Physical properties of young (3.5 Ma) oceanic crust from the eastern flank of the Juan de Fuca Ridge: Comparison of wireline and core measurements with global data

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[1] We compile and compare petrophysical data from the upper oceanic crust in Hole U1301B, on 3.5 Ma seafloor on the eastern flank of the Juan de Fuca Ridge. Measurements include core-scale (lab-based) and in situ (wireline) measurements of formation porosity, electrical resistivity, bulk density, P wave velocity, and gamma ray emission. A comparison between Hole U1301B data and those from other sites, ranging in age from 5.9 to 167 Ma, demonstrates some important differences. Hole U1301B samples tend to have lower bulk density values for a given porosity than do other young crustal sites. Hole U1301B samples also tend to have higher values of formation factor (the ratio of fluid conductivity to saturated rock conductivity), which may indicate development of tortuous microporosity that is more consistent with samples from older seafloor. Evaluation of global trends of petrophysical properties versus crustal age indicates that Hole U1301B in situ data is consistent with global trends, but core-scale P wave velocity and bulk density values fall below global trend values predicted for young crust. This last observation is likely related to basement topography and the regional exposure, until relatively recently, of basement outcrops around Site U1301. Until most of the exposed basement in this area was buried, hydrothermal circulation extracted much of the lithospheric heat, kept basement fluid temperatures low, and limited the rate and extent of alteration; a subsequent period of higher-temperature fluid circulation with more restricted and less oxidative conditions resulted in enhanced and pervasive alteration of crustal rocks.


1. Introduction

[2] Interactions between the lithosphere and hydrothermal fluids on the flanks of mid-ocean ridges result in considerable modifications in the compositions of crust and water. Much of this ridge-flank circulation occurs at low temperatures, leading to relatively slow reaction rates, but the magnitude and duration of ridge-flank hydrothermal alteration leads to large changes in the physical properties of the crust (particularly porosity, seismic velocity, and permeability) mainly through the formation of secondary minerals that replace original grains and fill void space [e.g., Houtz and Ewing, 1976; Alt et al., 1986; Jacobson, 1992; Alt, 1995; Carlson, 1998; Grevemeyer et al., 1999; Becker and Fisher, 2000; Jarrard et al., 2003; Johnson and Pruis, 2003]. The oceanic crust accumulates a thickening layer of relatively low-permeability sediments as it moves away from the ridge, which eventually limits the free exchange between ocean bottom water and the basaltic oceanic crust. The oceanic crust continues to lose a measurable fraction of lithospheric heat to a mean age of 65 Ma, but some seafloor areas lose heat advectively to much greater ages, and heat can be redistributed regionally by continuing circulation to ages over 100 Ma [e.g., Parsons and Sclater, 1977; Stein and Stein, 1992; Von Herzen, 2004]. Factors that contribute to variations in the distribution and intensity of ridge-flank hydrothermal circulation include the nature of crustal permeability, the properties of accumulating sediments, the extent of off-axis volcanic and tectonic activity, and the characteristics of basement topography, particularly the distribution of outcrops [e.g., Davis et al., 1992; Macdonald et al., 1996; Villinger et al., 2002; Fisher et al., 2003a, 2003b; Spinelli et al., 2004a]. The last factor in the list above is increasingly recognized to be important for facilitating the exchange of low-temperature fluids between the crust and ocean because the forces driving ridge-flank circulation are modest, the hydraulic impedance of ridge-flank sediments is great, and seamounts and other basement outcrops provide highly transmissive...
constrained [e.g., ridge flank hydrothermal processes, where the rates and an unusually young age makes this an ideal area to study].

JFR, on 0.9–3.6 Ma seafloor [Davis et al., 1997a].

Figure 1. (a) Location of ODP Leg 168 and IODP Expedition 301 drill sites; (b) schematic profile through the eastern flank of Juan de Fuca Ridge and location of Leg 168 and Expedition 301 drill sites (modified after Davis et al. [1997a]).

2. Drilling Results From Hole U1301B

[7] Core recovery in Hole U1301B basement averaged 30%. Basement consists of: (1) basalt-hyaloclastite breccia, (2) aphyric to highly phric pillow basalt, and (3) massive basalt [Fisher et al., 2005]. Pillow basalt was the most abundant rock type (Figure 2). The pillows have dominantly hypocrystalline textures with a glassy to microcrystalline groundmass and are sparsely to highly plagioclase ± clinopyroxene ± olivine phric. The pillows are sparsely vesicular, containing 1–5% round gas vesicles. Massive basalts consist of continuous sections of up to 4.5 m of similar lithology. The massive basalts are very similar to the
sparsely phyric pillow basalts. They are sparsely to highly vesicular, with an average of 1%–5% round gas vesicles, up to 3 mm in diameter. Massive unit 6 has a distinct 20 cm wide band in its center with 15% vesicles [Fisher et al., 2005].

Geochemical analysis of basalt samples indicates that they are normally depleted mid ocean-ridge basalt (MORB). Basement rocks are mostly slightly to moderately altered, with secondary minerals (1) lining or filling vesicles and cavities, (2) filling fractures and veins, (3) replacing phenocrysts, or (4) replacing interstitial mesostasis and glass. Thin section observations indicate that the degree of alteration varies between 5% and 25%, and up to ~60% in hyaloclastites. Clay minerals are the most abundant secondary minerals [Fisher et al., 2005].

3. Petrophysical Data Collection Methods

3.1. Shipboard Core Measurements

Sampling strategy and routines for laboratory core measurements and major results of these analyses are described in detail by Fisher et al. [2005] and summarized below. Laboratory methods followed standard ODP and IODP techniques [Blum, 1997]. P wave velocity was measured in three directions (x, y, and z) on 106 cubic samples after samples were cut and saturated with seawater. Only measurements in the vertical (z) direction are presented in this study. The density and porosity of most P wave velocity samples were also determined.

Moisture and density properties were determined on 83 discrete samples on the basis of wet and dry sample masses and volumes. Moisture content was determined by measuring the sample mass before and after removal of interstitial pore fluid through oven-drying for 24 h at 100–110°C. Dry volumes were determined with a gas pycnometer. Because samples are initially saturated with seawater, corrections for the mass and volume of salt were applied. These measurements do not require specific sample geometry, allowing moisture content and density to be determined on samples that were not properly shaped for measurements of P wave velocity (e.g., hyaloclastites). Shipboard core data (those presented herein and numerous additional analyses) are available from the IODP database (http://iodp.tamu.edu/database).
Table 1. List of Samples Analyzed in This Study and Results of Petrophysical Measurements (R_seawater = Resistivity of Samples Saturated With Seawater)\(^a\)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Depth, mbsf</th>
<th>Unit</th>
<th>R_seawater, W/m</th>
<th>Bulk Density, g/cm(^3)</th>
<th>Grain Density, g/cm(^3)</th>
<th>Porosity (fractional)</th>
<th>Formation Factor ± std. dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2R-1W</td>
<td>357.77</td>
<td>IC</td>
<td>58</td>
<td>2.71</td>
<td>2.83</td>
<td>0.07</td>
<td>287 ± 55</td>
</tr>
<tr>
<td>3R-1W</td>
<td>362.46</td>
<td>IC</td>
<td>145</td>
<td>2.72</td>
<td>2.84</td>
<td>0.06</td>
<td>699 ± 95</td>
</tr>
<tr>
<td>4R-3W</td>
<td>369.74</td>
<td>IC</td>
<td>114</td>
<td>2.83</td>
<td>2.93</td>
<td>0.08</td>
<td>543 ± 53</td>
</tr>
<tr>
<td>5R-2W</td>
<td>378.55</td>
<td>IC</td>
<td>111</td>
<td>2.77</td>
<td>2.88</td>
<td>0.06</td>
<td>553 ± 106</td>
</tr>
<tr>
<td>6R-1W</td>
<td>386.83</td>
<td>IC</td>
<td>32</td>
<td>2.60</td>
<td>2.78</td>
<td>0.10</td>
<td>160 ± 30</td>
</tr>
<tr>
<td>11R-1W</td>
<td>424.72</td>
<td>IC</td>
<td>125</td>
<td>2.74</td>
<td>2.84</td>
<td>0.06</td>
<td>614 ± 70</td>
</tr>
<tr>
<td>12R-1W</td>
<td>425.56</td>
<td>IC</td>
<td>81</td>
<td>2.81</td>
<td>2.90</td>
<td>0.05</td>
<td>400 ± 61</td>
</tr>
<tr>
<td>13R-1W</td>
<td>429.98</td>
<td>IC</td>
<td>132</td>
<td>2.83</td>
<td>2.91</td>
<td>0.04</td>
<td>645 ± 84</td>
</tr>
<tr>
<td>14R-1W</td>
<td>431.55</td>
<td>IC</td>
<td>61</td>
<td>2.63</td>
<td>2.78</td>
<td>0.08</td>
<td>309 ± 50</td>
</tr>
<tr>
<td>15R-1W</td>
<td>434.24</td>
<td>IC</td>
<td>172</td>
<td>2.66</td>
<td>2.78</td>
<td>0.07</td>
<td>872 ± 111</td>
</tr>
<tr>
<td>18R-2W</td>
<td>473.14</td>
<td>IC</td>
<td>6</td>
<td>2.98</td>
<td>3.09</td>
<td>0.06</td>
<td>241 ± 36</td>
</tr>
<tr>
<td>18R-3W</td>
<td>473.52</td>
<td>IC</td>
<td>123</td>
<td>2.91</td>
<td>3.06</td>
<td>0.03</td>
<td>631 ± 126</td>
</tr>
<tr>
<td>21R-4W</td>
<td>494.94</td>
<td>IC</td>
<td>145</td>
<td>2.77</td>
<td>2.87</td>
<td>0.05</td>
<td>742 ± 154</td>
</tr>
<tr>
<td>23R-2W</td>
<td>502.55</td>
<td>IC</td>
<td>159</td>
<td>2.88</td>
<td>2.95</td>
<td>0.04</td>
<td>785 ± 138</td>
</tr>
<tr>
<td>25R-2W</td>
<td>511.04</td>
<td>IC</td>
<td>65</td>
<td>2.75</td>
<td>2.89</td>
<td>0.07</td>
<td>325 ± 36</td>
</tr>
<tr>
<td>32R-1W</td>
<td>551.15</td>
<td>IC</td>
<td>100</td>
<td>2.73</td>
<td>2.84</td>
<td>0.06</td>
<td>536 ± 132</td>
</tr>
<tr>
<td>33R-2W</td>
<td>556.52</td>
<td>IC</td>
<td>94</td>
<td>2.72</td>
<td>2.82</td>
<td>0.06</td>
<td>474 ± 63</td>
</tr>
<tr>
<td>35R-2W</td>
<td>566.32</td>
<td>IC</td>
<td>192</td>
<td>2.87</td>
<td>2.93</td>
<td>0.04</td>
<td>983 ± 181</td>
</tr>
<tr>
<td>36R-1W</td>
<td>574.62</td>
<td>IC</td>
<td>86</td>
<td>2.72</td>
<td>2.84</td>
<td>0.07</td>
<td>441 ± 68</td>
</tr>
</tbody>
</table>

\(^a\)Std. dev: standard deviation.

3.2. Onshore Core Measurements

[11] Twenty basalt minicores of 2.54 cm in diameter and 2–3 cm in length were taken during IODP Expedition 301 for post-cruise measurements of electrical resistivity. Samples were taken immediately after splitting of the cores in order to prevent evaporation of pore fluids and thus precipitation of salt in the pore space. Samples were stored in seawater until the measurements were carried out. Measuring routines are principally those as described by Bartetzko et al. [2006]. Two current steel electrodes were placed on the faces of the minicore. Two thin copper wires were wrapped around the sample (distance between the wires 1 cm) to measure electrical potential. A constant current of 100 nA with a frequency of 8.3 Hz was introduced between the faces of the minicore. Two thin copper wires were placed on the faces of the minicore. Two thin copper wires were wrapped around the sample (distance between the wires 1 cm) to measure electrical potential. A constant current of 100 nA with a frequency of 8.3 Hz was introduced between the wires of the minicore. Two thin copper wires were wrapped around the sample (distance between the wires 1 cm) to measure electrical potential. A constant current of 100 nA with a frequency of 8.3 Hz was introduced between the wires of the minicore. Two thin copper wires were wrapped around the sample (distance between the wires 1 cm) to measure electrical potential. A constant current of 100 nA with a frequency of 8.3 Hz was introduced between the wires of the minicore.

3.3. Wireline Logging

[13] Wireline logging operations carried out in Hole U1301B are documented by Fisher et al. [2005, and references therein], and tools are described briefly in this section. All wireline logging data shown in this study are available from IDOP logging database (http://iodp.ldeo.columbia.edu/DATA).

[14] The caliper log is a mechanical measurement of borehole diameter, useful for assessing the reliability of other wireline logs, but also a semi-quantitative indicator of formation brecciation and fracturing, both of which can lead to borehole enlargements and washouts. Electrical resistivity was measured with an induction array tool, which uses a high-frequency alternating current to induce current flow in the formation. Wireline bulk density data were collected with a litho-density tool, which uses an active gamma ray source and a detector to record backscattered gamma rays, the intensity of which is proportional to formation density. The source and detector are pressed against the borehole wall during measurement, so irregular and washed-out intervals generally produce lower-quality data. A apparent formation porosity was measured with a tool that emits fast neutrons that are slowed by collision with particles of similar mass, mainly hydrogen atoms, which are often associated with water in porespaces. P wave velocity data were acquired with a tool having transmission and receiver tool sections separated by 3–4 m, and using frequencies of 8–30 kHz. Natural gamma ray intensity was measured by bismuth germanate scintillation.

4. Results

4.1. Comparison Between Physical Properties From Core Samples and Wireline Logs

[15] Petrophysical properties measured on core samples (shipboard and onshore) and by wireline logging are plotted together in Figure 2. Results of the shore-based core measurements are listed in Table 1. Density and porosity measured on core samples shipboard and onshore agree well. Bulk density varies between 1.86 and 3.03 g/cm\(^3\) (average value 2.76 ± 0.09 g/cm\(^3\)) and porosity varies between 0.02 and 0.30 (average value 0.06 ± 0.03). Grain density is 2.23 to 3.11 g/cm\(^3\) (average value 2.87 ± 0.06 g/cm\(^3\)). P wave velocity from core samples (measured shipboard only) ranges from 3.9 to 5.9 km/s (average value 5.16 ± 0.32 km/s), whereas electrical resistivity (measured onshore only) is 15 to 192 W/m. Formation factor (ratio of fluid conductivity to saturated rock conductivity) ranges from 73 to 983.
[16] Electrical resistivity values measured on core samples are generally higher than those measured by wireline logging (Figure 2). Bulk density values from core samples correspond to the highest density values from wireline logging, and porosity data from core samples are generally lower than estimates based on (neutron) porosity logs. Within the short depth interval where wireline P wave velocity logs are available, core and wireline data agree well and the mean core value is also close to the 5.0 km/s determined by check shot vertical seismic profiling [Fisher et al., 2005].

[17] Petrophysical properties determined from core samples and by wireline logging commonly differ for a variety of reasons, several of which are specific to fractured igneous rocks of the upper oceanic crust [e.g., Broglio and Moos, 1988; Jarrad et al., 2003]. First, core recovery in the upper oceanic crust is notoriously low and biased; recovery for massive units is favored, and regions having the most intense fracturing tend to be underrepresented. Second, core samples allow assessment of petrophysical properties at a spatial scale of centimeters, whereas wireline logs (of the type described in this study) resolves properties at scales of decimeters to meters. The latter may include fractures, breccia zones, and regions of intense alteration. Many of the rare breccia samples recovered on IODP Expedition 301 were dedicated to microbiological analyses [Fisher et al., 2005], but core measurements were completed on one breccia sample, and the results compare favorably to those from geophysical logging (Figure 2, data near 350 m below seafloor - mbsf).

[18] The discrepancy between petrophysical properties determined on core samples and by wireline logging is most apparent in Hole U1301B above 465 mbsf (200 m sub-basement; msb), where the caliper log shows common enlargements of the borehole. Logging tools that require contact with the borehole wall (including bulk density and neutron porosity) often lost contact with the borehole wall within this interval (particularly between 390–410 mbsf), and data from these instruments are considered to be less reliable than at greater depths. However, even at depths where the bulk density and neutron porosity logs cannot interpreted quantitatively, comparison with other wireline records (caliper, electrical resistivity, P wave velocity) suggests a consistent formation response indicative of fracturing, brecciation, and elevated porosity, particularly in the upper 100 m of the logged interval (Figure 2).

[19] Throughout the logged interval, the bulk density of core samples is consistent with the highest values determined in situ (with the exception of the single breccia sample described earlier). Above 465 mbsf, intervals of higher and lower bulk density alternate with a typical spacing of ten to several tens of meters (Figure 2). Below 465 mbsf, the typical bulk density determined by wireline logging is greater, and the low-density intervals are thinner than observed higher in the section.

[20] Although a similar pattern is apparent in core porosity and wireline neutron porosity data, the latter should be viewed cautiously. Porosity measurements made on core samples are based on simple (relatively direct) measurements of mass and volume, subject to the sampling bias described earlier, whereas neutron porosity measurements are based on the interaction between neutrons emitted from the logging tool and atoms in the formation. In clay-free sediments saturated with water this interaction depends mainly on hydrogen atoms in pore fluids. In igneous and metamorphic rocks, the formation tool response can be influenced by the presence of hydrous minerals (particularly secondary phases), neutron absorbers such as chlorine or gadolinium in the rock or the pore fluid/drilling mud (e.g., seawater), and the higher matrix density of the rocks [e.g., Lynes, 1989; Broglio and Ellis, 1990; Harvey and Brewer, 2005]. Although sophisticated logging tools minimize for some of these effects and provide neutron porosity values closer to porosities measured on core samples, neutron porosity values still overestimate porosity in the upper oceanic crust. We also calculated an "apparent porosity" log using the bulk density log and a range of mean grain density values, but this log was only marginally different from the neutron porosity log. Washed out intervals that yielded spurious (high) neutron porosities also yielded spurious apparent porosities. For this reason, the wireline neutron porosity data are not interpreted quantitatively in this study.

[21] Electrical resistivity measured on cores is generally higher than electrical resistivity from the same depth interval measured by wireline logging. In addition to the different measurement scale inherent in the two methods, there are also differences in the measurement principles applied in this case. Core samples were measured at low frequency (8.3 Hz) whereas the wireline logging tool used during Expedition 301 was an induction tool operating at high frequency (26.3 kHz) [Fisher et al., 2005]. The use of different frequencies may have an effect on electrical resistivity, however, the equipment used to measure electrical resistivity on core samples in this study is not suitable to measure electrical resistivity as a function of frequency.

4.2. Relationship Between Density and P Wave Velocity

[22] Figure 3a shows a crossplot of bulk density versus P wave velocity from core measurements for the different lithological units recovered from Hole U1301B. P wave velocity increases with bulk density, consistent with variations in porosity. There are no systematic differences in the general bulk density versus P wave velocity relationship on the basis of lava morphology although two samples from massive unit 6 show surprisingly low density and P wave velocity values. These samples are highly vesicular, up to 15% by volume. Figure 3a shows two regression functions for the Hole U1301B data set based on linear and exponential relationships (r^2 = 0.48 and r^2 = 0.47, respectively).

[23] Figure 3b compares the Hole U1301B data set with data from other boreholes drilled into oceanic crust (Table 2). P wave velocity increases with increasing density in these other data sets (both considered individually and in aggregate), but the Hole U1301B data cluster tends toward lower P wave velocity and density values. For the global data sets, linear and exponential regressions fit about equally well (coefficients of determination r^2 = 0.55 and 0.53). The regression functions for Hole U1301B indicate a more gradual increase in P wave velocity for the same increase in density as the global regression functions. Both the data set for Hole U1301B and the global data set analyzed in this study give a smaller increase in P wave velocity for the same increase in density than the data set...
analyzed by Christensen and Salisbury [1975], which includes basalt samples from Deep Sea Drilling Project boreholes.

4.3. Relationship Between Porosity and Density

Figure 4 shows crossplots of bulk density versus porosity measured on core samples. As expected, bulk density decreases with increasing porosity. As seen with the P wave velocity versus bulk density relationship, there is no systematic variation on the basis of lava morphology. Breccia samples have lower bulk density and considerably higher porosity than the more massive samples, and the vesicular samples from massive unit 6 have higher porosities than most of the other samples. Figure 5 compares bulk density versus porosity from Hole U1301B samples to those from the global data set (Table 2). Most porosities are between 0.015 and 0.08 and most of the bulk densities are between 2.8 and 2.95 g/cm$^3$ and correspond to grain density values between 2.9 and 3.0 g/cm$^3$. The global data follow a relatively consistent trend for porosities ≤0.07, but there is considerable scatter and a weaker bulk density versus porosity trend at higher porosities.

[25] Hole U1301B samples tend toward lower bulk density and higher porosity than the majority of the samples from other holes. More than half of the samples from Hole U1301B show grain density values below 2.9 g/cm$^3$. In contrast, Hole 504B samples tend to have higher bulk density for a given porosity than samples from other holes (Figure 5), suggesting higher grain densities. Measured grain densities of Hole U1301B samples vary between 2.2 and 3.1 g/cm$^3$, but most samples are between 2.7 and 3.0 g/cm$^3$ [Fisher et al., 2005]. The grain density of Hole U1301B samples generally decreases with increasing porosity. This may result from enhanced water-rock interaction and alteration, favored by greater rock surface area and/or higher permeability [e.g., Jarrard et al., 2003].

4.4. Relationship Between Formation Factor and Porosity

Although the formation factor, $F$, is commonly determined as the ratio of fluid conductivity to saturated
rock conductivity, it can also be described as the ratio of tortuosity, $a$, to porosity, $f$ [Kan and Sen, 1987]:

$$ F = \frac{a}{f} \quad (1) $$

Tortuosity is a geometric description that takes into account the indirect paths around mineral grains, sometimes defined as the square of the ratio of pore path length to sample thickness. Tortuosity may also account for variations in pore cross-sectional area and the connectivity of the pore space [e.g., Guguen and Palciauskas, 1994].

The formation factor of core samples from Hole U1301B decreases with increasing porosity, as with other petrophysical properties, there is no separation of units on the basis of lava morphology (Figure 6a). Application of equation (1) to Hole U1301B data suggests tortuosity in the range of 10–40. A comparison of Hole U1301B formation factor and porosity data with the global data set (Figure 6b) places Hole U1301B samples between those from Holes 504B and 896A (5.9 Ma seafloor south of the Costa Rica Rift) and those from Hole 801C (167 Ma seafloor of Pigafetta Basin, West Pacific). The apparent tortuosity of Hole U1301B samples is higher than for the samples from Holes 504B and 896A, perhaps indicating higher microporosity in Hole U1301B samples. Apparent tortuosity values are higher still in samples from Hole 801C, drilled into some of the oldest in situ oceanic crust.

5. Comparison Between Hole U1301B Petrophysical Data and Global Trends

Several studies have evaluated age-dependent changes in physical properties of the oceanic crust. Houtz and Ewing [1976] showed that seismic velocities increase with increasing age within the uppermost layer of the basaltic crust. P wave velocities, electrical resistivities and total gamma ray measured in situ using downhole wireline measurements also tend to increase with basement age [Bartetzko, 2005]. However, velocities and densities measured on drill cores often decrease with age while intergranular porosity increases [e.g., Johnson and Semyan, 1994; Johnston and Christensen, 1997; Jarrard et al., 2003]. These changes in physical properties with the age...
of the crust are interpreted to result mainly from the interaction of water and rock during the ridge-flank hydrothermal circulation. The circulating water causes sealing of voids and fractures with secondary minerals, which influences physical properties on a larger scale (seismic and wireline measurements) [e.g., Houtz and Ewing, 1976; Jacobson, 1992; Bartetzko, 2005]. The increase in P wave velocity and electrical resistivity represents a decrease in porosity, whereas an increase in total gamma ray results from the incorporation of potassium from seawater into secondary minerals. On the scale of core samples, basalt alteration is expressed as an increase in intergranular porosity and replacement of the original mineralogy by secondary minerals [e.g., Johnson and Semyan, 1994].

[30] Figure 7 shows the relationship between physical properties measured on core samples and measured in situ with basement age. P wave velocity, electrical resistivity, bulk density, and total gamma ray measured in situ using wireline tools increase with basement age, while P wave velocity and bulk density measured on core samples decrease. Properties determined with wireline data and core data converge for older crust. In situ properties from Hole U1301B follow global trends, although wireline P wave velocity and electrical resistivity data from Hole U1301B should be treated cautiously because (a) P wave velocity data are only available for the uppermost basement interval of Hole U1301B (85–150 msb) and (b) electrical resistivity was measured by wireline with an induction tool, compared to the galvanic tools used in other holes. Total gamma ray from Hole U1301B is slightly higher than expected from the global trend, but there is considerable variability in global data and total gamma ray intensity may be sensitive to both primary...
Geochemical analyses of fresh volcanic glass, which is considered to reflect primary magma composition, are not yet available for Hole U1301B. Therefore the contribution of primary potassium to total gamma ray cannot be estimated. 

P wave velocity and bulk density core data from Hole U1301B fall below global trends on the basis of crustal age (Figure 7). These low P wave velocity and bulk density values indicate higher alteration of the core samples than expected for young oceanic crust. High values of tortuosity in Hole U1301B samples (Figure 6), compared to core samples from Hole 504B and 896A, may indicate higher microporosity in Hole U1301B samples and also suggest enhanced alteration.

The trends for the core data plotted in Figure 7 were calculated excluding Hole U1301B. Including Hole U1301B results in very low correlation coefficients (−0.33 and −0.42 for bulk density and P wave velocity, respectively). We used the global trend for the core data from Figure 7 to calculate a theoretical mean value for bulk density and P wave velocity for core measurements of samples from Hole U1301B. These estimated values based on the global age-trend are considerably higher than values obtained from direct testing of core samples. For bulk density, the expected value from the age trend is 2.88 g/cm³ (compared to 2.75 g/cm³ from core measurements) and for P wave velocity the expected value is 5.73 km/s (compared to 5.16 km/s from the core data set). In order to check the statistical significance of Hole U1301B core observations, a t test was applied to compare the mean of measured values of core bulk density and P wave velocity from Hole U1301B with values determined from other basement holes (Table 3). The t test shows that the mean values of bulk density and P wave velocity are significantly different at a confidence level of 99% for Hole U1301B compared to other holes drilled into young crust (Holes 504B, 896A, 395A, and 1256D). For holes drilled into older crust (Holes 1224F, 418A, and 801C), differences in mean values compared to Hole U1301B are less significant. This result is consistent with the observation in Figure 7, that...
Table 3. Results of t Test to Determine Statistical Significance of Differences Between Results From Core Samples From Hole 1301B and Similar Samples From Other Ocean Boreholes in Basaltic Basement

<table>
<thead>
<tr>
<th></th>
<th>504B</th>
<th>896A</th>
<th>395A</th>
<th>1256D</th>
<th>1224F</th>
<th>418A</th>
<th>801C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk density</td>
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<td></td>
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<tr>
<td>P wave velocity</td>
<td></td>
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</tr>
<tr>
<td>1301B</td>
<td>99.99</td>
<td>99.99</td>
<td>99.99</td>
<td>99.99</td>
<td>88.00*</td>
<td>98.00</td>
<td>94.10*</td>
</tr>
</tbody>
</table>

*Numerical values are statistically significant. Values < 95% (marked with *) are considered not to be significant.

6. Constraints for the Hydrogeology at Juan de Fuca Ridge

[33] Thermal, pressure, and geochemical (pore fluid) data from Site U1301 and the surrounding region indicate vigorous regional and local convection of basement fluids at (relatively high) temperatures of 60–65°C [e.g., Davis et al., 1997b; Wheat et al., 2000; Davis and Becker, 2002; Fisher et al., 2003a, 2005; Spinelli et al., 2004b; Fisher, 2005]. The extent of fluid alteration determined from borehole and warm-seep fluid samples collected nearby at Site 1026 and Baby Bare outcrop suggests that water-rock interaction is unusually advanced for the age of the crust in this area [e.g., Mottl et al., 1998; Wheat et al., 2004]. Thus regional hydrogeological studies explain the intense alteration observed from samples from Hole U1301B on the core scale, but may not explain the more modest alteration apparent on the in situ scale.

[34] We explain the behavior in physical properties described above by the specific geological situation at the eastern flank of Juan de Fuca at the location of the drill site. Site U1301 is located on a buried basement high that was formed by a combination of tectonically created abyssal-hill topography and off-axis volcanic construction. The influence of ridge-flank volcanic processes on upper-basement topography near Site 1301 is readily apparent on maps of basement relief generated with combined seafloor swath-map and seismic data [e.g., Zühlke et al., 2005; Hutnak et al., 2006]. Site U1301 is located within 5–16 km of several present-day outcrops, and there was much more extensive basement exposure in this area in the last 100–500 ka [Hutnak and Fisher, 2007]. Hydrogeologic conditions during this time would have been very similar to those seen today near the western end of the ODP Leg 168 drilling transect [Davis et al., 1997a; Elderfield et al., 1999]. Baseline alteration and intensity would have increased and become more pervasive once rapid Pleistocene sedimentation buried most of the exposed basement around Site U1301.

[35] The current setting at Site U1301 is similar to that at ODP Site 896 on the southern flank of the Costa Rica Rift. Hole 896A was drilled into a small basement knoll (140–150 m high, 600–900 m in diameter) that sits atop an abyssal hill. This knoll was interpreted as a small volcanic cone emplaced off-axis [Swift et al., 1998]. Drilling results of Hole 896A show that fracturing is stronger and alteration is more pervasive than seen in neighboring Hole 504B [e.g., Harper and Tartarotti, 1996; Wilkens and Salisbury, 1996; Bartetzko et al., 2002]. Much like the basin surrounding Site U1301, basement at Site 896 was likely one of the last areas of seafloor to be buried by accumulating sediments. The rocks drilled in Hole 896A show a more widespread oxidizing alteration and higher water/rock ratios than observed at the neighboring Site 504 [e.g., Laverne et al., 1996]. Petrophysical Investigations on core samples indicate a change in the mechanical properties of the rocks due to microfissuring and/or pervasive alteration, as massive basalts of 896A have higher porosities than those of Hole 504B, and the relation between P wave velocity and density is different in the two holes. At similar densities, core samples from Hole 504B have higher P wave velocities than those of Hole 896A [Wilkens and Salisbury, 1996]. Similar relationships between bulk density and P wave velocity were observed for Hole U1301B. The strong fracturing in Hole 896A also resulted in very low electrical resistivity values measured in situ, which are below the global trend (Figure 7).

[36] Unlike Hole 896A, Hole U1301B does not penetrate what used to be a volcanic edifice; it is several kilometers from the nearest (former) edifice. Instead, the crustal stratigraphy and porosity structure in Hole U1301B is similar in some ways to that from Holes 504B and 395A. Both holes have an upper, highly porous and permeable interval (upper 130 and 300 m of basement, respectively) and a lower, porosity lower interval [e.g., Matthews et al., 1984; Pezard and Anderson, 1989]. Hole U1301B has an uppermost interval (above 465 mbsf) characterized by poor hole conditions, pervasive washouts, and thick zones of low bulk density and electrical resistivity in wireline logs, both indicating high porosity. The deeper (but still upper-crustal) interval is characterized by thinner zones having low bulk density and electrical resistivity. The entire upper crustal section around Hole U1301B is highly permeable [Fisher et al., 2008; Becker and Fisher, 2008], but wireline petrophysical data clearly distinguish between two regions within the upper crust (Figure 2). The high permeability of the upper crust at Site U1301B enables circulation of large quantities of fluids through the crust.

[37] Field studies and numerical modeling suggest that basement outcrops on ridge flanks become favored sites of hydrothermal discharge and recharge once most of the regional basement is buried and outcrops provide the few remaining access points for fluids to enter and exit the crust [e.g., Villinger et al., 2002; Fisher et al., 2003a, 2003b; Hutnak et al., 2006]. Therefore before most of the outcrops were buried around Site U1301, large quantities of water circulated through the rocks, resulting in a long initial period of low-temperature fluid circulation. When much of regional basement was exposed, hydrothermal conditions in basement were relatively open, and geochemical conditions were oxidative. This initial period was followed by a shorter, more recent period of higher-temperature fluid circulation (when basement conditions become more restricted and were less oxidative). In Hole U1301B, the initial alteration phase, resulting primarily in the formation of alteration halos rather than the sealing of fractures, was
long, compared to the second phase of pervasive alteration with sealing of fractures. We therefore observe highly altered rocks on the core scale, as alteration was intense, but a modest alteration on the wireline scale as alteration processes leading to the sealing of fractures were delayed.

7. Summary and Conclusions

[38] Circulation of hydrothermal fluids through the flanks of mid-ocean-ridge basins has important consequences for the composition of crust and water, and considerably changes the physical properties of the crust. In this study, we compared petrophysical data on two scales (core and wireline) from Hole U1301B drilled 3.5 Ma seafloor on the eastern flank of the Juan de Fuca Ridge and compared these data with data from other drillholes into upper oceanic crust ranging from 5.9 to 167 Ma in basement age. Site U1301 is located on a local buried basement high and until relatively recently basement outcrops around Site U1301 were exposed. Until most of the exposed basement in the area was buried, the rate and extent of alteration were limited because hydrothermal circulation extracted much of the lithospheric heat and kept basement fluid temperatures low. A subsequent period of higher-temperature fluid circulation with more restricted and less oxidative conditions followed when sedimentary burial increased and resulted in enhanced and pervasive alteration of crustal rocks. Our comparison shows that this geological situation influences the physical properties of the basement rocks at Site U1301. Bulk density values measured on core samples from Hole U1301B tend toward lower values for a given porosity than at other sites into young crust and also grain density is lower than measured at other sites. Low bulk and grain density values indicate a stronger alteration and enhanced replacement of original minerals by secondary phases than expected for the young basement age. Formation factor values derived from core measurements tend toward higher values for a given porosity and suggest a tortuous micro-porosity probably caused by alteration. Core-scale P wave velocity and bulk density values fall below global trend values predicted from petrophysical properties versus crustal age plots, confirming stronger alteration on the scale of core samples. In contrast, wireline in situ measurements are consistent with values predicted for young crust indicating modest alteration and open fractures. Particularly, the uppermost 200 m of basement in Hole U1301B are strongly fractured and the major fractures, where most fluid flow occurs, are still open. The results show that alteration processes in the oceanic crust can yield different intensities at the different scales of cores (microporosity) and wireline logs (fractures). The hydrothermal history of the crust surrounding Hole U1301B is likely to have been similar to that of other holes drilled into local basement highs. These tectonic-volcanic features would have been some of the last areas of regional basement exposure as the ridge flanks accumulated sediments and became increasingly isolated from the overlying ocean.

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