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Seawater recharge along an eastern bounding fault in Middle Valley, northern Juan de Fuca Ridge

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[1] A transect of four boreholes was drilled at ODP Site 855 in Middle Valley, a sedimented spreading center on the northern Juan de Fuca Ridge, near an eastern bounding (normal) fault. Systematic variations in pore water chemical profiles along this transect are consistent with recharge of seawater into basaltic crust along the exposed fault, followed by flow of formation fluid laterally within upper basaltic basement. Chemical data are interpreted using an advection-diffusion model, resulting in a seawater flux into the seafloor of ~9 $m^3\ yr^{-1}$ per meter of fault, with a specific discharge of $\geq$100 m yr^{-1}. Calculations suggest that flow is confined to a thin interval within upper basaltic basement. Integrating over the 17-km length of exposed fault results in a recharge flux that is only 3% of the present day, high-temperature hydrothermal discharge in Middle Valley. Most of the seawater recharge occurs elsewhere through more transmissive pathways. **Citation:** Wheat, C. G., and A. T. Fisher (2007), Seawater recharge along an eastern bounding fault in Middle Valley, northern Juan de Fuca Ridge, *Geophys. Res. Lett.*, *34*, L20602, doi:10.1029/2007GL031347.

1. Introduction

[2] Numerous studies of seafloor hydrothermal circulation have quantified fluid, heat, and solute fluxes at vent sites, but many fewer studies have quantified rates and processes of hydrothermal recharge, especially on young (<0.1 Ma) ''typical'' crust where permeable basalt is widely exposed, providing numerous pathways for seawater circulation [e.g., *German et al.*, 2004; *Fisher*, 2005]. Patterns of fluid circulation within young typical crust are inferred on the basis of vent distributions and geologic structures, including the presence of faults [e.g., *Haymon et al.*, 1991; *Delaney et al.*, 1992; *Kleinrock and Humphris*, 1996]. Conditions are considerably different at sedimented spreading centers. Because sediment is orders of magnitude less permeable than basalt of the upper oceanic crust [e.g., *Spinelli et al.*, 2004] and it reacts rapidly with recharging fluids, even at relatively low temperatures, geochemical pore water data provide natural tracers that allow recharge paths to be mapped and flow rates to be estimated [e.g., *Wheat and Mottl*, 2004].

[3] Middle Valley on the northern Juan de Fuca Ridge is a sedimented spreading center where moderately-high temperature hydrothermal fluids (up to 280°C) vent at the seafloor [e.g., *Cruse and Seewald*, 2006]. The basaltic crust in Middle Valley is covered with hundreds of meters of sediment in most places, except along the edges of the valley where basement outcrops. Seawater recharge for this hydrothermal system has been hypothesized to occur mainly along bounding faults and exposed basement that flank the valley, based mainly on consideration of thermal data [*Davis and Villinger*, 1992; *Stein and Fisher*, 2001]. One eastern bounding fault in Middle Valley was a target for drilling at Site 855 during Ocean Drilling Program (ODP) Leg 139 [*Davis et al.*, 1992] (Figure 1). We present systematic variations in sediment pore water chemical profiles from a series of holes at Site 855 to test the inference that this eastern bounding fault provides a pathway for seawater recharge, and assess the magnitude of inferred recharge relative to that required to supply venting in Middle Valley.

2. Geologic Setting and Previous Results

[4] Four sites were drilled in Middle Valley to resolve patterns of hydrothermal circulation and its role in the formation of massive sulfide ore deposits (Figure 1a). Site 855 was drilled along an eastern bounding fault, ~3 km from the closest area of hydrothermal venting (Bent Hill, Site 856) and ~6 km from the most active area of venting (Dead Dog, Site 858) [*Davis et al.*, 1992]. The eastern bounding fault at Site 855 dips 45° in towards the center of the valley, and has an offset of ~115 m, which is greater than the local average sediment thickness of ~90 m. This results in exposed basalt along the foot wall of the fault. Holes were drilled at distances of 40 m (Hole 855B), 70 m (Hole 855A), and 125 m (Hole 855C and D) west of the fault scarp (Figure 1b). The first two holes penetrated the foot wall of the fault, whereas the other two holes penetrated basalt (basement) at depths of 98 meters below seafloor (mbsf) (Hole 855C) and 108 mbsf (Hole 855D) in the hanging-wall block, a few tens of meters above the fault plane. The sediment column consists of a single lithologic unit composed mainly of dark green to gray clay. Graded turbidite sequences are common with thicknesses of 13 to 131 cm.

[5] Pore water was extracted from whole-round sections of sediment, squeezed at room temperature, and analyzed using standard shipboard [*Davis et al.*, 1992] and shore-based techniques [*Wheat and Mottl*, 1994]. Results from these analyses indicate that concentrations of dissolved ions in pore waters show systematic variations with depth (Figure 2). Typically, concentrations change from the value in bottom seawater near or at the sediment-water interface and reach a maximum or minimum value within the

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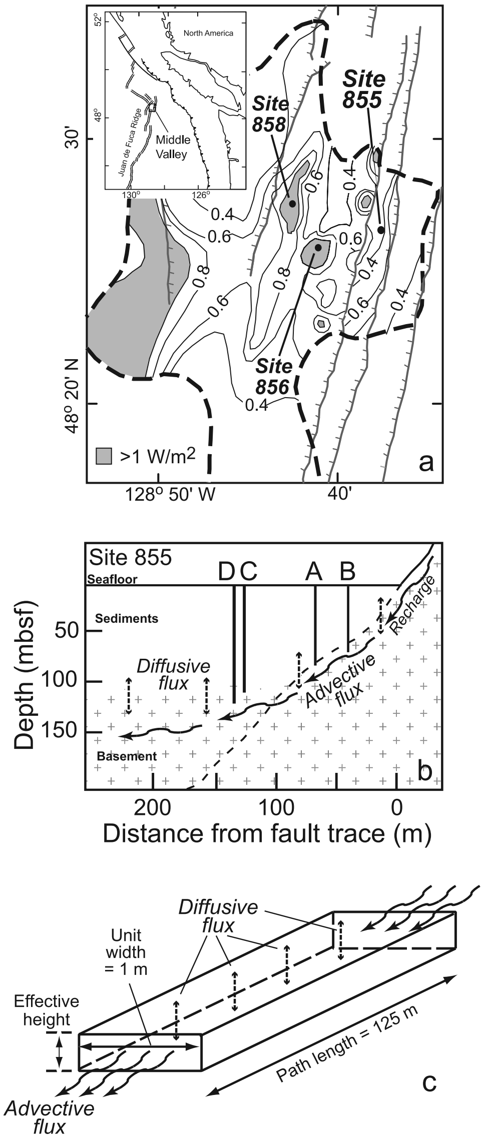

Figure 1. Site map and schematics illustrating processes discussed in this study. (a) Simplified tectonic and heat flow map of Middle Valley (modified from *Davis and Villinger* [1992], *Davis and Fisher* [1994], and *Stein and Fisher* [2001]). Inset shows regional location of Middle Valley. (b) Schematic profile across ODP Site 855, illustrating depths of four boreholes (A–D) and inferred depths to basement. Dashed line indicates inferred fault trace. Wavy lines and arrows show lateral movement of seawater recharge towards areas of high-temperature venting in Middle Valley. Dotted lines and arrows indicate diffusive exchange between the basement aquifer and overlying pore water. (c) Cartoon illustrating model components. The path length is the distance between the inferred point of recharge (intersection of the fault trace with the seafloor) and the farthest borehole (Hole 855C). The effective height is the thickness of the primary interval through which flow occurs, multiplied by the effective porosity. The box represents a unit width (1 m) of the flow path.

sediment column. Below the depth of this maximum or minimum the concentrations returns towards, but not necessarily reach, seawater concentrations at the sediment-basalt interface. Such profiles observed on ridge flanks have been attributed to diagenetic reactions within the sediment and diffusive exchange with bottom seawater that bounds both ends of the sediment column [e.g., *Baker et al.*, 1991].

3. Modeling and Discussion

[6] We constructed coupled fluid-solute transport models based on the hypothesis that hydrothermal recharge in Middle Valley flows from the ocean into the seafloor through valley-bounding normal faults, and then is transported laterally towards the valley center within permeable upper basement basalt [e.g., *Davis and Villinger*, 1992; *Stein and Fisher*, 2001]. Systematic changes in formation fluid composition along the Site 855 transect are used to estimate the rate of fluid transit. Formation fluids initially have the composition of seawater, but as this fluid flows through basement, solutes are exchanged diffusively with the overlying sediments and by reaction with the basaltic matrix through which it flows (Figure 1b). First we will examine the affect of diffusive exchange, then we will further constrain the hydrologic system based on seawater-basalt interactions.

[7] The volumetric flux per unit width perpendicular to flow ($m^3\ yr^{-1}\ m^{-1}$), along the boundary fault within upper basement, is determined from the diffusive flux at the sediment-basement interface (F_d) and the concentrations of bottom seawater and formation fluids (Figures 1c and 2). The diffusive flux perpendicular to fluid flow is modeled as [*Berner*, 1980],

$$F_d = -D_s \partial C/\partial z \tag{1}$$

where D_s is the porosity- and temperature-dependant sediment diffusion coefficient [*Li and Gregory*, 1974] and $\partial C/\partial z$ is the basal pore water chemical gradient (Table 1). In each hole and for each analyte considered, the deepest 4–6 sediment pore water concentrations were fit with a line to determine the gradient. Taking this gradient and extrapolating to the depth of basement determined from drilling data provides an estimate for the composition of the formation fluid [e.g., *Baker et al.*, 1991; *Elderfield et al.*, 1999; *Wheat et al.*, 2000] (Table 2). These estimates have a precision of ~2% for the major ions in seawater and ~5 μmol/kg for dissolved Mn and ammonium [e.g., *Wheat et al.*, 2004] (Tables 1 and 2).

[8] The model consists of a diffusive flux through a length (l), defined by the distance of the furthest borehole from the fault (125 m), a unit width (w) of one meter, and an advective flux within upper basaltic basement. The advective flux along the flow path is calculated from the concentration in seawater (C_{sw}), seawater density (ρ), and the volumetric flux (Q). Provided the volumetric flux is conservative, the chemical flux out (F_o) of the box is the sum of diffusive and advective fluxes:

$$F_o = F_d l w - C_{sw} Q \rho \tag{2}$$

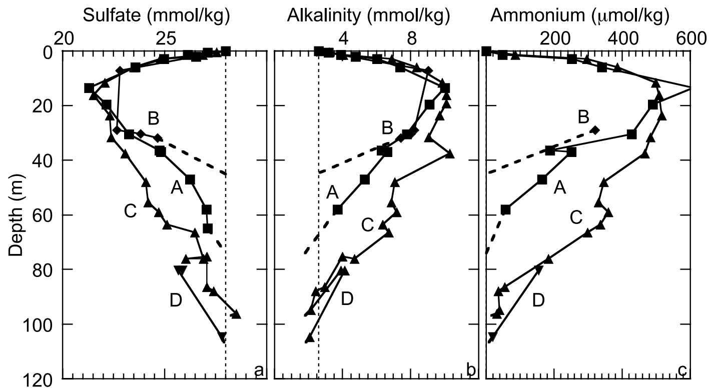

Figure 2. Depth profiles of pore water concentrations of sulfate, ammonium, and alkalinity at Site 855 [*Davis et al.*, 1992]. Dashed lines illustrate extrapolations to the sediment-basalt interface from which estimates of the composition of formations fluids in uppermost basement are based (Tables 1 and 2).

The composition of the formation fluid that exits the box is calculated and compared with the composition of seawater and formation fluids.

[9] The minimum volumetric flux per unit width of the flow path based on the ammonium data is 9 m^3 yr^{-1} m^{-1}, corresponding to a 5% change in basement fluid composition (Figure 3). A smaller volumetric flux, $Q = 3$ m^3 yr^{-1} m^{-1}, results in chemical changes much larger than observed (e.g., ammonium, 14 μmol/kg; alkalinity, 0.15 mmol/kg (6%); and sulfate, 0.9 mmol/kg (3%)) (Figure 3a). At a minimum unit flux of 9 m^3 yr^{-1} m^{-1} none of the other ions (e.g., Mg, Ca, Li, Mn, and sulfate) in formation fluids should be measurably different from those in seawater. Yet, concentrations of some of these elements are markedly different from seawater (Table 2).

[10] This simple model does not account for seawater-basalt reactions within the crust. To constrain the extent of these reactions we compare our data to data for formation fluids from ridge-flank sites ~20 to 40 km to the southeast (ODP Sites 1023–1025, Table 2). Even fluids from the coolest of the three flank sites (Site 1023), where reaction rates are half those at Site 855, have measurable chemical anomalies relative to seawater that are greater than those from Site 855. Formation fluids at these ridge flank sites probably reacted with basement for hundreds of years, given ^{14}C ages (Table 2) [*Elderfield et al.*, 1999] and the tendency for crustal fluids to lose ^{14}C by diffusion during transport [e.g., *Sanford*, 1997]. Thus the fluids at Site 855 must be much younger than those at Sites 1023–1025. Additional age constraints are provided by a 1.3-year-long laboratory seawater-basalt experiment conducted at cooler temperatures [*Seyfried*, 1977]. Fluids from these experiments show changes in concentration similar to those from Hole 855C, suggesting that the formation fluids from Hole 855C may be ≤1 year old, given somewhat higher temperatures at Site 855 than in the experiments. Thus, the lack of change in the calculated formation fluid composition in the presence of overlying pore water gradients constrains the unit volumetric flux (~9 m^3 yr^{-1} m^{-1}), whereas observed changes in the chemical composition of formation fluids resulting from seawater-basalt reaction constrain the age of the fluid (≤1 yr) and the specific discharge (>100 m/yr; distance from fault divided by age).

[11] The effective height of the interval through which seawater flows within basement ($h_{effective}$), the thickness of the basaltic layer multiplied by the effective porosity ($\varphi_{effective}$), is calculated from the volumetric flux per unit width and the specific discharge (Figure 3b). The effective porosity is the well-connected porosity through which most of the fluid flow occurs, and is likely to be considerably less than the bulk porosity of the crust. The effective height is 0.09 m for a unit volumetric flux of 9 m^3 yr^{-1} m^{-1} and a specific discharge of 100 m/yr. As explained earlier, the volumetric flux can not be smaller, and the specific discharge estimate is a minimum, so this is the largest possible effective height. An effective height of 0.09 m corresponds to a permeable basaltic layer 1.5–9 m thick, given an effective porosity of 1 to 5% (Figure 3b). This small effective height is consistent with fluid moving mainly along the valley-bounding fault and the surrounding damaged zone [e.g., *Bruhn*, 1994; *Caine et al.*, 1996], then continuing within basement along one or more thin stratigraphic layers.

[12] If we apply these calculations to the full 17-km-length of the fault adjacent to Site 855 (Figure 1a), the length inferred to contribute recharge to active venting within Middle Valley, the volumetric seawater flux is 1.5×10^5 m^3 yr^{-1}. This flux is only 3% of the estimated high temperature hydrothermal discharge in the valley, based on thermal data from the sediment and the overlying water column [*Stein and Fisher*, 2001]. Given the impermeable nature of sediment relative to basalt and the lack of basaltic outcrops within the central part of Middle Valley,

Table 1. Basal Sediment Pore Water Gradients for Selected Dissolved Ions at ODP Site 855[a]

	855A	855C
Alkalinity (mmol/kg/m)	−0.13	−0.10
Mg (mmol/kg/m)	0.07	0.02
Ca (mmol/kg/m)	−0.06	−0.02
Sulfate (mmol/kg/m)	0.09	0.06
Ammonium (μmol/kg/m)	−7.3	−7.1
Mn (μmol/kg/m)	−1.4	−0.95
Li (μmol/kg/m)	0.04	0.06

[a][*Davis et al.*, 1992; *Wheat and Mottl*, 1994].

Table 2. Compositions of Formation Fluids in Upper Basaltic Basement Estimated From Pore Water Studies on the Juan de Fuca Plate and Results From a 1.3-Year Seawater-(Hydrocrystalline) Basalt Experiment[a]

	BW	855A	855C	Exp.	1023	1024	1025
Temperature (°C)	2	26	34	25	16	23	41
Age (yr)	0			1.3	12,000	13,000	9,900
Alkalinity (mmol/kg)	2.55	1.8	1.8	1.8[b]	2.1	1.8	0.092
Mg (mmol/kg)	52.8	53	51	NC	48	42	27
Ca (mmol/kg)	10.2	10.6	12	12	12	17	36
Sulfate (mmol/kg)	28.1	28.2	28.2	NC	26	25	27
Ammonium (μmol/kg)	0	0	4	—	140	150	48
Mn (μmol/kg)	0	14	0	0	26	18	48
Li (μmol/kg)	26.6	27	24	—	24	27	23

[a]ODP Site 855 [*Davis et al.*, 1992; *Wheat and Mottl*, 1994] and ODP Sites 1023, 1024, and 1025 [*Davis et al.*, 1997; *Elderfield et al.*, 1999; *Wheat et al.*, 2003; *Wheat et al.*, 2004]. 1.3-year seawater-(hydrocrystalline) basalt experiment conducted by *Seyfried* [1977].

[b]During experiments the measured CO_2 decreased from 2.1 to 1.8 mmol/kg. NC means no change in concentration. No data (–).

boundary faults and associated basement outcrops are the most likely source of seawater recharge to the high-temperature vents [*Davis and Fisher*, 1994]. Thus it seems likely that the valley-bounding fault at Site 855, while providing a locally-permeable pathway for recharging fluids, is not typical of the primary recharge path for hydrothermal fluids in Middle Valley. Other faults, or other sections of the fault near Site 855, must provide more efficient pathways for recharging the remaining 97% of present day hydrothermal discharge. Of course, Site 855 samples a small part of a large and complex hydrogeological system; it would have been fortuitous if Site 855 were positioned where hydrogeologic properties and processes are typical of the primary recharge path(s). Even the recharge rates calculated in the present study at Site 855, which must be slower than most of the recharge supporting high-temperature hydrothermal vents in Middle Valley, are sufficiently rapid so as to prevent significant diffusive exchange with overlying sediments. These rapid rates of hydrothermal recharge also must limit the extent of water-rock interaction as recharge flows through basement, until these fluids are heated and have an opportunity to convect in the reaction zone below the vent fields.

[13] Resolving recharge paths for hydrothermal fluids along bare-rock spreading centers can be attempted using methods similar to those used here, but there are additional challenges. The lack of a sediment cap allows recharge to occur virtually anywhere that basalt is exposed. In addition, the lack of sediment makes sampling formation fluids, which were critical to the present study to assess fluid and solute fluxes, difficult. On the other hand, the relatively rapid rate of recharge inferred in Middle Valley, even along a flow path that contributes a small portion of the hydrothermal flux, suggests that tracer injection experiments may be possible within these systems, provided one can find a suitable site where the tracer can be introduced to the subsurface.

4. Conclusions

[14] We present pore water chemical data from Site 855 on the edge of Middle Valley, a sedimented spreading center

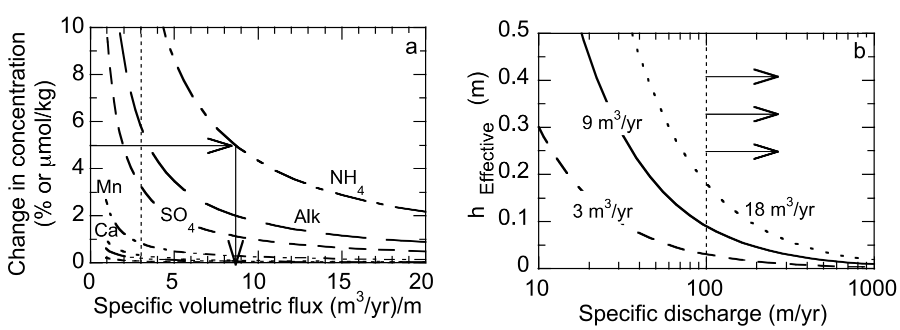

Figure 3. (a) Per cent (Ca, Mg, Li, sulfate, and alkalinity) or calculated (μmol/kg; ammonium and Mn) change in concentration as a function of the specific volumetric flux per unit width. None of the calculated values for Mg or Li are above 0.65%. Limits for detecting a change in the formation fluid concentration is ~2% of the seawater concentration for Ca, Mg, Li, sulfate and alkalinity and ~5 μmol/kg for Mn and ammonium. A volumetric flux of 9 $m^3\ yr^{-1}\ m^{-1}$ results in a change of ~5 μmol/kg ammonium, consistent with pore water data; in this setting basalt is not a likely source for ammonium at these concentrations. A dashed line for a specific volume flux of 3 $m^3\ yr^{-1}\ m^{-1}$ illustrates that such a low fluid flux results in calculated changes that are greater than those observed (Table 2). (b) The effective height of water (layer thickness multiplied by effective porosity) is constrained by a specific discharge of $\geq$100 m yr^{-1}, based on results of low-temperature seawater-basalt experiments, and a volumetric flux that is $\geq$9 $m^3\ yr^{-1}$.

on the northern Juan de Fuca Ridge, to constrain hydrogeologic pathways and processes associated with recharge through a valley-bounding fault. Pore water chemical data from a transect of sites above the fault are consistent with the hypothesis that that the fault provides a pathway for seawater to enter permeable basement and flow towards high-temperature vent fields several kilometers to the west; however, the calculated rate of recharge at Site 855 is so low that it can account for only ~3% of that needed to sustain hydrothermal vent fields currently active in Middle Valley, even when it is assumed that a 17-km-long section of the fault contributed to recharge. Calculations show that recharge near Site 855 flows within a thin layer of uppermost basement. Therefore, most of the recharge to this system must occur elsewhere through more transmissive pathways.

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References

Baker, P. A., P. M. Stout, M. Kastner, and H. Elderfield (1991), Large-scale lateral advection of seawater through oceanic crust in the central equatorial Pacific, *Earth Planet. Sci. Lett.*, *105*, 522–533.

Berner, R. A. (1980), *Early Diagenesis*, Princeton Univ. Press, Princeton, N. J.

Bruhn, R. L. (1994), Fracturing in normal fault zones: Implications for fluid transport and fault stability, in *The Mechanical Involvement of Fluids in Faulting*, edited by S. H. Hickman, R. Sibson, and R. Bruhn, pp. 231–246, U. S. Geol. Surv., Menlo Park, Calif.

Caine, J. S., J. P. Evans, and C. B. Forster (1996), Fault zone architecture and permeability structure, *Geology*, *24*, 1025–1028.

Cruse, A. M., and J. S. Seewald (2006), Geochemistry of low-molecular weight hydrocarbons in hydrothermal fluids from Middle Valley, northern Juan de Fuca Ridge, *Geochim. Cosmochim. Acta*, *70*, 2073–2092.

Davis, E. E., and A. Fisher (1994), On the nature and consequences of hydrothermal circulation in the Middle Valley sedimented rift: Inferences from geophysical observations, *Proc. Ocean Drill Program Sci. Results*, *139*, 695–718.

Davis, E. E., and H. Villinger (1992), Tectonic and thermal structure of the Middle Valley sedimented rift, northern Juan de Fuca Ridge, in *Middle Valley, Juan de Fuca Ridge*, *Proc. Ocean Drill. Program Initial Rep.*, vol. 139, edited by L. H. Dearmont, pp. 9–41, Ocean Drill Program, College Station, Tex., doi:10.2973/odp.proc.ir.139.102.1992.

Davis, E. E., et al. (1992), *Middle Valley, Juan de Fuca Ridge*, *Proc. Ocean Drill. Program Initial Rep.*, vol. 139, edited by L. H. Dearmont, 1026 pp., Ocean Drill. Program, College Station, Tex., doi:10.2973/odp.proc.ir.139.1992.

Davis, E. E., et al. (1997), *Hydrothermal Circulation in the Oceanic Crust: Eastern Flank of the Juan de Fuca Ridge: Sites 1023–1032* [CD-ROM], *Proc. Ocean Drill. Program Init. Rep.*, vol. 168, edited by A. T. Miller, 470 pp., Ocean Drill. Program, College Station, Tex.

Delaney, J. R., V. Robigou, R. McDuff, and M. Tivey (1992), Geology of a vigorous hydrothermal system on the Endeavor segment, Juan de Fuca Ridge, *J. Geophys. Res.*, *97*, 19,663–19,682.

Elderfield, H., C. G. Wheat, M. J. Mottl, C. Monnin, and B. Spiro (1999), Fluid and geochemical transport through oceanic crust: A transect across the eastern flank of the Juan de Fuca Ridge, *Earth Planet. Sci. Lett.*, *172*, 151–169.

Fisher, A. T. (2005), Marine hydrogeology: Recent accomplishments and future opportunities, *Hydrogeol. J.*, *13*, 69–97.

German, C. R., J. Lin, and L. Parson (2004), *Mid-Ocean Ridges, Hydrothermal Interactions Between the Lithosphere and Oceans*, *Geophys. Monogr. Ser.*, vol. 148, 318 pp., AGU, Washington, D. C.

Haymon, R. M., D. J. Fornari, M. H. Edwards, S. Carbotte, D. Wright, and K. C. Macdonald (1991), Hydrothermal vent distribution along the East Pacific Rise crest (9°09′–54′N) and its relationship to magmatic and tectonic processes on fast-spreading mid-ocean ridges, *Earth Planet. Sci. Lett.*, *102*, 513–534.

Kleinrock, M. C., and S. E. Humphris (1996), Structural control on seafloor hydrothermal activity at the TAG active mound, *Nature*, *382*, 149–153.

Li, Y.-H., and S. Gregory (1974), Diffusion of ions in sea water and in deep-sea sediments, *Geochim. Cosmochim. Acta*, *38*, 703–714.

Sanford, W. E. (1997), Correcting for diffusion in Carbon-14 dating of ground water, *Ground Water*, *35*(2), 357–361.

Seyfried, W. E. (1977), Seawater-basalt interaction from 25°–300°C and 1–500 bars: Implications for the origin of submarine metal-bearing hydrothermal solutions and regulation of ocean chemistry, Ph.D. dissertation, 242 pp., Univ. South. Calif., Los Angeles.

Spinelli, G., E. Giambalvo, and A. T. Fisher (2004), Hydrologic properties and distribution of sediment, in *Hydrogeology of the Oceanic Lithosphere*, edited by E. E. Davis and H. Elderfield, pp. 151–188, Cambridge Univ. Press, Cambridge, U. K.

Stein, J. S., and A. J. Fisher (2001), Multiple scales of hydrothermal circulation in Middle Valley, northern Juan de Fuca Ridge: Physical constraints and geologic models, *J. Geophys. Res.*, *106*, 8550–8563.

Wheat, C. G., and M. J. Mottl (1994), Data report: Trace metal composition of pore water from Sites 855 through 858, Middle Valley, Juan de Fuca Ridge, *Proc. Ocean Drill. Program Sci. Results*, *139*, 749–755.

Wheat, C. G., and M. J. Mottl (2004), Geochemical fluxes through mid-ocean ridge flanks, in *Hydrolgeology of the Oceanic Lithosphere*, edited by E. E. Davis and H. Elderfield, pp. 627–658, Cambridge Univ. Press, Cambridge, U. K.

Wheat, C. G., H. Elderfield, M. J. Mottl, and C. Monnin (2000), Chemical composition of basement fluids within an oceanic ridge flank: Implications for along-strike and across-strike hydrothermal circulation, *J. Geophys. Res.*, *105*, 13,437–13,447.

Wheat, C. G., H. W. Jannasch, M. Kastner, J. N. Plant, and E. H. DeCarlo (2003), Seawater transport and reaction in upper oceanic basaltic basement: Chemical data from continuous monitoring of sealed boreholes in a mid-ocean ridge flank environment, *Earth Planet. Sci. Lett.*, *216*, 549–564.

Wheat, C. G., H. W. Jannasch, M. Kastner, J. N. Plant, E. H. DeCarlo, and G. Lebon (2004), Venting formation fluids from deep-sea boreholes in a ridge flank setting: ODP Sites 1025 and 1026, *Geochem. Geophys. Geosyst.*, *5*, Q08007, doi:10.1029/2004GC000710.

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