us to determine how subsurface sedimentary microbial activities and communities vary from gyre center to gyre margin.

The sites in the second transect have been in the southern portion of the present gyre (Sites U1369 and U1370) or south of the gyre (Site U1371) for tens of millions of years. Particularly at Site U1371, chlorophyll-a concentrations and primary productivity are much higher than at all of the sites in the northern transect (Fig. 1). This transect helps document how subsurface sedimentary microbial activities and communities vary from gyre center to gyre margin. Because Site U1371 provides an anoxic standard of comparison for the other sites, it is also crucial for documenting the potential uniqueness (or ubiquity) of the microbial communities and activities that persist in the low-activity, low-biomass sediment beneath the gyre center.

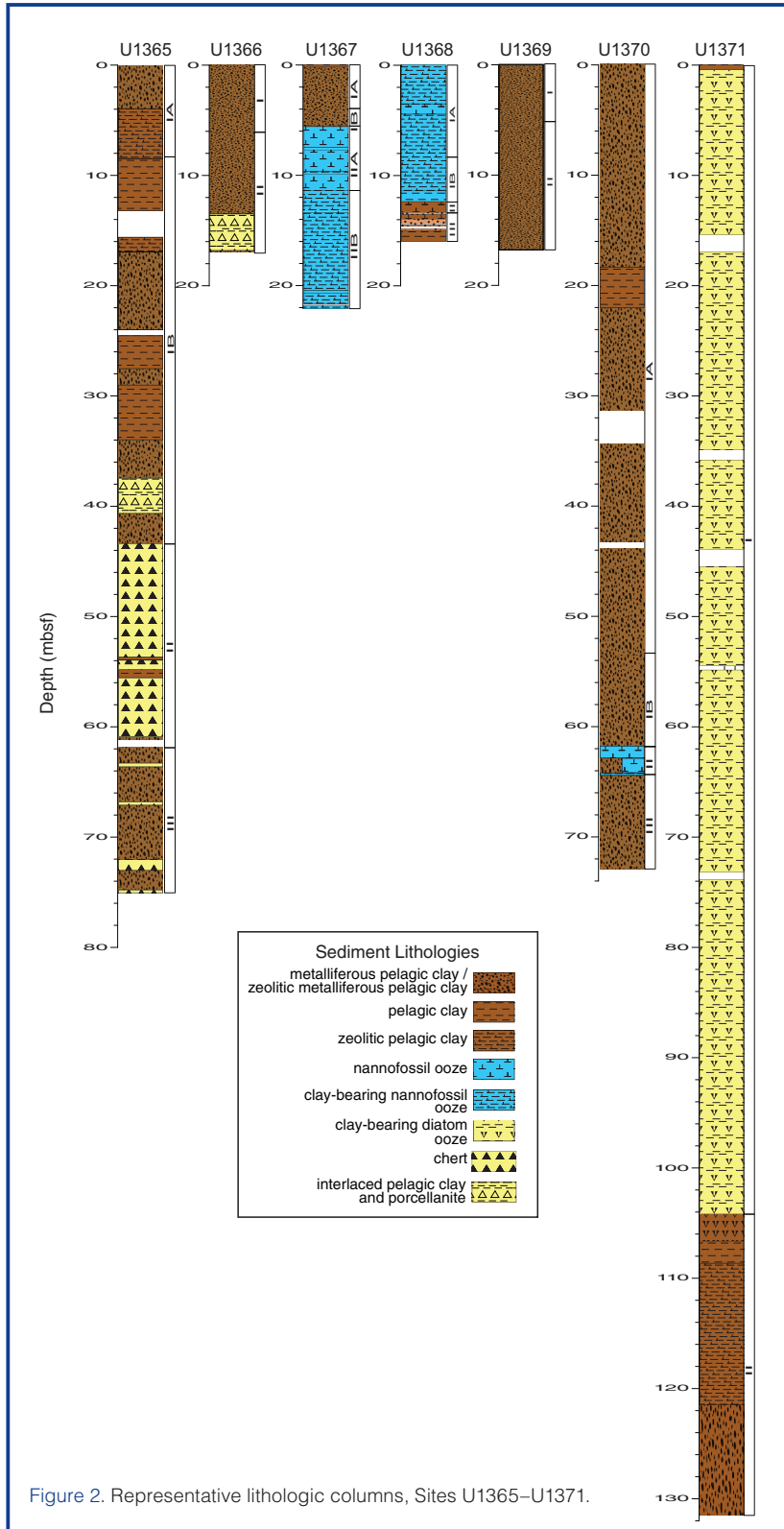


Figure 2. Representative lithologic columns, Sites U1365–U1371.



The northern sequence of sites (U1365–U1368) is placed on basaltic basement of steadily increasing age from east to west (Fig. 1). Basaltic basement ranges in age from 7 Ma to as much as 125 Ma (Site U1365). Basement age of the southern sites ranges from 39 Ma to 73 Ma. Their water depths generally follow the classic curve (Parsons and Sclater, 1977) of increasing water depth with increasing basement age. These sites allow the Exp. 329 science party to document the mineralogic and hydrologic evolution of the basement and its implications for metabolic habitability and microbial communities in ocean crust under very thin sediment cover.

## Expedition Synthesis

### Sediment

The dominant lithology is zeolitic metalliferous clay at the deeper water sites on older basement (58 Ma to  $\leq 120$  Ma) within the gyre (Sites U1365, U1366, U1369, and U1370; Figs. 1, 2). Manganese nodules occur at the seafloor and intermittently within the upper sediment column at these sites. Chert and porcellanite layers are pronounced in the lower half of the sediment column at Sites U1365 and U1366. The dominant lithology is carbonate ooze at Site U1368, the site on youngest basement (13.5 Ma) and, consequently, in the shallowest water. At Site U1371, which lies on relatively old basaltic basement (71.5–73 Ma) just south of the gyre, the dominant lithology is siliceous ooze, although metalliferous zeolitic clay dominates the lowest portion of this sediment column.

The dominant lithology shifts from clay to carbonate ooze at depth in two of the sites (Fig. 2). At Site U1367, the transition from clay to carbonate at 6–7 mbsf marks the time that the site subsided beneath the carbonate compensation depth (CCD) as the underlying basement cooled with age. At Site U1370, carbonate ooze is the dominant lithology for a short interval deposited during planktonic foraminiferal Zone P1. This foraminifer-bearing interval is most simply interpreted as resulting from the CCD diving to greater water depth than the water depth of this site during the early Paleocene interval of low planktonic carbonate production and low organic flux to the seafloor.

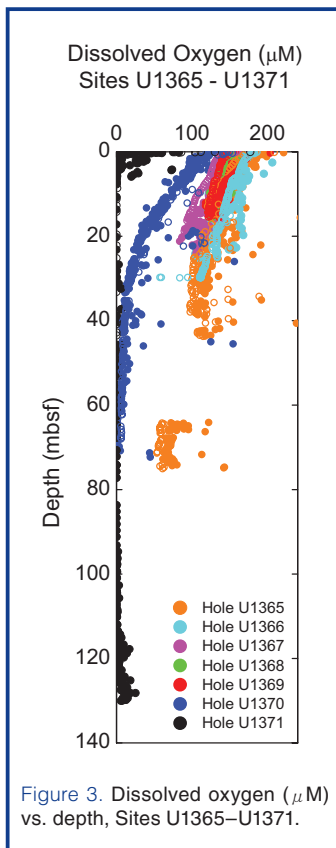


Figure 3. Dissolved oxygen ( $\mu\text{M}$ ) vs. depth, Sites U1365–U1371.

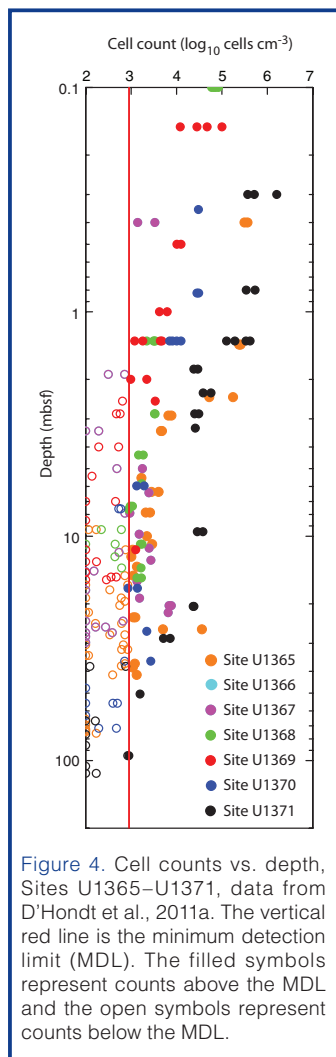


Figure 4. Cell counts vs. depth, Sites U1365–U1371, data from D'Hondt et al., 2011a. The vertical red line is the minimum detection limit (MDL). The filled symbols represent counts above the MDL and the open symbols represent counts below the MDL.

Sediment thickness is generally very low throughout the gyre (Fig. 2). When sites of broadly similar age are compared (Site U1366, 84–120 Ma; Site U1369, 58 Ma; Site U1370, 74–80 Ma; and Site U1371, 71.5–73 Ma), thickness of the sediment column generally increases with increasing distance from the gyre center (Figs. 1, 2).

### Sedimentary Microbial Communities and Habitability

Throughout the SPG (Sites U1365–U1370), dissolved oxygen and dissolved nitrate are present throughout the entire sediment column (Fig. 3), indicating that microbial respiration is oxic throughout the column, as predicted by D'Hondt et al. (2009) and Fischer et al. (2009). The concentration profiles indicate that the subsurface rate of microbial respiration is generally extremely low.

In contrast, at Site U1371 in the upwelling zone just south of the gyre (Fig. 1), detectable dissolved oxygen and dissolved nitrate are limited to just below the sediment/water interface and just above the sediment/basalt interface. Between these interfaces, the sediment is anoxic. Very high concentrations of dissolved (presumably reduced) manganese indicate that manganese reduction is a prominent electron-accepting process throughout most of this sediment column, with very short intervals of iron reduction suggested by minor peaks in dissolved iron concentration associated with local minima in dissolved manganese concentration. The rapid drop of dissolved oxygen and nitrate below their detection limits at the upper and lower edges of this sediment column and the relatively high concentrations of dissolved phosphate within this column indicate that the subsurface rate of microbial respiration is much higher at this site than at the sites located in the gyre.

At the sites located within the gyre (Sites U1365–U1370), microbial cell counts are below  $\sim 10^6$  cells  $\text{cm}^{-3}$  near the seafloor and decrease rapidly with depth (Fig. 4). These concentrations are three or more orders of magnitude lower than at the same sediment depths in all sites previously cored by scientific ocean drilling (Kallmeyer et al., 2012). Microbial cell counts are generally higher at Site U1371 than at the sites within the gyre

(Sites U1365–U1370), but are lower than at all other sites previously drilled.

At the sites in the gyre, total organic carbon (TOC) and total nitrogen decline rapidly with depth in the upper sediment column and are generally constant at greater depth. In contrast, at Site U1371, TOC and total nitrogen are generally much higher than at the other sites at all depths.

The presence of dissolved oxygen, dissolved nitrate, dissolved phosphate, and dissolved inorganic carbon throughout the entire sediment column at all sites in the gyre (Sites U1365–U1370; Fig. 3), indicates that microbial life is not limited by availability of electron acceptors or major nutrients (carbon, nitrogen, and phosphorus) in this sedimentary environment. Although dissolved oxygen is absent from most of the sediment column at Site U1371, the presence of dissolved sulfate, dissolved phosphate, and dissolved inorganic carbon throughout its entire sediment column indicates that microbial life is not limited by availability of electron acceptors or major nutrients in this sedimentary environment either.

**Basalt and Basalt Alteration**

The uppermost basaltic basement at Site U1365 is composed of lava flows, whereas the uppermost basement at Sites U1367 and U1368 is primarily composed of pillow basalt. Some flows at U1365 are only decimeters thick, whereas other flows are tens of meters thick.

Alteration in lava flow units, as evident at Site U1365, appears to be strongly controlled by lithologic structure, with most alteration focused at the flow boundaries (Fig. 5). In contrast, alteration in pillow lava units (the dominant igneous lithologies at Sites U1367 and U1368) appears to be more evenly distributed.

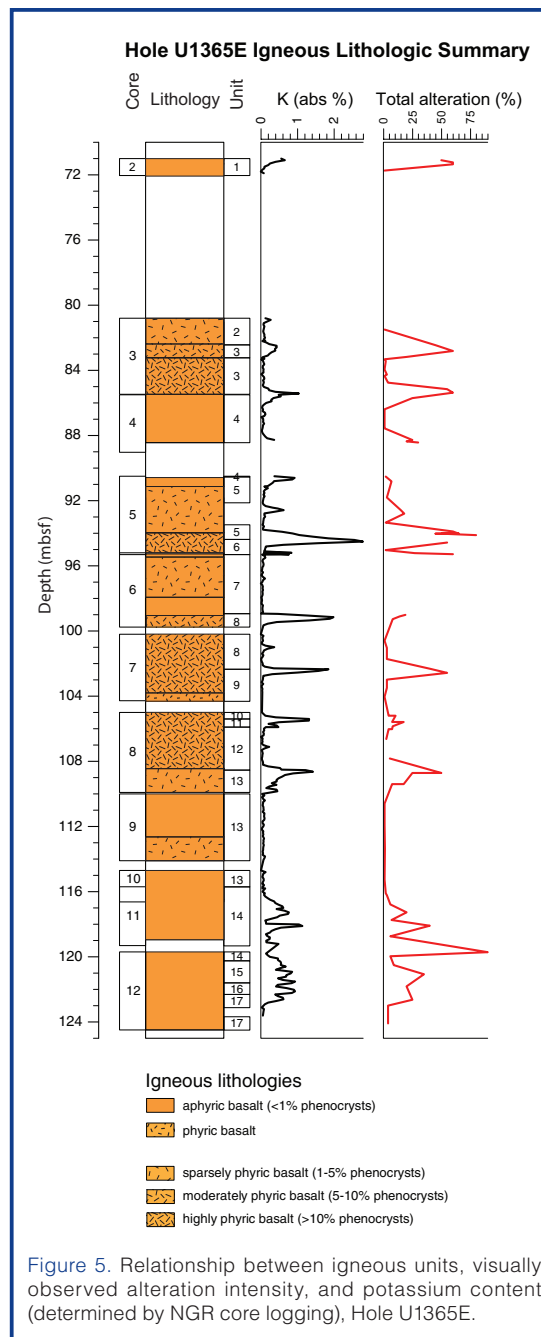
At all sites, the presence of dissolved oxygen in the lowermost sediment at below-deepwater concentrations (Fig. 3) suggests that either (1) basement oxidation has occurred since seawater migrated into the formation or (2) oxygen has been lost to the overlying sediment along the flow path.

At the sites with oldest basement, alteration of the basement basalt continues on the timescale of formation fluid replacement. Natural gamma radiation (NGR) core logs, downhole NGR logs (Site U1368), and chemical analyses of the rock demonstrate that potassium has been consistently taken up during basalt alteration at all three sites where the basaltic basement was drilled (Sites U1365, U1367, and U1368). At the sites with deepest sediment (Site U1365, where basalt was drilled, plus Sites U1370 and U1371, where basalt was not drilled), dissolved potassium concentrations are noticeably lower in the deepest sediment than in the shallow sediment, indicating that (1) dissolved potassium fluxes into the underlying basalt and (2) basalt alteration continues despite the great age of basement at all three sites (84–120 Ma, 74–79.5 Ma, and 71.5–73 Ma, respectively).

At all three sites where basement was cored by rotary core barrel (RCB; Sites U1365, U1367, and U1368), secondary minerals provide evidence of both oxidative alteration (iron oxyhydroxide and celadonite) and oxygen-poor alteration (saponite and secondary sulfides). Some samples have undergone multiple stages of alteration. Late vein infills suggest that alteration may be continuous, or at least occurs intermittently throughout the life of the ocean crust. At Site U1365, the presence in the lowermost sediment of dissolved Mg at below-deepwater concentrations and dissolved Ca at above-deepwater concentrations indicates that basalt-water interaction in the form of Mg exchange for Ca has occurred since seawater migrated into the formation. This exchange may continue to drive late-stage calcite precipitation, despite the great age of basement at this site (80–120 Ma).

**Habitability of Basaltic Basement**

Profiles of dissolved oxygen, dissolved inorganic carbon, dissolved nitrate, and dissolved phosphate in the lowermost sediment at each site indicate that if microbial life is present in the uppermost basalt (Fig. 4), it is not limited by access to electron acceptors (oxygen and nitrate) or major nutrients (carbon, nitrogen, and phosphorus).



## Past Microbial Activity?

Tube-like micro-scale weathering features occur in altered glass from Site U1365. They are arranged in discrete clusters or in masses adjacent to or near fractures and iron oxyhydroxide within the glass. Similar features have been observed in marine basaltic glass elsewhere and attributed to microbial origin (Fisk et al., 1998).

## Technical Advances

Exp. 329 used a wide range of instruments and techniques that have not been used often on scientific ocean drilling expeditions. Details of their application are provided in the “Methods” chapter of the IODP Proceedings (Exp. 329 Scientists, 2011), particularly in the sections on biogeochemistry, microbiology, and physical properties.

Two new technical approaches were used by the Exp. 329 Scientific Party on an experimental basis, with the intention of refining them for future application. The first of these techniques was a new method of cell counting using flow cytometry (Morono et al., 2011). The second was use of NGR core logging for shipboard quantification of absolute concentrations of  $^{238}\text{U}$ -series elements,  $^{232}\text{Th}$ -series elements, and potassium (Dunlea et al., 2013).

## The IODP Expedition 329 Scientific Party

Nathalie Dubois, Tim Engelhardt, Helen Evans, Timothy Ferdelman, Britta Gribsholt, Robert N. Harris, Bryce W. Hoppie, Jung-Ho Hyun, Jens Kallmeyer, Jinwook Kim, Jill E. Lynch, Satoshi Mitsunobu, Yuki Morono, Richard W. Murray, Takaya Shimono, Fumito Shiraishi, David C. Smith, Christopher E. Smith-Duque, Arthur J. Spivack, Bjorn Olav Steinsbu, Yohey Suzuki, Michal Szpak, Laurent Toffin, Goichiro Uramoto, Yasuhiko T. Yamaguchi, Guo-liang Zhang, Xiao-Hua Zhang, Wiebke Ziebis.

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