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Key Points:
- Borehole *T* indicates shallow present circulation, conductive regime > 750 mbsf
- Narrow fault zones have seismic, *T*, resistivity signal indicating localized flow
- Hydration of gabbroic oceanic core complexes is limited below fault damage zone

Correspondence to:
D. K. Blackman,
dblackman@ucsd.edu

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Geophysical signatures of past and present hydration within a young oceanic core complex

Donna K. Blackman[1], Angela Slagle[2], Gilles Guerin[2], and Alistair Harding[1]

[1]Scripps Institution of Oceanography, La Jolla, California, USA, [2]Lamont-Doherty Earth Observatory, Palisades, New York, USA

Abstract Borehole logging at the Atlantis Massif oceanic core complex provides new information on the relationship between the physical properties and the lithospheric hydration of a slow-spread intrusive crustal section. Integrated Ocean Drilling Program Hole U1309D penetrates 1.4 km into the footwall to an exposed detachment fault on the 1.2 Ma flank of the mid-Atlantic Ridge, 30°N. Downhole variations in seismic velocity and resistivity show a strong correspondence to the degree of alteration, a recorder of past seawater circulation. Average velocity and resistivity are lower, and alteration is more pervasive above a fault around 750 m. Deeper, these properties have higher values except in heavily altered ultramafic zones that are several tens of meters thick. Present circulation inferred from temperature mimics this pattern: advective cooling persists above 750 m, but below, conductive cooling dominates except for small excursions within the ultramafic zones. These alteration-related physical property signatures are probably a characteristic of gabbroic cores at oceanic core complexes.

1. Introduction

The circulation of seawater within the oceanic lithosphere enables exchange between the deep and surface components of the Earth's overall chemical/physical system. At slow spreading ridges, long-lived hydrothermal circulation, both high and low temperature, is a more important contributor to this exchange than was previously appreciated, and vent fields are associated with several detachment faults and oceanic core complexes [*German and Lin*, 2004; *McCaig et al* 2010]. The pattern and extent of subseafloor circulation and alteration associated with these features are at present poorly known. Deep drilling and logging can document in situ patterns of alteration and connect them to physical properties, opening up the possibility of more widespread mapping of alteration patterns in oceanic core complexes by geophysical surveys, as well as providing data for more realistic present-day hydrothermal circulation models [*McCaig et al* 2012]. These in turn can test the end stage for core complex cooling rate models derived from clay mineralogy [*Nozaka et al*., 2008] and thermochronology [*Schoolmeesters et al*., 2012]. In this study, new borehole logging results from 1.2 Myr old lithosphere on the flank of the mid-Atlantic Ridge, 30°N, are combined with prior core analyses to assess the distribution of seawater circulation associated with unroofing of intrusive ocean crust by detachment faulting. Such ground truth has not been available previously, and our results, together with the expected global distribution of oceanic core complexes [*Escartín et al*., 2008], have implications for both the thermal and hydration structures of a notable portion of slow-spread crust.

In the latest data, three physical properties in particular record the history of fluid flow within the upper 1.4 km of the Atlantis Massif oceanic core complex: temperature, acoustic velocity, and resistivity. Rock type plays an important role in the extent to which the latter two properties reflect seawater interaction with the crust, so aspects of primary (e.g., proportion olivine) and secondary (alteration) mineralogy also need to be considered. Structural features within the geologic section control the ability of seawater to penetrate the crust. These range from pervasive fractures within the damage zone underlying the exposed detachment fault to narrow, isolated shear zones that occur within the lower half of the drill hole, deeper than 750 meters below seafloor (mbsf), where most of the section does not appear to have hosted significant past or present fluid flow [*Blackman et al*., 2011]. Correlated downhole variations in geophysical, lithologic, and structural properties in the footwall to the detachment allow us to identify present-day fluid pathways and examples of lithospheric hydration that will be retained throughout the plate's history.

The inside corner lithosphere at the eastern intersection of the mid-Atlantic Ridge and the Atlantis transform fault comprises the Atlantis Massif (Figure 1a). Long-lived slip along a rift-parallel normal fault near the spreading axis unroofed the footwall, which rolled over to form the characteristic corrugated dome capped

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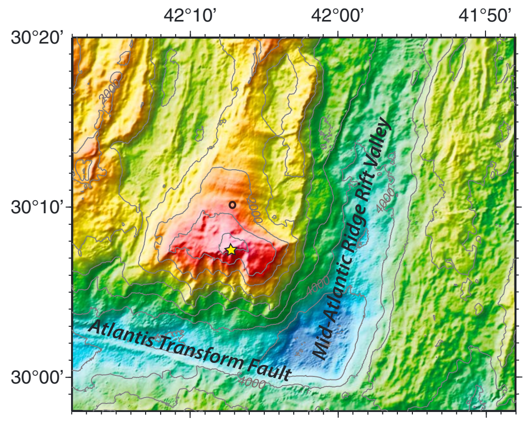

Figure 1. Tectonic setting of Atlantis Massif. Bathymetry (500 m contour interval) shows massif on the inside corner of the ridge-transform intersection. IODP Hole U1309D (circle) and Lost City hydrothermal vent field (star) are shown on the corrugated dome of the core complex.

by the exposed detachment [*Cann et al*., 1997; *Karson et al*., 2006; *Morris et al*., 2009]. Integrated Ocean Drilling Program (IODP) Expeditions 304 and 305 recovered a dominantly gabbroic section from the 1415 m deep Hole U1309D [*Blackman et al*., 2011]. Significant circulation of seawater within the detachment zone has been documented at this and other oceanic core complexes [*McCaig et al*., 2010]. Hydrothermal circulation caused alteration to talc-tremolite schist, which enhanced strain localization in the main detachment shear zone. Present-day hydrothermal venting occurs just below the southern peak of Atlantis Massif, at the Lost City field. Hosted in serpentinized peridotite, these carbonate chimneys vent fluid with temperatures of 40°–90°C [*Kelley et al*., 2005].

Both tectonics and seawater circulation affect temperature within an oceanic core complex, so it is useful to consider a reference model in which neither process has occurred. For Atlantis Massif, a 3-D model accounts for the juxtaposition of the older plate to the south of the Atlantis transform fault that cools the subaxial zone at the southern end of the spreading segment. Plate-driven mantle flow and lithospheric cooling were predicted [*Blackman et al*., 2008] assuming constant thermal diffusivity, half spreading rate of 12 mm/yr [*Pariso et al*., 1996], and top (seafloor) and bottom (100 km) boundaries of 0°C and 1350°C, respectively. Deviations from this reference model indicate the extent of heat advection by fault-controlled uplift of a deeper, warmer section of crust and/or cooling associated with seawater circulation.

2. Downhole Properties of Domal Core of Atlantis Massif

Hole U1309D was designed as a deep hole, with a reentry cone and the upper 20 m cased. Core recovery during Expeditions 304/305 was high, averaging ~75% throughout the hole and 90–100% for several 100+ m sections. Primary lithology includes diabase, the majority of which occurs in the upper 130 mbsf; gabbroic rocks that make up 89% of the section; and olivine-rich rocks (olivine-rich troctolite (ORT), dunite, wehrlite, and harzburgite) account for 6%. ORT occurs in six 1–3 m thick intervals at various depths from 495 to 1235 mbsf. Two additional intervals, each many tens of meters thick, are dominated by ORT with gabbroic rocks interspersed: 310–350 mbsf and 1094–1197 mbsf.

Four phases of logging were carried out in Hole U1309D, three on Expeditions 304/305 in late 2004/early 2005. Instrument and weather problems precluded acquisition of sonic logs, and a vertical seismic profile in the 800–1400 mbsf interval before the drill ship had to leave the site. The last logging phase took place during IODP Expedition 340T in 2012. The 7 year hiatus allowed temperatures in the borehole to return to equilibrium following the disruption by drilling operations. For the first run on Expedition 340T, the Modular Temperature Tool was mounted at the bottom of the Triple Combo tool string (that measured resistivity, density and gamma ray data, and borehole diameter). Run-in rates were slow, so as to minimize mixing and obtain the most accurate temperature reading possible. Additional runs provided sonic velocity, magnetic susceptibility, and a vertical seismic profile. Where coverage overlapped, velocity and resistivity measured during Expedition 340T were in excellent agreement with values obtained during Expeditions 304/305.

The measured temperature is within 8°C of the reference model value throughout the hole (Figure 2), when a shift is applied so that the top model value matches the observed seafloor temperature of ~7°C. The upper part of the section is consistently cooler than predicted but the base is slightly hotter. The interval below ~750 mbsf appears to be in a purely conductive regime, with a linear gradient of 112.6°C/km. Above this depth, the gradient decreases steadily with proximity to the seafloor. Removing the observed deep linear gradient highlights the difference between the conductive lower regime and the advective thermal signature in the upper half of the section (Figure 2b).

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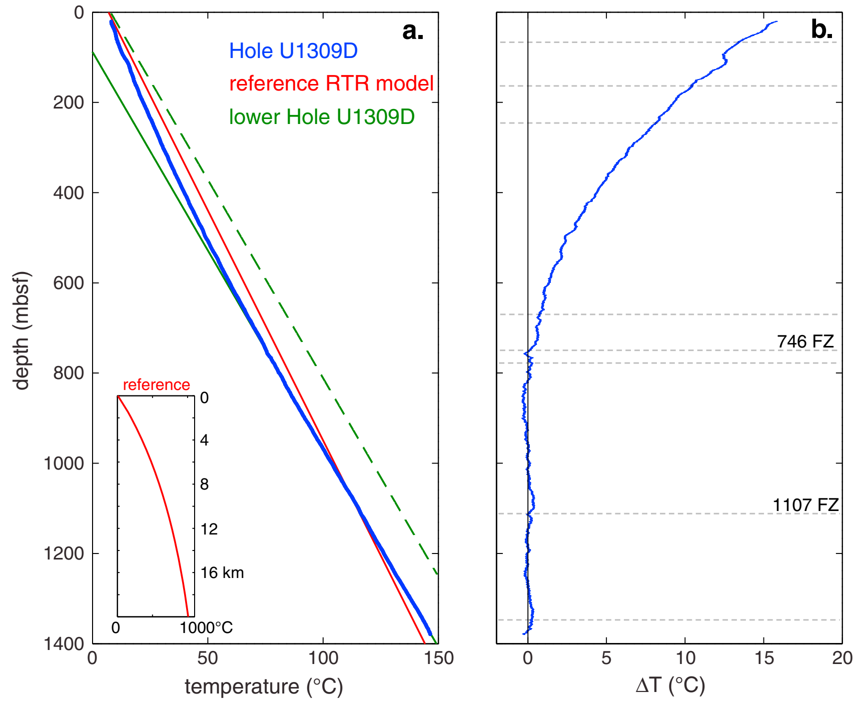

Figure 2. Temperature (*T*)-depth profiles at Hole U1309D. (a) Measured *T* is shown by blue curve. Reference curve (red) is shown for borehole location within 3-D passive mantle flow and lithospheric cooling model (inset shows prediction to 20 km subseafloor). Green curve indicates conductive gradient measured in Hole U1309D for 750–1400 mbsf interval: Solid: actual borehole fluid *T* in this interval projects to −11.5°C at seafloor; dash: gradient shifted to match the observed seafloor *T* of 7°C. (b) Measured borehole fluid *T* minus lower hole gradient. Gray dash indicates fault zones. The *T* deviations occur at 750 and 1107 mbsf faults.

The inference of a conductive regime below ~750 mbsf rests on thermal conductivity being near constant. Shipboard measurements [*Blackman et al*., 2006] indicate an average value of 2.28 ± 0.25 W/m°C for all gabbroic samples tested from 763 to 1285 mbsf. ORT samples have higher thermal conductivity (3.1–3.4 W/m°C in the 1080–1200 mbsf interval). Individual measurement uncertainty is ~0.1 W/m°C. There is no significant conductivity trend across the ~750–1400 mbsf interval; thus, we infer that advective heat loss in the interval is negligible. The heat flow computed from the average thermal conductivity and gradient for the lower part of the section is 257 mW/m^2.

A few small deviations in temperature occur within the broader trends (Figure 2b), two located near subsurface fault zones identified on the basis of core and borehole data [*Blackman et al*., 2006]. These deviations at ~750 and ~1100 mbsf are small, 0.5–0.7°C, but have been detected in these locations on every logging run with a temperature sensor, including on Expedition 305, although it was not clear then that the signals were reliable. The deviation near 100 mbsf is of similar magnitude, but occurs over a wider interval than the other two, and is more difficult to characterize since the broader trend appears to also be changing at shallower depths. There was almost no recovery from 102 to 117 mbsf, which could indicate the presence of highly fractured rock. Variability of 0.2–0.3°C, about a local linear trend, also occurs throughout the interval 480–550 mbsf.

The 746 mbsf fault is the most significant fault in the section. Recovery from the corresponding 5 m interval was very low (17%), and the core obtained was all fault rock. A study of that core and the Expedition 305 logging data [*Michibayashi et al*., 2008] indicate that the fault is centered at 746 mbsf and that the permeability of the fault rock is high, relative to the adjacent gabbroic rock. Higher permeability means locally increased pore water. The observed temperature deviation of the borehole fluid indicates that fluids originating elsewhere currently percolate through this fault zone.

Fault rock was also recovered from 1107 mbsf, and the intensity of cataclastic structures was much higher there than in the surrounding rocks [*Blackman et al*., 2006]. The zone of deformation is narrow, ~12 cm, and is

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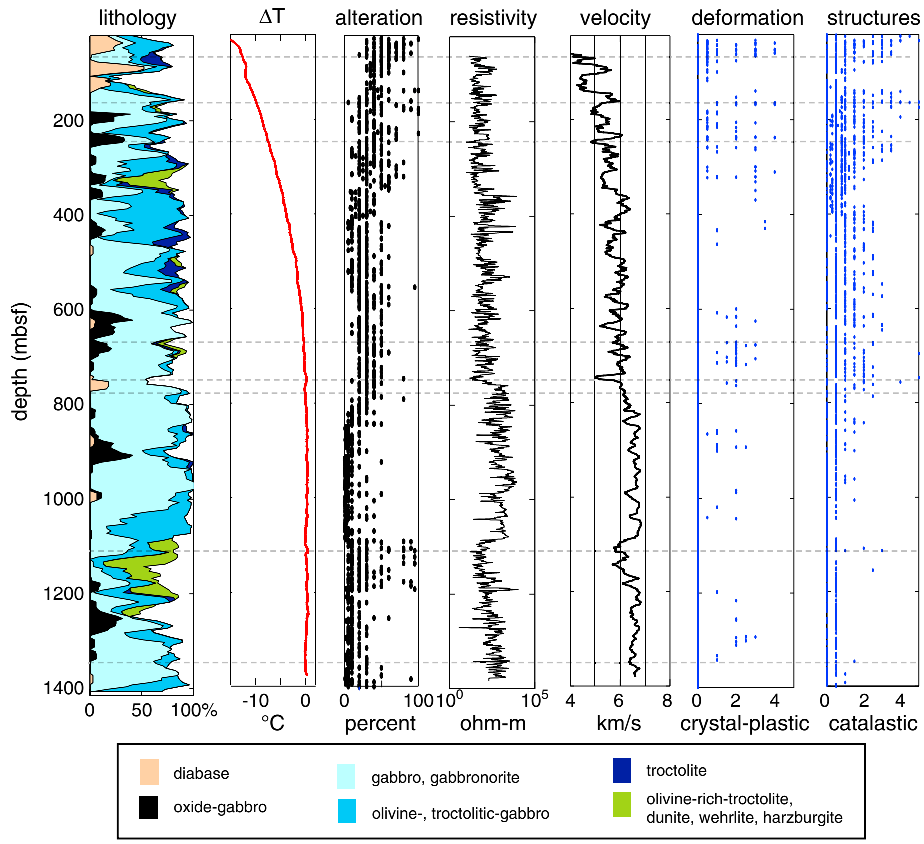

Figure 3. Downhole properties at Hole U1309D. Lithology column shows percentage of each recovered rock type, 20 m running boxcar average; white indicates unrecovered section. ΔT shows difference between thermal gradient in lower hole (>750 mbsf) and measured borehole fluid temperature. Alteration shows overall value of individual core pieces from Expedition 304/305 visual descriptions. Resistivity plot shows *R*5 (deepest penetration) value with 1 m running boxcar average. *P* wave velocity has 10 m running boxcar filter applied. Intensity (0–5, low–high) of crystal-plastic and cataclastic structures identified in core on Expedition 304/305 is shown by blue dots. Gray dashed lines indicate fault zones identified from cores/logs [*Blackman et al.*, 2006].

well constrained due to good recovery. Again, this is the site of a local temperature deviation, which indicates ongoing fluid percolation.

The general increase in seismic velocity with depth is punctuated by local variations that are associated with alteration and/or deformation structures within the section. Borehole compressional wave speed (V_p) increases irregularly from 5 to 6 km/s over the interval 100–350 mbsf. Average V_p of 6.0 km/s characterizes the 350–800 mbsf interval. Most of the 800–1400 mbsf interval has an average V_p of 6.6 km/s; the section 1080–1220 mbsf is slower by 0.5–1 km/s. Downhole variation in velocity corresponds closely with overall degree of alteration (Figure 3). This is evident for the large intervals just described, where sections hundreds of meters thick can be described in terms of average V_p. It also holds for a few 10–100 m thick intervals, where local alteration is higher than in the surrounding rocks. The deeper ORT zone (1094–1197 mbsf) is the clearest example, with a drop in V_p throughout the zone, as well as local variability, where values are lowest in intervals with the greatest overall alteration. The shallower ORT zone (310–350 mbsf) also has lower V_p than the adjacent rock. The increase in V_p below the base of this zone is greater than that into the section above the ORT. Again, this velocity increase is coincident with a drop in the overall alteration of the section, averaged over 5 m intervals, from 40–50% at shallower depths to 15–25% below 350 mbsf. Velocity also decreases within a narrow interval about the 746 mbsf fault zone (Figure 3).

Resistivity shares the first-order correspondence with alteration and structure observed for velocity, but second-order differences in the downhole signatures of these properties also occur in Hole U1309D. Unaltered gabbroic intervals have the highest resistivity (10^3–$10^{3.5}$ Ω m). The pervasively altered

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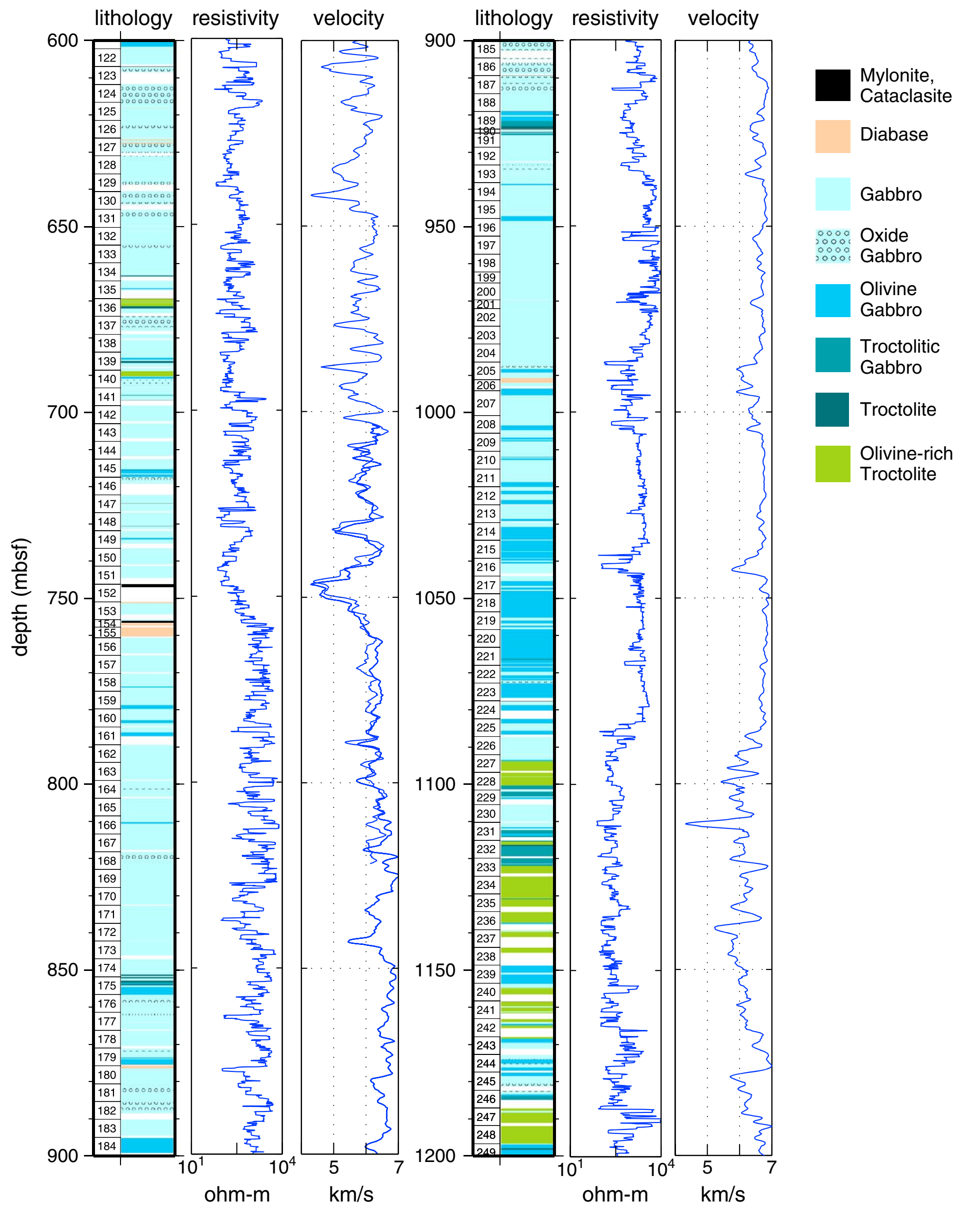

Figure 4. Expanded view of core lithology, wall rock resistivity, and wall rock *P* wave velocity for a portion of Hole U1309D (600–1200 mbsf). Core pieces plot at the top of cored interval (core # at left); white shows unrecovered section. A boxcar filter was employed for 1 m running average of the logged deep resistivity and velocity.

(andfractured) section above 300 mbsf has the lowest resistivity ($10^{1.5}$–$10^{2.5}$ Ω m). Resistivity increases rapidly below the base of the shallower ORT zone but alteration does not appear to be the determining factor. Whereas V_p increases steadily from the base of the altered ORT zone, resistivity does not jump in value from 10^2 to 10^4 Ω m (1 m running average) until ~10 m deeper (360 mbsf), at the top of an olivine gabbro interval. The intervening gabbro and oxide gabbro have resistivity similar to that of the ORT zone. Around the 746 mbsf fault, resistivity drops steadily from 730 to 746 mbsf, the local low, and then climbs steadily until 760 mbsf, which coincides with the top of a thin diabase unit (Figure 4; 1 m running average). V_p, in contrast, has a narrow low of 5 km/s centered at 730 mbsf, climbs back to 6.5 km/s by 735 mbsf, and then displays a roughly symmetric, 25 m wide low reaching <5 km/s centered on the fault. As for resistivity, the diabase unit marks the apparent boundary of fault-related changes in velocity. Both resistivity and V_p begin to decrease at 1080 mbsf, associated with a gabbroic unit that is adjacent to the top of the ORT zone. Resistivity drops more sharply, from $10^{3.5}$ to $10^{2.5}$ Ω m, and remains near the latter

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value through 1165 mbsf. V_p is more variable throughout this interval, but all values are notably lower than the steady 6.7–6.8 km/s of the overlying ~175 m. Resistivity increases below 1165 mbsf but continues to be somewhat variable, though with an overall increase toward the bottom of the hole where values are near the maximum reached in the 800–1080 mbsf interval. The 10 m running average of V_p shows a leveling off in value, with a 6.6 km/s average for the lower portion of the hole (Figure 3).

3. Discussion

Only a few holes in the history of deep-sea scientific drilling have provided in situ seismic velocity data, the subsurface property most commonly used to infer structure from regional surveys, in lower oceanic crustal rocks. Hole 735B on the flank of the Southwest Indian Ridge is the only other drill site with a significant intrusive crustal section. Hole 1256D on the flank of the equatorial East Pacific Rise is the only hole where a complete sampling of intact upper oceanic crust and of the uppermost plutonic section was achieved. Sonic logs were recorded with limited levels of success in these two holes [*Iturrino et al*., 2002; *Guerin et al*., 2008], so the logs recorded during Expedition 340T in Hole U1309D represent the most complete profile currently available for examining the role of hydration and alteration on the physical properties of lower oceanic crust.

The new logs and prior core description data indicate that the fault zone at ~750 mbsf marks a boundary between distributed present-day circulation in the upper section and essentially conductive thermal conditions in the deeper section. Prior petrologic analyses showed that alteration below 800 mbsf exists only in local zones around igneous contacts, faults, and portions of the ORT zone [*Blackman et al*., 2011; *Nozaka and Fryer*, 2011]. The strong correlation of borehole V_p and alteration in Hole U1309D means that high-resolution seismic methods in the shallow crust may be able to contribute to quantifying the extent of hydration of the oceanic lithosphere. The intrinsically low reflectivity amplitude of alteration boundaries would require that such intervals be a few hundred meters thick and have greater lateral extent to be visible. Recent waveform inversion results at the Atlantis Massif [*Harding et al*., 2012] affirm a prior finding at the Kane oceanic core complex [*Canales*, 2010], where a lens of lower velocity material can extend a few kilometers within the footwall to a core complex detachment fault. However, even if laterally extensive, the scale of the deeper, highly altered ORT in Hole U1309D is near the minimum thickness and impedance contrast for a low velocity lens that could be detected by surface seismic data.

Estimates of recent seawater circulation in the upper section of the Atlantis Massif suggest that downflow dominates in the vicinity of Site U1309 but that a component of lateral flow probably also exists, at least in a few narrow fault zones. A simple model of porous crustal downflow [*Turcotte and Schubert*, 1982] predicts concavity that matches what is observed in the upper section temperature profile in Hole U1309D if recent flow rates are around 1 cm/yr. If lateral advection dominated instead, a porous flow model would require rates that scale with the thickness of the zone experiencing the out-of-section flow. Magnitudes up to 100 times greater than the vertical-only porous flow model would be needed to produce the concavity of the measured temperature profile if flow occurred mainly in a 100 m thick highly fractured zone. Numerical models of intracrustal hydrothermal flow in a cross section that includes Hole U1309D and the Lost City vent field illustrate the viability of downflow at Site U1309, advection within a permeable upper layer, whose base mimics topography along the core complex, and upflow at Lost City with fluid temperatures in the 40–90°C range [*McCaig et al*., 2012].

Localized temperature deviations measured adjacent to two fault zones in the deeper section (746 and 1107 mbsf) of Hole U1309D indicate that lateral percolation of fluid can occur presently at depth in exposed oceanic core complexes. Microstructural study of samples across a fault zone at 159–174 mbsf in Hole U1309D [*Hirose and Hayman*, 2008] predicted the likelihood of such flow, particularly for deformed zones where altered ultramafic rock contacts cataclastic gabbroic rock. The 159–174 mbsf fault is not associated with a borehole temperature deviation, so if fluid still percolates along it, either the temperature is not anomalous or the rates are very slow. For those faults where present-day flow does occur, the broader cooling effect and the spatial extent of any associated permanent geophysical signature are limited. The highly altered ORT intervals indicate that fluid flow in the first 1–2 Myr of crustal evolution during core complex formation is also rather localized (or short lived), since adjacent gabbroic units are only slightly altered.

Downhole alteration and deformation structures in ODP Hole 735B, at the Atlantis Bank core complex, have some similarity to that observed at the Atlantis Massif. A notable crystal-plastic shear zone at ~960 mbsf

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marks a change below which overall alteration and intensity of deformation are lower than the averages for the section above [*Dick et al*., 2000]. Again, in the deeper section, hydration is limited, with little altered (<5%) intervals a few hundred meters thick bounded by narrow zones where alteration spikes. Unfortunately, the lack of logging data below 600 m in Hole 735B makes it impossible to directly compare hydration and physical property signatures between Atlantis Massif and Atlantis Bank. The upper sections of these two core complexes are less similar, due to Atlantis Bank's past subaerial exposure/erosion and multiple intrusions of oxide-rich melt and associated alteration [*Dick et al*., 2000].

Our findings suggest that a large portion of the oceanic lithosphere experiences very little contact with seawater beneath the upper, few hundred meters thick, pervasively fractured section. Even in our study area, where detachment faulting dominated the early evolution and one might expect an upper end-member case of the extent of crustal deformation, a major portion of the intrusive crust has experienced only localized flow and associated cooling/alteration. It is unlikely that subsequent, much more subdued tectonic forces associated with the slow aging of the oceanic lithosphere would introduce major new pathways for significant additional deep hydration. As integration of the borehole and regional seismic data are completed near the Atlantis Massif and for other recently surveyed core complexes, an estimate of slow-spread intrusive crustal hydration, prior to its being subjected to subduction forces, may be attainable.

4. Conclusions

Our results confirm that seawater circulation in the deeper part of the Atlantis Massif oceanic core complex below ~750 mbsf has been limited. Alteration, which we find to be inversely correlated with borehole V_p and resistivity, records the history of crustal seawater circulation and shows variable decrease of intensity with depth and only very localized flow below several hundred meters subseafloor depth. Present-day perturbation from a conductive thermal regime is minimal below ~750 mbsf. In contrast, the ongoing advection in the overlying section is indicated by the curvature in the temperature gradient. Simple models suggest that flow rates on the scale of centimeters per year may persist within the uppermost section of high-relief tectonic windows, well beyond their initial formation, but that deeper lithospheric hydration is very limited.

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