Geology and Fluid Discharge at Dorado Outcrop, a Low Temperature Ridge-Flank Hydrothermal System

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Abstract Two expeditions to Dorado Outcrop on the eastern flank of the East Pacific Rise and west of the Middle America Trench collected images, video, rocks, and sediment samples and measured temperature and fluid discharge rates to document the physical and biogeochemical characteristics of a regional, low-temperature (~15 °C) hydrothermal system. Analysis of video and images identified lava morphologies: pillow, lobate, and sheet flows. Glasses from collected lavas were consistent with an off-axis formation. Hydrothermal discharge generally occurs through pillow lavas but is patchy, sporadic, and sometimes ceases at particular sites of discharge. Yearlong temperature measurements at five of these discharge sites show daily ranges that oscillate with tidal frequencies by 6 °C or more. Instantaneous fluid discharge rates (0.16 to 0.19 L/s) were determined resulting in a calculated discharge of ~200 L/s when integrated over the area defined by the most robust fluid discharge. Such discharge has a power output of 10–12 MW. Hydrothermal seepage through thin sediment adjacent to the outcrop accounts for <3% of this discharge, but seepage may support anoxic sediment column. High extractable Mn concentrations and depleted δ13C in the low but variable organic solid phase suggest that hydrothermal fluids provide a source for manganese accumulation and likely enhance the oxidation of organic carbon. Comparisons of the physical and geochemical characteristics at Dorado and Baby Bare Outcrops, the latter being the only other site of ridge-flank hydrothermal discharge that has been sampled directly, suggest commonalities and differences that have implications for future discoveries.

Plain Language Summary Below the seafloor in the upper volcanic crust (underneath the sediment) seawater circulates through permeable rocks much like groundwater flows through aquifers on land. This circulating flow of seawater through the oceanic crust transports 25% of the global heat loss, most of it as cool hydrothermal seawater on the flanks of mid-ocean ridges. However, only two sites of this low-temperature hydrothermal discharge have been discovered, even though many such sites must exist. This study presents and links geologic, chemical, and hydrologic observations from one of these two discharge sites. We show that discharge is patchy and sporadic, and it occurs through pillow lava formations that were formed by off-axis volcanism. Measured hydrothermal fluid discharge rates are consistent with regional models. The low-temperature discharge does not alter basaltic rocks at the seafloor even those rocks that were collected from areas of fluid discharge. However, the hydrothermal flow does affect the chemistry of the thin sediment next to the outcrop. This work provides the foundation for understanding fundamental processes that have shaped Earth’s history.

1. Introduction

About one quarter of the Earth’s geothermal heat loss occurs by subsurface hydrothermal circulation on the flanks of mid-ocean ridges (Sclater et al., 1980). Seawater circulation within the oceanic crust on ridge flanks is driven by a hydrothermal siphon and guided by seamounts and other smaller basaltic outcrops that penetrate lower permeability sediment (Fisher, Davis, et al., 2003; Fisher, Stein, et al., 2003; Fisher & Wheat, 2010; Hutnak et al., 2008). The number of potential seamount-to-outcrop and seamount-to-seamount flow paths number in the billions among the projected tens of millions of basaltic exposures that rise more than 100 m above the sediment plain (Lauer et al., 2018; Wessel et al., 2010). To date, only two ridge-flank
hydrothermal discharge sites, driven primarily by lithospheric heating, have been sampled directly: Baby Bare Outcrop on the eastern flank of the Juan de Fuca Ridge and Dorado Outcrop on the eastern flank of the East Pacific Rise (Mottl et al., 1998; Wheat et al., 2017). The discharge of hydrothermal fluid, which is altered by seawater-basalt reactions, diffusive exchange with overlying sediment pore waters, microbial metabolic activity, and conductive heating, rivals the Earth's riverine flux. Hydrologic and chemical processes can result in small changes in the chemical composition of this discharging fluid that can impact global geochemical budgets (e.g., Coogan et al., 2016; Elderfield & Schultz, 1996; Johnson & Pruis, 2003; Wheat et al., 2003, 2017). The logistical challenge of finding and sampling these relatively low-temperature hydrothermal environments limits important progress in constraining these fluxes and chemical exchanges.

The first direct sampling of ridge-flank discharge occurred at Baby Bare Outcrop on the eastern flank of the Juan de Fuca Ridge. Baby Bare Outcrop resides on 3.5-Ma crust that has experienced off-axis volcanism and fault-generated abyssal hill formation, resulting in a mostly sediment-buried ridge upon which Baby Bare Outcrop is located (Karsten et al., 1998). Discharge of hydrothermal fluids is controlled by faulting and occurs in areas with thin or no sediment (Becker et al., 2000; Davis et al., 1992; Wheat et al., 2000). The maximum fluid discharge temperature at Baby Bare Outcrop is 25 °C, but these fluids cooled conductively during ascent from a temperature of ~64 °C in upper basaltic basement in an area where the measured heat flow is the value predicted from lithospheric cooling models after correcting for regional sedimentation and hydrothermal rebound (Davis et al., 1992, 1999; Hutnak et al., 2006; Hutnak & Fisher, 2007; Wheat et al., 2004). The chemical composition of fluids discharging from Baby Bare Outcrop is distinctly different from bottom seawater with highly elevated Ca concentrations and nearly all of the Mg removed from the seawater source (Monnin et al., 2001; Mottl et al., 1998; Sansone et al., 1998; Wheat et al., 2002; Wheat & Mottl, 2000).

However, Baby Bare Outcrop represents a highly reacted end-member of ridge-flank hydrothermal circulation that is not representative of much of the global discharge from ridge flanks, because the upper basaltic crust is unusually warm (64 °C), especially for a 3.5-Ma crust (Mottl et al., 1998). In contrast, hydrothermal discharge from Dorado Outcrop on the eastern flank of the East Pacific Rise (Figure 1) is more representative of global conditions responsible for the extraction of much of Earth's geothermal heat (Wheat et al., 2017). Dorado Outcrop is about 0.5-km wide and 2-km long, rises approximately 150 m above the sediment plain, overlies ~23-Ma crust, and is surrounded by a large region having a seafloor heat flow that is 10–40% of the value predicted by lithospheric models (Fisher, Stein, et al., 2003; Hutnak et al., 2007; Spinelli & Underwood, 2004). This low heat flow results from the advective extraction of heat from the crust by rapidly flowing fluids. Recharge and discharge through several seamounts and other outcrops in the region were identified, based on either depressed (seawater recharge) or elevated (hydrothermal discharge) seafloor heat flow approaching a seamount or outcrop (Fisher, Stein, et al., 2003; Hutnak et al., 2007). Discharge (12.3 °C) at the Dorado Outcrop is slightly cooled from a moderately warmed (~15 °C) formation fluid, which is recorded 96 hr of video from the seafloor at Baby Bare Outcrop during four dives (J2-751, J2-752, J2-756, and J2-757). Frame grabs of videos collected by the ROV Jason II are available on the
2.2. Temperature Measurements

Measurements of in situ temperature were taken to constrain the maximum temperature of fluid discharge using temperature probes that were mounted on *Jason II* and *Alvin*. Temperature measurements also were made using five self-recording temperature (Onset) loggers that were deployed in 2013 and recovered in 2014. These loggers were deployed to assess temporal variability in fluid discharge characteristics, recording temperature every 30 min. Power spectral analysis of the five, yearlong temperature records was completed to quantify dominant frequencies in the data. Additional multiday deployments were made in 2014 with temperature and dissolved oxygen (DO) instruments (prototype RBR, Inc. instruments). Measurements of temperature and DO were recorded at 5-min intervals. Two of these instruments were deployed twice, each for 3 to 4 days, at Markers R and W within meters of Marker K (Figure 1).

Figure 1. The inset shows the location of Dorado Outcrop (yellow circle) in context of the East Pacific Rise (EPR), Cocos-Nazca Spreading Center (CNSC), Middle America Trench (MAT), Cocos Ridge (CR), and South America Trench (SAT). Seafloor morphology of Dorado Outcrop is overlain on a bathymetric map with 10-m contours. Visual observations of sheet, pillow, and lobate lava formations are indicated in reference to markers (letters) that were primarily deployed at sites of fluid discharge. Two topographic highs are observed, one at each end of the outcrop. In the middle lies a saddle with a U-shaped feature, which appears to be an arcuate failure surface. There are debris fields visible adjacent to the outcrop below this feature and on the eastern side of the outcrop, which has the steepest slope. Markers R and W (locations not shown) are colocated with marker K at the scale of this map. Marker W is shown in Figure 2b. Bathymetric data are from the AUV *Sentry* (Wheat et al., 2017).
2.3. Measurements of Instantaneous Discharge Rate

In 2014 instantaneous discharge rates were calculated, based on visual observations of a dye and particles within a marked cylinder, to provide an order of magnitude assessment of discharge in reference to published estimates. A 15-cm-long, 6.2-cm inner diameter (I.D.) cylinder was attached to a PVC end cap (16.7 cm I.D.) and marked with 1-cm increments. A hose connected the base of the end cap to a 21-L container within which 0.5 g of rhodamine was dissolved in bottom seawater that was collected from a hydrocast about 50 m above the outcrop. Measurements of discharge velocities were made by resting the PVC end cap on the seafloor over points of discharge, releasing the dye into the base of the PVC end cap via the hose and visually monitoring the cylinder for several minutes to document the ascent of the dye or an occasional particle (supporting information Figure S1). The rate at which dye or particles ascended was determined by slowing the video to 1/4 speed and observing the rising plume of dye and/or particles relative to 1-cm marked increments on the cylinder.

2.4. Basalt Analysis

Thirty-three rocks were recovered from which 15 rocks (16 samples) were analyzed for major and trace element composition to constrain mid-ocean ridge basalt (MORB) type and the extent of alteration from interaction with seawater. Analyses included X-ray fluorescence (at ICBM, University of Oldenburg) and inductively coupled plasma mass spectrometry (at University of Bremen) following extraction and dissolution. At the GeoForschungsZentrum Potsdam, H2O and CO2 concentrations were measured by a VARIO EL III elemental analyzer, and Fe2+ contents were determined by potentiometric titration. Fe3+/∑Fe values report the fraction of ferric iron and were computed from measured ∑Fe (total Fe from X-ray fluorescence) and Fe2+ = ∑Fe − Fe3+ (Fe3+ from titration). In addition, glass that was recovered from two of these samples was analyzed by electron microprobe analysis and laser ablation inductively coupled plasma mass spectrometry for major and trace element compositions at the University of Bremen. Also, one micritic carbonate coating, which was recovered between altered basalt and Mn crust, was analyzed for 87Sr/86Sr isotopic compositions using a thermal ionization mass spectrometer at the MARUM, Center for Marine Environmental Sciences, University of Bremen (e.g., Deniel & Pin, 2001). Details of the analytical procedures and uncertainties based on Jochum et al. (2005) are provided in the supporting information.

2.5. Sediment Collection and Analysis

Sediment was collected in 2014 using push and gravity cores to recover thin sediments that approach the basaltic outcrop. Ideally, such cores would recover the complete section to validate the fluid composition in the upper basaltic crust and assess the impact of this fluid on sediment through which it seeps. Analyses included a probe to determine dissolved oxygen concentrations (e.g., Orcutt et al., 2013), and pore waters were extracted into acid-cleaned syringes using rhizons, discarding the first 2 ml of sample. Extracted fluids were filtered with a disposable 0.45-μm filter into acid-cleaned high density polyethylene bottles and analyzed for dissolved nutrients (nitrate, phosphate, and silicate) and major, minor, and trace elements using the same protocols that were used to measure solute concentrations in discharging fluids (Wheat et al., 2017). Sediment was dried, ground, and analyzed for organic carbon, extractable metal concentrations, and carbon isotope values (e.g., Mehra and Jackson, 1960, as described in the supporting information. Results of pore fluid and sediment analyses are archived in the Biological and Chemical Oceanography Data Management Office (Wheat et al., 2016a, 2016b).

3. Results and Discussion

3.1. Lava Morphology

Almost 2,000 images, including frame grabs from videos, were used to identify lava morphologies on Dorado Outcrop. Lava morphologies were classified as pillows (Figures 2a and 2b), lobate (Figure 2c), or sheet flows (Figure 2d and supporting information Figure S1 and Tables S1–S3). In general, sediment coverage was thicker on the lobate flows than on pillow mounds and sheet flows. In many places, sediment thickness was thin enough to reveal geomorphologic features. The only areas that were absent of sediment were (1) the pillows in the area of Markers R, W, and K, (2) a few random lobate patches such as at those at Marker A (supporting information Figure S2), and (3) the undersides of ledges, crevices, and holes. The general lack of sediment on Dorado Outcrop is likely the result of oceanic currents, consistent with the relatively
Figure 2. Seafloor images of Dorado Outcrop taken in 2013 during Jason II and Sentry dives and in 2014 during Alvin dives. (a) Rounded pillows with a dusting of sediment on the northwest peak at 3,018-m water depth (J2-757). (b) Pillows with signs of alteration and cracking but without sediment on the terraced southwest face of the southeast peak at 2,990-m water depth. Also pictured is a site marker (W), RBR logger, and seven brooding octopods (Alvin-4778). (c) Lobate flow with thick sediment layer on the southwest face of the southeast peak at 3,143-m water depth (J2-751). (d) Sheet flow with two holes and light sediment coverage on the northeast face of northwest end at 3,021-m water depth (J2-757). (e) Sediment, broken sheet, sheet ledge, and pillow mix on the northeast face of the southeast end at 3,043-m water depth (J2-757). (f) Lobate and broken basalt mix on the southwest face of the southeast end at 2,949-m water depth (Sentry 216). (g) Fissure in pillows with heavy sediment coverage on the northwest face of the southeast peak at 3,012-m water depth (J2-751). (h) White carbonate substrate and lobate lava on the southwest face of southeast peak at 3,018-m water depth (J2-757).
high density and diversity of benthic biota (supporting information Figure S3) and a scoured ~20–30 m deep and ~400- to 500-m-wide depression on the southwestern side of the outcrop (Wheat et al., 2017).

Lobate flows with a cobbly-like texture were the most common type of lava formation observed (Figure 2c). These flows dominate the southwest and northeast faces and the central depression (Figure 1). Lobate flows observed on shallow slopes likely formed during rapid lava emplacement. The cobbled appearance of many lobate flows could be from cracking after lava drained or where the flow became jumbled (e.g., Clague & Paduan, 2009).

Pillows are the second most common lava type. Pillow mounds (Figure 2a) are rounded and cylindrical flow lobes (e.g., Chadwick & Embley, 1994; Figure 1). Pillow structures on Dorado Outcrop include elongate pillows, striated pillows, and radial fracture patterns (supporting information Figure S4). Drained pillows are evidence for an internal network of lava distribution (Hon et al., 1994; Smith et al., 2002). Pillow morphology is indicative of relatively slow lava emplacement compared to lobate flows (Clague & Paduan, 2009). Some lobate flows are mixed with pillow flows. For instance, on the northeast face of the southeast end of the outcrop a pattern of lobate sections is divided by pillow mounds. This pattern of lobate and pillows is consistent with a series of steps: (1) surface solidifies and becomes brittle, (2) pressure from continuous lava supply builds, and then (3) the crust breaks and pillow extrusions form by flowing away from the source (Clague & Paduan, 2009; Hon et al., 1994).

The least commonly observed basalt morphology is sheet flows (Figure 2d), which are smooth continuous surfaces observed on topographic highs (i.e., Ballard et al., 1979). Some sections of the outcrop have blocky pieces of broken sheets (Figure 2e), some of which are surrounded by lobate flows (Figure 2f). The formation of sheet flows is a function of topography, effusion rate, and eruption duration (Clague & Paduan, 2009; Hon et al., 1994).

In addition, Dorado Outcrop has the following three geomorphological features: small skylights up to tens of centimeters in diameter (Figure 2f, for example, holes described in Hartwell et al., 2018), linear breaks, and carbonates. Skylights are ubiquitous around the outcrop on sheet flows and form when a section of a lava tube collapses (Peterson et al., 1994). Linear cracks in the basalt (Figure 2g) are tens of centimeters to a meter wide and have two primary orientations: northeast/southwest at an angle of 261 ± 13° (n = 8) and northwest/southeast at an angle of 324 ± 18° (n = 8); smaller cracks (less than tens of centimeters) were observed on pillow and sheet surfaces around the outcrop. Each of the large cracks was in a pillow flow (supporting information Figure S5). Six cracks were observed on the northeast face of the southeast end near a 50-m-high (3,027–3,071 m water depth) wall composed of truncated pillows with radial patterns and talus piles at the base, both evidence of tumulus formation. A tumulus forms as cooling crust traps increasing hydrostatic pressure, resulting in expansion and cracking and steep-sided pillow ridges (Clague & Paduan, 2009; Hon et al., 1994; Smith et al., 2002; Walker, 1991). The third feature is characterized by patches of white substrate (Figure 2h). Such white patches were observed among all lava types (supporting information Figure S6). One of these pieces was recovered (sample AT-26-09-J2-757-RO-7), consisting of carbonate.

3.2. Basalt Type and Age Constraints

Chondrite-normalized rare earth element (REE) patterns of two glass samples show an enrichment in light rare earth elements, which is distinctly different from the light rare earth element-depleted pattern commonly observed in normal mid-ocean ridge basalt (N-MORB; Figure 3; Arevalo & McDonough, 2010). The REE patterns of these glass samples are consistent with an off-axis formation, where this type of slightly enriched MORB (or transitional MORB; T-MORB) is common. Additional evidence for an off-axis formation is based on Zr/Nb weight ratios of 16 basaltic samples (sample AT-26-24-4776-RS-7 was split to assess the rim and core alteration; supporting information Tables S4–S6). Most of these basaltics were collected from pillow flows (Figure 4), and most have Zr/Nb weight ratios in the range of 15 to 16 with three samples having values between 19 and 27. The lower ratios contrast greatly with N-MORBs, which have Zr/Nb weight ratios that are >30 (McDonough & Sun, 1995). Given these ratios and REE patterns, we classify basaltic from Dorado Outcrop as N-MORB to T-MORB indicative of an off-axis origin.

Given that the upper portions of Dorado Outcrop formed off axis, we determined the $^{87}$Sr/$^{86}$Sr of a biogenic carbonate, which contained tests of various sizes (50–400 μm) of the planktonic foraminifera Globigerinoides.
of Neogene age (sample AT-26-09-J2–757-RO-7; supporting information Figure S5). The $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic composition of this piece of white carbonate exposed to bottom seawater was $0.708503 \pm 0.000005$ (2σ). This ratio is the expected ratio for a carbonate that was precipitated from seawater $18.5$ Ma (McArthur et al., 2001), assuming that the carbonate was not overprinted by hydrothermal or diagenetic processes. Thus, the minimum age for the formation of Dorado Outcrop is $18.5$ Ma, relative to a magnetic age of about $23$ Ma for the underlying crust. These data also indicate that the carbonate material precipitated early in the evolution of Dorado Outcrop when it was relatively close to the spreading center on the East Pacific Rise.

### 3.3. Relationship Between Volcanic Substrate and Fluid Discharge

Temperature measurements with probes attached to either *Jason II* or *Alvin* were made within cracks, under pillows, in places with staining on basalt, and near the sediment-basement contact (Figure 5). The most vigorous hydrothermal fluid discharge was located in the Marker K area and at Markers A and M. The area around Marker K also had many female octopuses that were brooding their eggs (Hartwell et al., 2018). We used the presence of octopuses as indicators of sites of fluid discharge. Discharge was evident as *shimmering* water (due to the contrast in refractive index with bottom seawater) and was common throughout the ~25-m$^2$ area defined by Markers R, W, and K, including the rectangular 16-m$^2$ area defined by Markers R and K on the corners. Here pillow lavas look glassy with a thin coat of black staining, probably the result of manganese oxide formation. In contrast, at other sites, such as at Marker A, discharge occurred through rubble (supporting information Figure S2). Here too, the dark staining is evident at the point of discharge. Discharge along the southeastern side near Markers H and M occurred through a field of pillow flows. Combined, these observations are consistent with discharge at Dorado Outcrop mainly

![Figure 3. Rare earth element (REE) data are normalized versus chondrite (McDonough & Sun, 1995) for two glassy basaltic samples from Dorado Outcrop (blue circles and red squares). Data are compared to normal mid-ocean ridge basalt (N-MORB, black diamonds; Arevalo & McDonough, 2010), consistent with Dorado Outcrop having an off-axis volcanic source.](image)

![Figure 4. Bathymetric map of Dorado Outcrop with 10-m contours, site markers (teal triangles), rock samples with labels (purple circles), and observations of pillow lava formations (white squares).](image)
through the low slope relief of pillow flows and not through sheet or lobate flows. This flow pattern is in contrast to observations at Baby Bare Outcrop, which is mostly covered with a thin veneer of sediment and where faults oriented parallel to the active ridge to the west control hydrothermal discharge (Becker et al., 2000).

3.4. Thermal Characteristics of Discharge

Two hundred and twelve temperature measurements were made using the sensor attached to Jason II or Alvin during two expeditions, spanning temperatures from a bottom seawater value of 1.8 °C to a high of 12.3 °C during the Alvin expedition in 2014 and a single measurement of 12.5 °C recorded in 2013 (Figure 5 and supporting information Table S7). On repeated visits in 2013 no visible change in discharge rate was observed at Markers A, K, M, and H during the 2-week expedition. Discharge in the Marker K area appeared to be robust and relatively uniform during operations in 2013 and 2014. In contrast, when we initially returned to Marker A in 2014, there was no active discharge from the stained areas that discharged fluids in 2013. We did, however, revisit Marker A 6 days later in 2014 and measured 7.6 °C fluids, indicating that discharge can be ephemeral. Thus, discharge sites on Dorado Outcrop show evidence for transient discharge dynamics on subannual timescales, likely influencing both discharge rate and temperature.

One-year temperature records document temporal variability in fluid discharge temperatures of 1.8 °C to 11.9 °C (Figure 6 and supporting information Tables S8–S13). While most of the records show near-uniform average daily temperatures throughout the deployment, the sensor at Marker R (green symbols, Figure 6a) showed a dramatic change over a period of 2 days during which the temperature dropped from ~8 °C to ~3 °C. Video comparison of this site during deployment and recovery indicates that the sensor was moved, likely from activity of nearby brooding octopuses. Most of the observed variability in temperature likely results from conductive cooling of hydrothermal fluids during ascent—as discharge rates slow, conductive losses become a larger portion of the overall heat loss (Wheat et al., 2017). Such conductive heat loss during fluid ascent was observed at Baby Bare Outcrop (Wheat et al., 2004) and within seafloor hydrothermal systems, in general (e.g., Corliss et al., 1979).
Daily ranges in fluid temperature during the 1-year deployments were 6 °C or more and higher (2.0 °C to 12.3 °C) during the shorter, 3- to 4-day deployments (Figure 6 and supporting information Tables S8–S12). These 3- to 4-day records (Figure 6b and supporting information Table S13) illustrate a temporal component to fluid discharge with two cycles of high and low temperatures per day. Power spectral analysis of the five yearlong temperature records indicates harmonic oscillations with strong tidal frequencies but lacks significant correlation with tidal frequencies within less than 1 day (Figure 7). Pressure and temperature responses to tidal forcing have been recorded in all ridge-flank borehole observatories, and a temperature response to tidal frequencies was observed in springs on Baby Bare Outcrop (e.g., Davis & Becker, 1999; Wheat et al., 2004). Temperature-tidal correlations of discharging fluids are generally attributed to tidal fluctuations in bottom current intensity and direction that affect the benthic boundary layer, whereas there was a lack of a correlation in temperature data from within the main conduit of high-temperature hydrothermal systems (Barreyre et al., 2014; Little et al., 1988; Schultz et al., 1996; Sohn, 2007; Tivey et al., 2002). No current data are available to assess coherence between bottom current speed and direction and probe response at Dorado Outcrop.

3.5. Instantaneous Fluid Discharge Rate and Power Output

We measured the instantaneous discharge rate at several locations within the Marker R-K area using a dye experiment on Alvin dive 4,784 (supporting information Figure S1). Ascent rates of 5 to 7 cm/s were observed in the marked cylinder (6.2-cm I.D.), corresponding to a flow of 0.16 to 0.19 L/s. If this flow rate, which stems from a footprint of the 8-inch PVC end cap (219 cm²), is extrapolated to the area of 25 m² from which ubiquitous discharge was observed, the calculated fluid flux is ~200 L/s, which is about 2%–20% of the total discharge from Dorado Outcrop estimated from chemical (3,000 L/s; Wheat & Fisher, 2008) and thermal data (10^3–10^4 L/s; Hutnak et al., 2008) and hydrologic modeling (1,000–7,000 L/s; Lauer et al., 2018) constraints. Dye experiments would be consistent with the chemical-based estimate if the latter used a lower effective porosity consistent with recent tracer
studies on the eastern flank of the Juan de Fuca Ridge (Neira et al., 2016; Wheat & Fisher, 2008). The calculated instantaneous fluid discharge from the Marker R-K area (200 L/s) and hydrothermal fluid temperature (13 °C greater than bottom seawater) results in a power output of 10–12 MW. This power output is about an order of magnitude greater than the power output from Baby Bare Outcrop (Wheat et al., 2004) and is equivalent to the power output of three to four 350 °C black smokers vents with a discharge of 1 m/s through a 5-cm diameter orifice.

3.6. Alteration of Basalt and Fluid Discharge

Most of the rock samples that were collected from Dorado Outcrop were removed from pillow structures, and about half of these rock samples were removed from areas that were bathed in hydrothermal fluids (Figure 4 and supporting information Table S4). Three alteration types of the whole rock samples were defined, based on macroscopic and thin section observations (supporting information Tables S5 and S6): (1) samples \( n = 5 \) that show a grayish alteration color of the matrix and olivine phenocrysts that remain completely fresh or are only partly replaced by cryptocrystalline secondary minerals; (2) samples \( n = 5 \), including the core of AT-26-24-4776-RS-7) that show a grayish alteration color of the matrix but olivine phenocrysts are completely pseudomorphed by cryptocrystalline secondary minerals, mainly composed of Mg-smectites; and (3) samples \( n = 6 \), including the rim of AT-26-24-4776-RS-7) that have a brownish altered matrix halo that occurs on the rims of rock fragments, with olivine phenocrysts completely pseudomorphed mainly by K-rich clay minerals and oxides.

The penetration depth of the brownish alteration at the rims varies from 0.5 to 6 cm, measured from the rock surface toward the center of single rock fragments (supporting information Table S4). This brownish layer is a sign of low-temperature alteration by oxygenated seawater. The decreasing MgO contents with increasing water content are consistent with the destruction of Mg-rich primary phase minerals like olivine and pyroxene with increasing degrees of alteration/hydration (Figure 8). Rocks of alteration type (2) did not show significant MgO losses, despite high H2O gains (Figure 8). The precipitation of Mg-smectites inhibits a loss of Mg of the altered whole rocks. The Mg-smectite-rich rock samples were taken from the interior parts of the lava; thus, they were not directly exposed to seawater. This indicates that a strong MgO-loss is limited to oxic alteration of basalt with K-rich clay minerals dominating the alteration mineral assemblage, similar to the observations of the brownish altered domains of alteration type (3).

Other proxies of oxidation alteration, such as increases in Fe\(^{3+}/\sum\text{Fe}\) and decreases in SiO\(_2\), are evident. These basalts also show an increase in Al\(_2\)O\(_3\) and Fe\(_2\)O\(_3\), as well as increasing P\(_2\)O\(_5\) and U content. The iron is strongly oxidized as indicated by the high Fe\(^{3+}/\sum\text{Fe}\). Fe\(_2\)O\(_3\) is immobile and becomes passively enriched in basalts altered under oxic conditions, as silica is lost. A slight enrichment in alkali metals with increasing water content was observed (supporting information Tables S5 and S6). Such changes are consistent with measured chemical changes in the discharging fluid, assuming that Mg is removed in the crust immediately subsurface by the precipitation of Mg-smectites as a secondary mineral (Wheat et al., 2017). However, the subtle Mg depletions in discharging fluids relative to seawater are inconsistent with the Mg-losses observed for basalts altered under oxic conditions (Figure 8). We therefore suggest that the suboxic, grayish alteration type (Mg-smectite rich) is the most dominant Mg-related reaction that removes Mg currently along the fluid flow path.

As noted above, these basalts formed at least 18.5 Ma ago and have been exposed to seawater since they formed. The impact of hydrothermal discharge is likely relatively recent, requiring millions of years for sediment to accumulate and restrict recharge and discharge sites. Thus, even though some rocks were collected within present-day discharge areas, it is not surprising that there is no clear delineation in the data between the extent of alteration for those rock samples collected within active discharge areas and those away from active discharge sites, given that (1) the discharging fluid was almost identical to bottom seawater in composition (Wheat et al., 2017), (2) the warmest recorded temperatures were observed in cracks from which it was not possible to collect rock samples, (3) fluid discharge mixed rapidly with bottom seawater, and (4) most rocks that were collected would have encountered temperatures that were only a few degrees above ambient bottom seawater.
3.7. Effect of Discharge Through Thin Sediment on Pore Water Compositions

Sediment push and gravity cores were collected in 2014 to help constrain the impact of diagenetic reactions and consequences of seepage through thin sediment by attempting to collect the entire sediment column to the basement contact (e.g., Orcutt et al., 2013; Rudnicki et al., 2001; Wheat & McDuff, 1994). Pore fluid dissolved oxygen generally decreases with increasing depth from bottom seawater values to near-zero values within the upper few centimeters below the seafloor (cm-bfs), consistent with microbial oxygen respiration (Figure 9). In contrast, one profile shows a similar initial decrease with depth but then concentrations of DO increase with depth to the value in the discharging (formation) fluid (~54.5 μM), which is about half of the concentration in bottom seawater (Wheat et al., 2017). This profile is consistent with the active transport (diffusion and advection) of DO into the sediment column from a basement aquifer that contains DO (e.g., Orcutt et al., 2013; Ziebis et al., 2012).

Concentrations of major and minor ions in pore waters are indistinguishable from bottom seawater, consistent with the discharging spring fluids (Wheat et al., 2017). Only those ions that are influenced by microbial processes differ significantly from their seawater values (e.g., Froelich et al., 1979). Three of the push cores (4777-8, 4782-9, and 4783-21) had downcore nitrate profiles that were consistently within the range of bottom seawater concentrations, indicating that significant seepage of nitrate-rich formation fluids must occur to maintain these profiles (e.g., Wheat & Fisher, 2008). In contrast, nitrate profiles from gravity cores show the effects of typical sedimentary microbial processes, a loss of nitrate and an increase in dissolved manganese (Figure 10).

Comparison of dissolved phosphate versus manganese concentrations shows increases as a result of microbial respiration in samples from gravity cores; however, there is notable removal of phosphate within cores where seepage occurs (Figure 10; Wheat et al., 2003). This removal is likely related to P incorporation onto
Fe- or Mn-oxide surfaces (McManus et al., 1997), most of which can be accounted for by reaction within the basaltic crust prior to seepage into the sediment. The altered seafloor-exposed basalts do show the corresponding enrichment in P and U, indicative of sorption of oxyanions to the positively charged surfaces of Fe-oxyhydroxide phases (supporting information Tables S5 and S6).

Diagenetic reactions alter the chemical composition of formation fluids that seep through the overlying sediment column. However, little hydrothermal seepage occurs through sediment on or near the outcrop, because sediment is orders of magnitudes less permeable than the underlying basalt, and the driving force for crustal circulation at low temperatures is several to tens of kPa (Fisher, Davis, et al., 2003; Lauer et al., 2018; Spinelli et al., 2004). For example, assuming an average seepage rate of 5 m/yr (consistent with flow though thin sediment at Baby Bare Outcrop; Wheat et al., 2004) from an area that is an upper bound (20-m wide and 1-km long both east and west of Dorado Outcrop), the calculated seepage flux of formation

Figure 9. Sediment profiles of dissolved oxygen (DO) and weight percent (solid phase) manganese, iron, and organic carbon (OC). Red-filled diamonds are data from push cores taken from areas with pore water seepage, transporting oxygenated formation fluids into the overlying sediment. Green open triangles and blue squares represent push core and gravity core data, respectively, from areas that currently lack seepage. Note the two different depth scales.

Figure 10. Sediment pore water nitrate and phosphate are plotted against dissolved manganese to indicate biogeochemical processes in seepage-influenced sediment. Mn concentrations in pore water rise when nitrate values are depleted, but Mn reduction is initiated when nitrate concentrations are ten to 20 μmol/kg. Phosphate concentrations rise in the gravity core data from nitrification and Mn reduction and are depleted in the push cores with active fluid seepage consistent with a depleted phosphate concentration in the basaltic formation fluid within upper basaltic basement. Red circles represent push core data from areas with pore water seepage. Blue squares represent gravity cores that lack seepage. Green triangles represent push cores that are not significantly influenced by current seepage. The black circle represents bottom seawater.
3.8. Effect of Discharge Through Thin Sediment on Sediment Solid Phase Composition

Solid phase extractable Mn is generally enriched within the upper 10 to 20 cm-bfs in push cores relative to the data from gravity cores that were distal to the outcrop (Figure 9). The three gravity cores that were collected away from the influence of fluid seepage have low extractable Mn concentrations throughout the sediment column, suggesting that the typical regional values should be low. The low values for the gravity cores are likely driven by the oxidation of organic matter, which mobilizes excess extractable Mn (e.g., McManus et al., 2012). Although organic carbon oxidation will also occur within the push cores, we speculate that the generally higher extractable Mn concentrations in the push cores may be driven by variable supply of Mn from the transport of dissolved Mn to these sediments from below. The source of this dissolved Mn could be from the combination of reductive dissolution of Mn from deeper within the sediment, followed by reoxidation of the Mn within the upper centimeters of sediment or from seepage of formation fluid through the sediment column. The latter seems counterintuitive given that the formation fluid has a Mn concentration that is <0.1 μmol/kg (Wheat et al., 2017). However, for a 10 cm-long sediment column, consistent with the section that shows higher Mn concentrations (1 wt% Mn), assuming the formation fluid provides 0.05 μmol Mn kg⁻¹ (50 nmol/kg) and a seepage rate is only 10 cm/yr, then it would take only 8,000 years to supply hydrothermal dissolved Mn to deposit the observed solid phase Mn enrichment. Given that fluid discharge has likely occurred for millions of years at Dorado Outcrop, it is reasonable to conclude that the observed Mn enrichments in all of the push cores are at least partially of hydrothermal origin. This notion is consistent with the result that the altered volcanic rocks are significantly depleted in MnO (0.12 wt%) relative to fresh glass (0.2 wt%) and that there is a general trend of higher degree of alteration with greater Mn depletion. The same arguments could be made for observations of Fe enrichments in near-surface sediments (Figure 9); however, there is much more overlap between the gravity core and push core values. This overlap is consistent with the likelihood that organic carbon oxidation does not have as much of an impact on iron distributions within the upper few centimeters as compared to Mn. Precipitation of Fe and Mn oxides in the sediment would also remove other ions (i.e., phosphate, vanadium, and a host of other trace metals).

In contrast to Mn, the weight percentage (wt%) of organic carbon (OC) concentrations in push cores from near discharge sites vary from being enriched (1 to 1.5 wt%) to depleted (0.2 wt%) relative to the background core (0.5 wt%; Figure 9). In addition, samples from a number of cores have values that approach 0.1 wt% organic carbon, values that are not observed in the longer gravity cores. Such low organic carbon contents are likely driven by increased remineralization, resulting from the increased flux of oxidants from seepage (i.e., Wheat & McDuff, 1994). Alternatively, it is possible that the lower carbon contents for some of the cores are a product of winnowing of fine materials; however, such a process would need to be particularly selective in both time and space. If winnowing of fine organic matter were an explanation for the variability in organic carbon, it could impact the cycling of Mn discussed above.

The δ¹³C of the bulk organic carbon differs from about −20‰ to about −24‰. The core with the strongest evidence of fluid seepage (core 4777-8) has two samples with δ¹³C-organic values that are among the most negative in their ¹³C values, and their corresponding organic carbon concentrations are among the lowest (Figure 11). It appears that as organic carbon values decline, which occurs generally with increasing depth below the surface (Figure 9), the organic carbon isotope values become more negative; this effect is more pronounced in the push cores with the lowest organic carbon contents (Figure 11). This pattern implies that

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**Figure 11.** Inverse weight percent organic carbon and δ¹³C of sediment recovered from a gravity core (GC-03) that was distal to fluid discharge and push cores from Alvin dive 4,777. The push cores with the red symbols were collected near sites of fluid discharge. The more recalcitrant organic material is depleted in ¹³C.
the more recalcitrant organic material has more negative $\delta^{13}C$ values, not only near areas of fluid discharge but also throughout the region (Drenzek et al., 2007).

### 4. Summary Implications for Fluid Discharge on Ridge Flanks

To date, two sites of ridge-flank hydrothermal discharge driven by lithospheric heating have been studied in detail: Baby Bare and Dorado Outcrops (Figure 12). Both are topographic highs that extend <200 m above a sediment plain, are elongated in a direction parallel to the active spreading center that generated the crust on which they lie, have a footprint above the sediment that is ~1 km$^2$, are surrounded by areas where the sediment is hundreds of meters thick, are abyssal structures that formed by off-axis volcanism, and were formed sufficiently long ago that there is no residual heat from cooling magma. Baby Bare Outcrop is located on an uplifted ridge with a normal fault defining the western boundary (Becker et al., 2000). Unfortunately, there is insufficient seismic reflection coverage around Dorado Outcrop to resolve the buried topography of the volcanic crust in detail; however, bathymetric data are not consistent with an elongated buried ridge developed by a fault.

Three-dimensional models of crustal ridge flank hydrothermal circulation indicate that the size of the basaltic edifice that rises above the seafloor shapes the subsurface hydrology (e.g., Lauer et al., 2018; Winslow & Fisher, 2015). Large seamounts can be a source of recharge and discharge simultaneously, whereas smaller outcrops such as Baby Bare and Dorado Outcrops tend to be sites of discharge only. Because of the complex nature of simulated flow paths and the potential for short fluid pathways that potentially result in minimal thermal and chemical alteration within large volcanic features (seamounts), discovering sites of fluid discharge on such features will be difficult. In contrast, small outcrops (<1 km$^2$) that formed by off-axis volcanism and/or normal faulting offer the best opportunity to find and sample cool hydrothermal discharge, in part because small features are easier to survey during a normal length (3 weeks on site) oceanographic expedition.
We speculate that the rate of crustal accretion impacts discharge style, which is highly localized at both outcrops. For example, at Baby Bare Outcrop, most discharge occurs along faults and where sediment is absent (Becker et al., 2000; Wheat et al., 2004). Here the sediment is generally thick enough that distinct lava morphologies associated with discharge cannot be determined. In contrast, most of Dorado Outcrop has a thin (centimeters or less) layer of sediment, allowing the morphology of volcanic basement to be resolved. Discharge from Dorado Outcrop occurs mainly through pillow lava structures in the absence of faults; however, the structure beneath the surficial basal layer is unknown.

Abyssal faulting along the medium-spreading crust at Baby Bare Outcrop continues off axis as evident from a sedimented fault where the seepage rate of hydrothermal fluid increased toward the fault (Becker et al., 2000). On a larger scale Baby Bare Outcrop resides on an elongated ridge that is parallel to the spreading center to the west. Flow within this ridge is from south to north, constrained by thermal and chemical data (Fisher, Davis, et al., 2003; Wheat et al., 2000) and documented with chemical tracers (Neira et al., 2016) along a bathymetric structure that is bounded by abyssal faulting (Karsten et al., 1998). In contrast, the fast-spreading crust upon which Dorado Outcrop resides lacks linear topographic structure and surficial faulting structures. Thus, the source for the discharging fluid is less certain, consistent with a more heterogeneous permeable crustal fabric with little evidence that the crustal fabric imparts a preferential flow direction.

The yearlong record and repeat visits at Dorado Outcrop reveal episodic discharge that is modulated by tides (Figures 6 and 7). Discharge can cease for periods of days or longer, then restart. Discharge at Baby Bare Outcrop also has a tidal signal (Wheat et al., 2004). While there are no yearlong records of temperature at Baby Bare Outcrop, a return visit years after the initial discovery located discharge at the most active site (Huber et al., 2006; Johnson, 2003), consistent with continuity in discharge in the Marker K area on Dorado Outcrop. It remains uncertain whether the thermal and chemical oscillations have a tidal signal because of changes in bottom currents or crustal hydrologic properties. Such changes in flow coupled with the low driving forces (several to at most tens of kilopascals) require a permeable crust; however, there is a paucity of data to characterize the extent of heterogeneity and interconnectivity of permeable pathways in the upper crust to understand temporal aspects of discharge such as how circulation of hydrothermal fluids in this region may be influenced by tides.

Discharge from Dorado Outcrop does not significantly influence the alteration of basalts that are exposed at the seafloor compared to sites without discharge. However, subsurface alteration at both outcrops is likely very different. At Baby Bare Outcrop, the regional basaltic basement is 64 °C, resulting in a highly altered crustal fluid that is almost depleted in Mg and enriched in Ca by more than 5 times the seawater concentration (Mottl et al., 1998). In contrast, discharge at Dorado Outcrop stems from cool (15 °C) and oxic formation fluids with a composition that is similar to bottom seawater (Wheat et al., 2017). These thermal and chemical differences are a function of the extent of basaltic exposure, sedimentation rate, and age and permeability of the volcanic crust. There are few outcrops on the eastern flank of the Juan de Fuca Ridge around Baby Bare Outcrop, and upper crustal permeability appears to be moderately high (10−13 to 10−12 m²; Winslow et al., 2016), resulting in relatively slow flow of hydrothermal fluid that has considerable time to warm and react during transport. In contrast, the crust around Dorado Outcrop appears to be more permeable (on the order of 10−10 to 10−9 m²; Lauer et al., 2018), perhaps as a consequence of a faster-spreading rate during crustal formation (Fisher, Stein, et al., 2003), and subsurface fluid flow is currently so rapid that it extracts 60%–90% of lithospheric heat on a regional basis. However, these are generalizations. The crustal fabric is much more complicated as indicated by the sharp boundary in heat flow, which is not a plate boundary, which resides to the south of Dorado Outcrop where the heat output is the same as that predicted by lithospheric models (Fisher, Stein, et al., 2003).

Another influence on basaltic alteration is time. Fluids have discharged through Baby Bare and Dorado Outcrops at most 3.5 and 23 Ma, respectively. At Dorado Outcrop discharge in its present form is restricted to sedimentation that first seals much of the crust then minimizes potential discharge sites regionally and locally. Given sedimentation rates of ~17 m during the Pleistocene (1.77 Ma) and 42 m since the Pliocene (5.7 Ma), discharge in its current form at Dorado Outcrop is likely restricted to several million years (Wilson et al., 2003). Similarly, rapid deposition of turbidites (~80 m) during the Quaternary would have focused discharge at Baby Bare Outcrop (Davis et al., 1997). Data from both outcrops underscore that
discharge and the effect of discharge on thermal and chemical fluxes vary on many scales: from hours to geologic time.

A small fraction of fluid discharge occurs through thin sediment on and next to Dorado and Baby Bare Outcrops. If seepage is sufficiently fast, variations in chemical profiles of pore water provide a measure of the composition of the formation fluid. If seepage is slow, such that the flux from reactions is greater than or similar to the transport flux, then the pore water chemical data mainly provide a measure of diageneric and authigenic reactions. Data from Dorado Outcrop present characteristic differences in sediment composition with pore water seepage compared to sediment collected away from the outcrop. A similar situation exists for Baby Bare Outcrop. Results from these sites suggest that sediment pore water studies provide a means to locate features with discharge and provide an initial indication of the composition of the formation fluid. However, seepage through sediment occurs only where sediment cover is thin, generally within a few tens of meters of the outcrop edge, and comprises a small fraction of the total fluid flux compared to that which occurs at focused, unsedimented discharge sites.

Given the size of the global heat flow deficit, there must be millions of additional ridge-flank, hydrothermal systems that remain to be discovered. Dorado Outcrop is a useful representative of one end-member, with rapid flow, a short residence time in the crust, and cool and relatively unreacted fluids. Baby Bare Outcrop represents another end-member, with slow-flowing, warm, and highly reacted fluid representing the last phase of hydrothermal circulation that was once much more vigorous. Additional ridge-flank discharge sites need to be discovered to elucidate how crustal spreading rate, structure, off-axis volcanism, and sedimentation can influence hydrothermal processes. These processes have likely operated through much of Earth’s history, but we are just beginning to quantify and understand their variety and significance.

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References


Hon, K., Kauahikaua, J., Denlinger, R., & Mackay, K. (1994). Emplacement and in...


