Surface area measurements of marine basalts: Implications for the subseafloor microbial biomass

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[1]   These first measurements of specific surface area (SSA) of bulk samples of subsurface marine basalts were undertaken to determine the potential area available for microbial colonization. SSA ranged from 0.3 to 52 m^2/g of basalt with the lowest value coming from pillow basalt and the highest value from breccia. The average for massive and pillow basalts combined was 2.3 m^2/g. The total specific surface area of the extrusive volcanic rocks of the ocean crust is estimated to be 10^{24} m^2. This surface area could provide attachment for up to 10^{34} cells if cell density is the same as that of experimentally colonized basalt surfaces. Independent measures and calculations of biomass in basalts suggest that cell densities on surfaces are only 10^{-4} times those in laboratory experiments and, therefore, the surface area of basalt does not limit microbial biomass in the igneous ocean crust. **Citation:**   Nielsen, M. E., and M. R. Fisk (2010), Surface area measurements of marine basalts: Implications for the subseafloor microbial biomass, *Geophys. Res. Lett.*, *37*, L15604, doi:10.1029/2010GL044074.

1.   Introduction

[2]   The surface area of oceanic basalt is an important parameter for evaluating the chemical balance between seawater and the crust as well as understanding the available space for attached microorganisms in the ocean subsurface biosphere. Basalt makes up a 2 to 4 kilometer thick layer of ocean crust that covers 50% to 60% of the Earth's surface and thus basalts are the most abundant rock type in the Earth's crust. The ocean crust also contains the world's largest aquifer through which the entire ocean may circulate about five times per million years [*Johnson and Pruis*, 2003]. Chemical exchange between the ocean and the ocean crust is controlled by the dissolution rate of basalts which is dependent on the specific surface area of the basalts [*Hodson*, 1998]. As seawater circulates through the crust, it dissolves igneous minerals, precipitates secondary minerals, and exchanges cations and anions with crustal rocks. By these processes, the fluid-rock interaction has played an important role in the evolution of the Earth [*Brady and Gíslason*, 1997].

[3]   In addition to the vast potential for water-rock interaction, the ocean crust aquifer may represent one of the largest microbial habitats on Earth. Multiple investigations suggest the presence of an extensive microbial biosphere in the ocean crust including electron microscopy and biomolecular analyses [*Thorseth et al.*, 2001], fluid samples from seafloor observatories [*Cowen et al.*, 2003], *in situ* hybridization, microscopic and phylogenetic analyses [*Santelli et al.*, 2008], and clone libraries and functional gene analyses [*Mason et al.*, 2009]. It is now generally accepted that microorganisms exist in the deep subsurface but the magnitude and activity of the microbial community is poorly constrained. More than 99% of microorganisms in aquifers are attached to mineral surfaces [*Lehman et al.*, 2001; *Whitman et al.*, 1998], so knowing surface area is an important constraint on potential microbial biomass in rocks. In this investigation we evaluate the first reported values of SSA for bulk rock samples recovered from the ocean crust [*Nielsen and Fisk*, 2008] in terms of the potential oceanic crust subsurface biosphere.

2.   Regional Setting, Samples, Methods

[4]   The samples for this study were collected from the Integrated Ocean Drilling Program borehole 1301B (47° 45.228′N, 127°45.827′W in 3.5 Ma crust) on the east flank of Juan de Fuca ridge [*Fisher et al.*, 2005]. The borehole penetrated 318 m into volcanic rock and 69 m of basalt were recovered (22% recovery). Twelve samples from the 318-meter section were used for this study. Three principle rock types were identified: (1) pillow basalt, (2) massive basalt, and (3) mixed basalt and hyaloclastite breccia, all of which are typical of the extrusive pillow and sheet flow layer of the ocean crust. Pillow basalts, were the dominant lithology in hole 1301B, followed in abundance by massive basalts. Basalt-hyaloclastite breccias, which are the fractured and cemented margins of pillow lavas and sheet flows, were a minor component (about 1.5%) of the recovered core. The rocks from borehole 1301B are typical of the majority of extrusive igneous rocks of the ocean crust in terms of mineralogy [*Fisher et al.*, 2005]. That is, they are composed of plagioclase feldspar, pyroxene, olivine phenocrysts and a fine-grained matrix (groundmass) made up of the same minerals plus minor amounts of volcanic glass and other minerals.

[5]   The basalts reacted with seawater, which transformed some phenocryst and groundmass minerals into secondary minerals and amorphous phases and filled some pore space with secondary minerals. In borehole 1301B the phyllosilicates saponite and celadonite were the most abundant secondary minerals. Iddingsite and calcium carbonate were also present and zeolites were tentatively identified in the matrix of the breccia [*Fisher et al.*, 2005]. Shipboard scientists estimated the level of alteration of basalts from borehole 1301B and the pillow lavas and massive lavas were described

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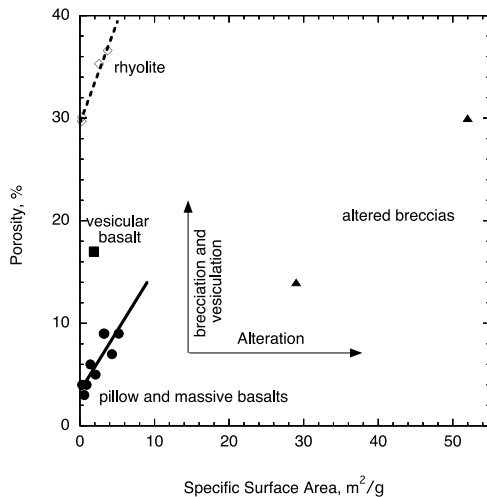
Figure 1. Specific surface area and porosity of basalts from the study area. Circles and square are pillow lavas and massive basalts (square is a vesicular pillow basalt). Triangles are breccias. Solid line is the best fit to the nine solid circles. Porosity data are from shipboard analyses [*Fisher et al.*, 2005]. Surface area measurements are from *Nielsen and Fisk* [2008]. Open diamonds are data for rhyolite from *Yokoyama and Banfield* [2002] and the dashed line is the linear fit of the rhyolite data.

as having either "slight" or "slight to moderate" alteration whereas the two breccia samples were "highly" altered.

[6] Aboard ship, cubes two centimeters on a side were cut from basalts and five physical properties (bulk density, grain density, porosity, thermal conductivity, and seismic velocity) were measured according to standard methods [*Fisher et al.*, 2005]. Values for the samples used in this study are summarized by *Nielsen and Fisk* [2008]. The specific surface area (SSA, m^2/g) of seven pillow lavas, three massive basalts, and two breccias were later measured on the same samples using the Brunauer, Emmett, and Teller (BET) method (ASAP 2000, Micromeritics, USA [*Brunauer et al.*, 1938]). SSA is commonly measured on powders, crushed and granular material, and natural and synthetic clays; and clays are commonly used as standards [*Gregg and Sing*, 1982]. In this study, we measured SSA on subsamples cut from the shipboard samples and kaolinite clay was used as a standard. BET measurements were made with both N_2 and Ar gas, and the results presented here are based on the more precise Ar measurements. Details of the method used and the complete SSA results can be found in an IODP Data Report [*Nielsen and Fisk*, 2008].

3. Results

[7] SSA of the twelve samples ranges from 0.3 to 52 m^2/g. The SSA of pillow basalts and massive basalt are statistically indistinguishable and together average 2.3 ± 1.6 m^2/g. The two breccias have SSA of 52 m^2/g for the shallower sample (86 m into volcanic rock) and 29 m^2/g for the deeper one (300 m into volcanic rock).

[8] Figure 1 shows the relationship of SSA with sample porosity ($r^2 = 0.85$, $P \leq 0.05$) excluding the two breccias and a highly vesicular pillow basalt. This relationship is expected if porosity is made up of small void spaces rather than

macroscopic vesicles. We expected the degree alteration to be correlated with SSA, because secondary phyllosilicates, which have high surface areas, are present as alteration products in these. Zeolites were also tentatively identified in the breccias. This expectation was confirmed because the highly altered samples (the two breccias) had the highest SSA and their surface areas were higher than would be predicted using the porosity-SSA relationship of the less altered samples (Figure 1). On the other hand, there was no correlation between samples identified as having "slight" or "slight to moderate" alteration and SSA.

4. Discussion

4.1. Previous Studies

[9] In previous studies, SSA was determined for certain igneous silicate minerals such as olivine, pyroxene, feldspar [the most common minerals in marine basalts; *Brantley and Mellott*, 2000], alkali feldspars [*Hodson*, 1998], and for soil silicate grains [*Anbeek*, 1992]. SSA of bulk geological samples such as volcanic ash [*Delmelle et al.*, 2005], sandstone [*Colon et al.*, 2004], basalt gravel [*Stevens and McKinley*, 2000; *Tokunaga et al.*, 2003], flood basalt [*Schaef and McGrail*, 2009], rhyolite [*Yokoyama and Banfield*, 2002], granite [*André et al.*, 2009], and marine sediments [*Mayer*, 1994] have also been measured. To our knowledge, these include the only SSA measurements of bulk basalt samples.

[10] As expected, our SSA values are generally higher than those reported by *Brantley and Mellott* [2000] for primary silicate minerals that are typically present in seafloor basalts. They report a range of SSA from 0.5 to 1.8 m^2/g for crushed and size-sorted (40 μm-diameter) plagioclase feldspar, pyroxene, and olivine. The difference between mineral and bulk rock SSA likely reflects the differences in the samples. Those of *Brantley and Mellott* [2000] are monomineralic grains of uniform size and our samples are whole-rocks that contain groundmass, a range of crystal sizes including fine-grained quench crystals, intergranular pore space, and secondary phyllosilicates. Size and arrangement of the pore spaces in the groundmass appears to affect surface area more than the surface areas of minerals that form the rock [*Fischer and Gaupp*, 2004], so the SSA of the bulk rocks is likely to be larger than of primary minerals extracted from basalts. SSA of secondary minerals such as clays (SSA of 11 to 71 m^2/g [*Swartzen-Allen and Matijevic*, 1974]) and zeolites (SSA of 500 to 800 m^2/g [*Yang*, 1987]) could have contributed to the SSA measured in our samples, which have experienced some alteration. Alteration minerals should not be present in monomineralic samples of plagioclase, pyroxene, and olivine, all of which have a lower SSA than bulk basalts.

[11] Our data for pillow and massive basalts fall within the range of previous values for basalt. Crushed basalt gravel had a SSA of 1 m^2/g [*Stevens and McKinley*, 2000], SSA of 11.5 m^2/g was reported for a 2 to 6 mm size fraction of basalt [*Tokunaga et al.*, 2003], and *Schaef and McGrail* [2009] reported values of 20 and 7.8 m^2/g for crushed and sieved samples (2 to 0.42 mm size fraction) of Columbia River flood basalt. *Brady and Gíslason* [1997] report a value of 0.2 m^2/g for a 75 to 125 μm size fraction of pulverized and sieved seafloor basalt. In these four previous studies, SSA was required to determine basalt dissolution rates, and the mineralogy, porosity, bulk density, and amount of
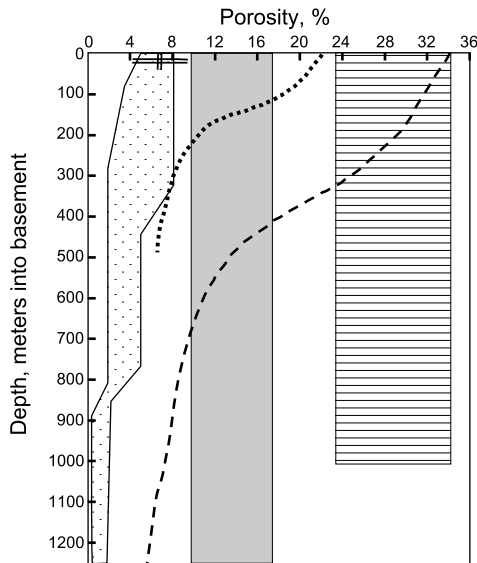
Figure 2. Porosity of the ocean crust. Stippled area, discrete sample porosity from Site 1256D [*Expedition 309 and 312 Scientists*, 2006]; double cross, average and standard deviation of discrete drilled sample porosity for the upper 50 m of the ocean crust from 0 to 170 Ma [*Johnson and Semyan*, 1994]; gray vertical bar, average of four Layer 2 models for porosity based on seismic velocities compiled by *Carlson and Herrick* [1990]; horizontal hatched bar, average three models of porosity of Layer 2A based on seismic velocities compiled by *Carlson and Herrick* [1990]; dotted line is modeled porosity based on logging [*Wilkens et al.*, 1988]; dashed line, modeled porosity based on seismic velocities [*Carlson and Herrick*, 1990].

alteration were not reported. We suspect that the higher values of SSA in the Tokunaga et al. and Schaef and McGrail studies are related to one of these unreported parameters, such as the degree of alteration. The other two reported values [*Brady and Gíslason*, 1997; *Stevens and McKinley*, 2000] are close to those found in this study for the pillow lavas and massive lavas.

4.2. Porosity-SSA

[12] Our measurements of shallow subseafloor basalts show that SSA and porosity are strongly correlated with the exception of one pillow basalt rim (square in Figure 1) and two highly altered breccias (triangles). A relationship between porosity and SSA was also observed in extrusive rocks (rhyolite [*Yokoyama and Banfield*, 2002]) but not in intrusive rocks (granite [*André et al.*, 2009]). The exceptional pillow rim in our study has a SSA similar to other pillow basalts, which suggests the bubbles (vesicles) contribute to the sample's porosity but do not contribute significantly to its SSA (vertical arrow in Figure 1). The breccias have much higher SSA than would be predicted from the porosity-SSA relationship (Figure 1), which suggests that their high degree of alteration contributes to their higher SSA (horizontal arrow in Figure 1). If the porosity-SSA correlation for subseafloor basalts is generally applicable to seafloor extrusive volcanic rocks, then the correlation and the published porosity measurements of seafloor

basalts can be used to estimate the total surface area of the shallow ocean crust (Layer 2A).

[13] The porosity of discrete samples of the upper kilometer of the ocean crust (Layer 2A) is typically 2% to 8% (Figure 2). Porosity decreases with depth and is 1% to 3% in sheeted dikes and gabbros. Porosity of discrete samples is less than porosity determined by downhole logging and seismic methods because these methods include large scale porosity such as interflow voids and fractures [*Carlson and Herrick*, 1990; *Wilkens et al.*, 1991] (Figure 2). This large-scale porosity will not have a significant effect on the SSA of the crust. Although the large-scale porosity decreases with age of the crust [*Carlson and Herrick*, 1990], the porosity of discrete sample does not change significantly with age [*Alt et al.*, 2005; *Johnston and Christensen*, 1997; *Salisbury et al.*, 1996] and possibly increases with age [*Johnson and Semyan*, 1994]. The total specific surface area of basalt of the upper ocean crust Layer 2A (pillow and sheet flows) can be calculated as 10^{24} m^2. This is based on the percent of the Earth's surface that is covered by ocean crust (60%), the thickness of Layer 2A (typically 500 to 1000 m and taken as 500 m for this calculation), the density of basalt of 2.8 g/cm^3 and an average SSA of basalt of 2 m^2/g.

4.3. Implications for the Subseafloor Biosphere

[14] In a seminal paper, *Whitman et al.* [1998] calculated the magnitude of the microbial biosphere for a variety of habitats including aquatic habitats, the oceanic sediment, soil, and the terrestrial subsurface. We seek to extend that work to estimate the biomass of the 500 m thick Layer 2A below the sediments and to determine if specific surface area limits this biomass. We used two methods to estimate cell numbers in the igneous ocean crust – (1) that of *Gold* [1992], which is based on the porosity of rock and (2) the extrapolation of microbial biomass in sea floor basalts [*Einen et al.*, 2008; *Santelli et al.*, 2008] to cell numbers in ocean crust Layer 2A. Using the average porosity of discrete samples in Layer 2A of 4% (Figure 2, the volume of Layer 2A (1.5×10^{23} cm^3), the amount of pore space occupied cells (0.0016%) used by *Gold* [1992], and the average cell volume of 1×10^{-12} cm^3 results in 9×10^{29} cells in Layer 2A. For comparison, *Whitman et al.* [1998] estimate the open ocean contains 1.1×10^{29} cells and marine sediment contains 38×10^{29} cells. Using the same biomass to cell number conversion as Whitman et al., alternate estimates of the number of cells in marine sediments are 7×10^{29} cells [*Parkes et al.*, 1994] and 11×10^{29} cells [*Lipp et al.*, 2008].

[15] In two published studies molecular techniques determined cells/g of rock to be 10^6 to 10^9 [*Santelli et al.*, 2008] and 0.6 to 4×10^6 [*Einen et al.*, 2008]. A calculation based on the lower range of cell numbers per gram of basalt (0.6 to 4×10^6 cells/g), the volume of Layer 2A, and the density of basalt yields 3 to 20×10^{29} cells in Layer 2A. The molecular measurement of biomass and the model calculation based on porosity result in similar numbers of cells in the upper igneous crust. If 99% or more of cells measured by the molecular techniques are attached [*Lehman et al.*, 2001; *Whitman et al.*, 1998] and with a total crust SSA of 10^{24} m^2, the ocean crust is colonized at a density of 0.3 to 2×10^6 cells/m^2.

[16] The density of colonization of the igneous crust based on these two methods is considerably less than measured attached cell densities of 4 to 8×10^9 cells/m^2 on a colonized

basalt fracture in a laboratory experiment [*Lehman et al.*, 2001] and $\sim 10^{10}$ cells/m^2 observed in an electron microscope image of living and fossil microorganisms on a vesicle wall ($\sim 10^{10}$ cells/m^2 [*Kruber et al.*, 2008]). This difference suggests microorganisms colonize the surface area of the shallow ocean basalts at densities that are only 0.01% to 0.02% of that found in laboratory experiments or that much of the surface area of basalts is not accessible to microorganisms. It is clear that a basalt fracture in a laboratory culture is not likely to replicate the physical and chemical conditions in the ocean crust.

[17] Two cautions about this calculation are needed. The first is that molecular techniques were applied to surface basalts [*Einen et al.*, 2008; *Santelli et al.*, 2008] and these basalts are representative of a thin skin of basalts that were exposed to abundant seawater. Deeper in the crust, low flow rates will likely limit the availability of metabolic energy. For this reason, total cell counts in the deeper ocean crust could be less than estimated here. Also porosity that is connected by pore throats that are less than 500 nm in diameter will restrict movement of cells [*Männik et al.*, 2009] and limit the availability of surfaces that can be colonized. While the isotherms for our samples suggested they were mesoporous, they were not amenable to pore-size distribution analyses because of unclosed hysteresis loops and the lack of an asymptote at high relative pressures [*Nielsen and Fisk*, 2008; *Sing*, 1989]. Additional measurements of the surface area of the bulk samples would be required to determine the size distribution of pore throats and estimate how much of the SSA of basalts is available for microbial colonization.

5. Conclusion

[18] The first measurements of specific surface area of bulk samples of basalts show that the average SSA of subseafloor pillow and massive basalts is 2.3 ± 1.6 m^2/g. Brecciated and altered samples can have much higher SSA; up to 52 m^2/g in this study. SSA is important for understanding the potential biomass of the ocean crust, as most subsurface cells are attached. Ocean crust pillow basalts and sheet flows colonized at a level observed on basalt fractures in experiments and fresh basalt glass vesicles in seafloor lavas would result in an ocean crust biomass that is several orders of magnitude greater than would be expected based on basalt microbial biomass [*Einen et al.*, 2008; *Santelli et al.*, 2008] and based on the percent of porosity occupied by microorganisms [*Gold*, 1992].

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