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Endeavour Segment of the Juan de Fuca Ridge

ONE OF THE MOST REMARKABLE PLACES ON EARTH

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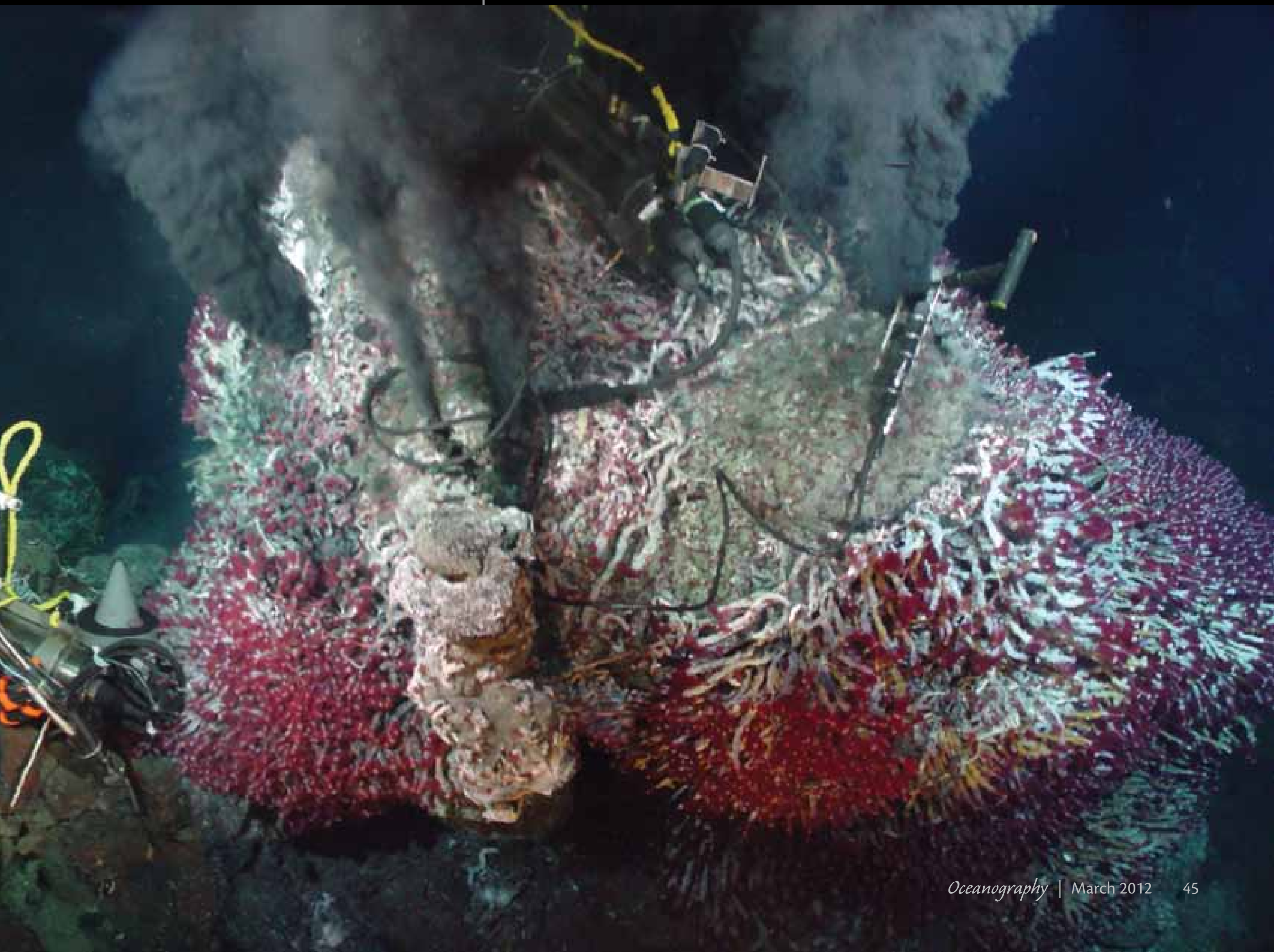
This photomosaic of the hydrothermal edifice called Sully in the Main Endeavour Field, Endeavour Segment of the Juan de Fuca Ridge, shows multiple black smoker orifices present in 2004. The active chimneys host lush tubeworm colonies. This edifice was the first place where successful measurements of the "sounds" of black smokers were made (sensor at top of chimney on right; Crone et al., 2006), leading to the hypothesis that vent sounds may provide navigational cues for organisms in the deep sea. It has also been instrumented several times with a temperature-chlorinity probe (sensor to left of chimney; e.g., Larson et al., 2009) to investigate active boiling processes. The pressure housing of the temperature-chlorinity probe is 50 cm long, and the edifice is at a water depth of ~ 2,200 m. The images were taken with the Canadian robotic vehicle ROPOS on Dive 849 in 2004. M. Elend, University of Washington, completed the photomosaic.

ABSTRACT. Endeavour Segment of the Juan de Fuca Ridge is one of three Integrated Study Sites for the Ridge 2000 Program. It is a remarkable, dynamic environment hosting five major hydrothermal fields, numerous smaller fields, and myriad diffuse-flow sites; magma chambers underlie all fields. Over 800 individual extinct and active chimneys have been documented within the central ~ 15 km portion of the ridge, with some edifices reaching 50 m across and up to 45 m tall. Fluid flow is focused along faults within the rift zone, and seismically active faults along the western axial valley wall have been used by both magmas and upwelling hydrothermal fluids. There is significant chemical heterogeneity in basalt compositions within the axial rift valley, with the greatest diversity occurring near the base of the western axial valley wall where normal, transitional, and enriched type mid-ocean ridge basalts occur within tens of meters of each other. Endeavour is the only site where seismic intensity has been linked directly to heat flux at the individual vent field scale. Installation of the world's first high-power and high-bandwidth cabled observatory at Endeavour via NEPTUNE Canada ensures that new discoveries along the Juan de Fuca Ridge will continue into the future.



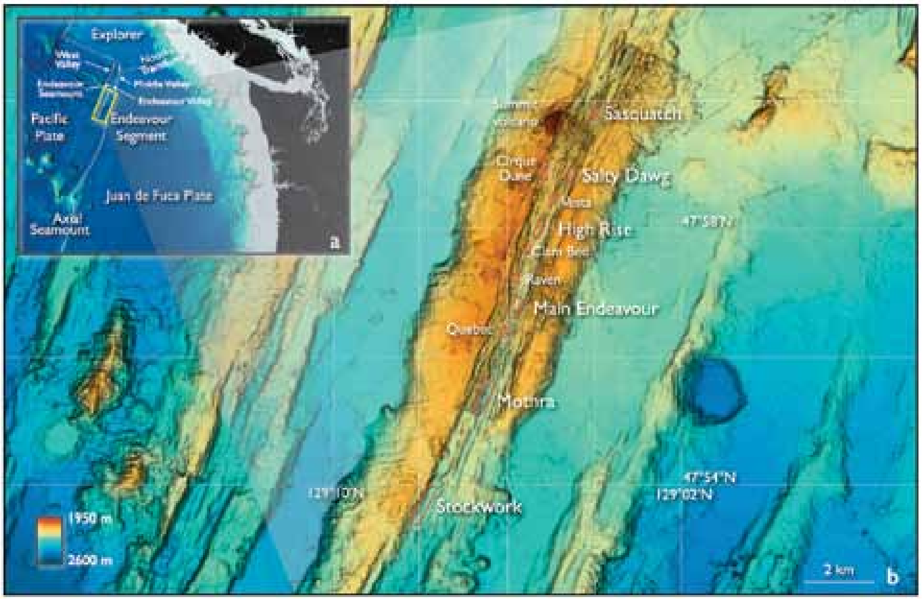


Figure 1. (a) The Endeavour Segment is located ~ 300 km off the coast of Vancouver Island and is a Canadian Marine Protected Area. It is bounded to the north by Middle Valley and West Valley, and to the south by the Cobb propagator. (b) The Main Endeavour Field was chosen as the Ridge 2000 Endeavour Integrated Study Site bull's-eye because of its large and vigorously venting sulfide structures, because it was believed to be dominantly in a tectonic phase with significant seismic activity, and because it had a rich history of study by a diverse array of investigators. The lower-resolution multibeam bathymetry was collected during the University of Washington Keck-funded cruises using the R/V *Thompson* EM300 system. The ~ 5 m resolution bathymetry was collected during the Keck-University of Washington Visions05 (http://www.visions05.washington.edu) cruise using the autonomous underwater vehicle *ABE* as part of a site survey effort for NEPTUNE Canada.

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THE ENDEAVOUR INTEGRATED STUDIES SITE

The Endeavour Segment of the Juan de Fuca Ridge is one of the most remarkable submarine volcanic-hydrothermal systems on Earth. It was chosen as a Ridge 2000 Program Integrated Study Site (ISS) to advance understanding of linkages among physical, chemical, and biological processes at an intermediate-spreading mid-ocean ridge (Figures 1 and 2). At the time of the ISS implementation in 2003, the hallmark features of this area, which made it an engaging and exciting area for interdisciplinary investigations, included:

- The presence of five known major hydrothermal fields at various stages of evolution and numerous smaller fields, all within a distance of 15 km
- Steep gradients between and within the vent fields in solution chemistry, volatiles, and temperature
- Intense phase separation processes (boiling and condensation) ongoing for over two decades with fluid temperatures up to 402°C and fluids with a salinity one-tenth that of seawater
- Dense and diverse biological communities in myriad diffuse-flow sites both within the vent fields and distal to them
- An overlying dynamic hydrothermal plume along much of the central portion of the segment
- High levels of seismicity, well-monitored though the Sound Surveillance System (SOSUS) array
- A magma-driven hydrothermal system markedly different than the one present beneath the East Pacific Rise (EPR), with hydrothermal edifices > 30 m tall common

In addition, the 1999–2000 seismic events and associated injection of melt beneath the Endeavour Segment (Davis et al., 2001; Lilley et al., 2003; Bohnenstiehl et al., 2004, Wilcock et al., 2009); the prior > 15 year history of mapping, sampling, and outreach activities; and strong collaborative efforts with Canadian scientists working within this Marine Protected Area made Endeavour an optimal site to study one of the key questions in the Ridge 2000 Program: how do biological, chemical, thermal, and hydrological processes respond to magmatic/tectonic events?

This past decade of Ridge Interdisciplinary Global Experiments (RIDGE), Ridge 2000, and associated studies at Endeavour were largely funded by a five-year award to the University of Washington (UW) from the W.M. Keck Foundation. This work has resulted in a series of spectacular discoveries about this complex volcanic, tectonic, and hydrothermal setting and has highlighted many of the significant differences between this system and that operating at the EPR—an ISS site focused on a volcanically active, fast-spreading mid-ocean ridge (Table 1). Endeavour hosts some of the most intensely active hydrothermal fields known, with > 800 individual extinct and active chimneys documented within the central ~ 15 km portion of the ridge (Clague et al., 2008). Indeed, one sulfide-hosted microbe recovered from the Mothra Hydrothermal Field grows at 121°C—only one organism has been cultured at higher temperatures (122°C) (Kashefi and Lovely, 2003; Takai et al., 2008). Long-lived chimneys at times have grown to 45 m above the surrounding seafloor and 50 m across. Endeavour is the only area where seismic intensity has been linked directly to heat flux at the individual vent-field scale (Wilcock et al., 2007; Kellogg, 2011). Although it was initially believed that basalts comprising the flanks were much older than the flows in the axial rift, new geological observations and U-Th disequilibria indicate that most axial valley basalts and some on both flanks are Holocene in age (Gill and Michael, 2008; Dreyer et al., 2010). Other surprising finds are that at least 10 discrete mantle melting episodes

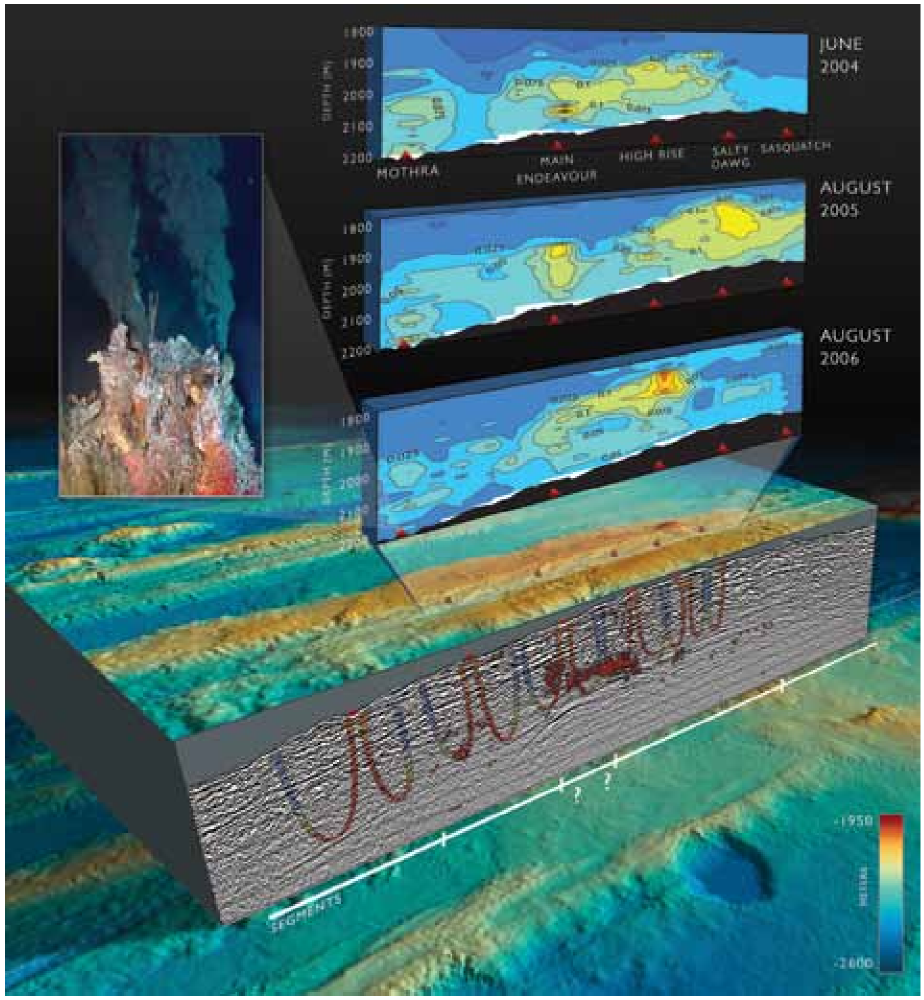

Figure 2. Interdisciplinary lithosphere-to-hydrosphere representation of Endeavour Segment. This image shows the surface bathymetry underlain by multichannel seismic results from Carbotte et al. (2002) and Van Ark et al. (2007). For ease in viewing and graphical representation, the along-axis transect has been moved slightly to the east of the ridge axis; the white dashed line indicates the location of the along-axis survey line within the axial rift. A magma chamber reflector is found beneath all five of the vigorously venting hydrothermal fields (red triangles), as well as beneath the newly discovered Stockwork system to the far south, which is underlain by another strong reflector defined by Van Ark et al. (2007). The magma chamber near the inflated, shallowest section of the ridge shoals to a depth of ~ 2.1 km beneath the seafloor and deepens significantly to the south to a depth of 3.3 km (Van Ark et al., 2007). Differences in seismic reflection indicate that the magma chamber is composed of about four sections. The red circles show the hypocenters for double-difference locations lying within 1 km of the location of the seismic profile (Wilcock et al., 2009). Also shown are inferred patterns of upflow and downflow (arrows) as first described by Delaney et al. (1997). The three panels projected above the spreading center show the potential temperature anomaly sections resulting from repeat hydrography surveys in the summers of 2004–2006 (Kellogg and McDuff, 2010). Historically, the Main Endeavour and High Rise hydrothermal fields have yielded the largest and most intense buoyant plumes, corresponding to the largest and most vigorously venting hydrothermal structures and the most intense seismic activity. Also shown is an image of the 380°C hydrothermal vent Sully, hosting a vibrant tubeworm community.

at Endeavour have produced different parental magmas in the last 10,000 years, and that these magmas were not homogenized in the kind of axial magma chambers that underlie Endeavour today (Woodcock et al., 2007, and recent work of author Gill). Installation of the world's first high-power (10 kW) and high-bandwidth (10 Gbs) cabled observatory at Endeavour via NEPTUNE Canada and at Axial Seamount through the National Science Foundation's Ocean Observatories Initiative (OOI) ensures that new discoveries along the Juan de Fuca Ridge will continue into the future with special emphasis on the time domain.

GEOLOGIC OVERVIEW

The 90 km long Endeavour Segment is part of a dueling propagator with the Cobb Segment to the south and Middle/West Valley to the north (Figure 1; Karsten et al., 1986). The central third of the segment is a 25 km long volcanic high split by a 75–200 m deep, 0.5–1 km wide steep-sided axial rift. This central rift hosts five major hydrothermal vent fields (from north to south: Sasquatch, Salty Dawg, High Rise, Main Endeavour, Mothra), more recently discovered smaller fields (Raven, Stockwork), and several distal, diffusely venting fields (Cirque, Dune, Clam Bed, Quebec), making it one of the most active hydrothermal areas known on the mid-ocean ridge (MOR) system (Figure 1; Kelley et al., 2002). The valley exhibits an hourglass shape, becoming narrowest immediately south of Main Endeavour Field (MEF) and broadening to a width of ~ 3 km at the south end of the segment (Delaney et al., 1992). The northern portion also broadens, with intense horst and dissected ridge development beginning near High Rise and extending north of Summit Volcano.

The outer flanks of the ridge are bounded to the east and west by low-relief, several-kilometer-wide plains, which were initially believed to be heavily sedimented (Figure 1). Based on 2001–2005 UW and joint UW-Monterey Bay Research Aquarium Institute (MBARI)

Table 1. Comparison of Endeavour Segment and East Pacific Rise Integrated Study Site Characteristics

	East Pacific Rise	Endeavour
Spreading Rate	• 110 km per million years	• 60 km per million years
Axial graben/trough	• < 5–15 m deep • < 50–400 m width	• 75–200 m deep • < 500 m–1 km width
Axial magma chamber	• Four segments[1,2,3] • ~1.4–1.7 km deep	• Four segments[3,4] • 2.1–3.3 km deep
Basalts	• More evolved to south[5] • Mainly N-MORB	• More evolved to south[6,7] • Wide range in chemistry independent of differentiation (60% E-MORB)
Flows	• Frequent eruptions (decade)[8–11] • Sheet flows dominate axis • Overfilling of axial summit trough common	• Less frequent intrusions common[7,12,13] • Sheet flows, lobate, pillows • Flank eruptions common – pillows
Faults	• Hundreds of meters in length, < 10 m throw[10] • Volcanic overprinting	• 1 km length, tens of meters throw[12–13] • Highly tectonized
Black smokers	• < 30 vents over 18 km[11, 14–16] • Typically < 10 m tall pinnacles common	• > 800 chimneys over 15 km[12,13,17–19] • Five major hydrothermal fields • Rise up to 45 m above seafloor • Up to 600 m in length
Diffuse flow	• ~ 10 x 10 m in area, sparse[11,14] • Perturbed by seismic events	• ~ 20 x 50 m or more in area, common[12,18,20,22] • Proximal and distal to major fields • Perturbed by seismic events
Fluids	• Phase separation common [16–23] • Perturbed by eruptions • Basaltic influence	• Phase separation common[24–26] • Enriched in NH_4, relatively high pH, $\delta^{13}CCH_4$ ~ 55‰ • Basaltic and sediment influence

[1]Harding et al., 1993; [2]Kent et al., 1993; [3]Carbotte et al., 2012, in this issue; [4]Van Ark et al., 2007; [5]Smith et al., 2001; [6]Karsten et al., 1990; [7]current work of author Gill and colleagues; [8]Perfit and Chadwick, 1998, [9]Soule et al., 2005; [10]Escartín et al., 2007; [11]Fornari et al., 2004; [12]Delaney et al., 1992, [13]Glickson et al., 2007; [14]Shank et al., 1998, [15]Ferrini et al., 2007, [16]Von Damm et al., 2000; [17]Robigou et al., 1993; [18]Kelley et al., 2002; [19]Clague et al., 2008; [20]Lilley et al., 2003; [21]Wilcock et al., 2009; [22]Hooft et al., 2010; [23]Von Damm, 1995; [24]Butterfield et al., 1994; [25]Delaney et al., 1997; [26]Lilley et al., 1993. N-MORB = Normal mid-ocean ridge basalt. E-MORB = Evolved mid-ocean ridge basalt.

surveys of this area, it is now clear that the eastern plain is marked by very extensive sheet flows and collapse basins, with only with only 10–15 cm of sediment. In contrast, the half-ridge located ~ 3 km east of the ridge flanks is capped by ~ 1 m of sediment. It is presumed that the flows covered the thick pre-existing sediment cover. However, these flows did not breach Endeavour Segment because the western plain is still capped by a thick sediment cover.

CHALLENGING THE LONG-STANDING BELIEF THAT ENDEAVOUR WAS IN A TECTONIC PHASE

Early seismic studies of Endeavour Segment found no evidence for a significant crustal magma body beneath the ridge axis (Cudrack and Clowes, 1993). This ridge segment was long believed to be in a tectonic state, with robust hydrothermal venting fueled by heat mined from the cooling lower crust (Wilcock and Delaney, 1996). This view was called into question when new seismic studies conducted at Endeavour under the Ridge 2000 Program detected a bright seismic reflection in the mid-crust consistent with the presence of melt (Figure 2; Carbotte et al., 2006, and 2012, in this issue; Van Ark et al., 2007). This reflection, interpreted to arise from a thin sill of magma, is detected beneath the 25 km long rifted axial high within the center of Endeavour Segment. From north to south, it is at a depth of 2.2 to 3.3 km beneath the seafloor. From variations in the depth, width, and amplitude of the magma lens reflection imaged on a suite of across- and along-axis seismic lines, the magma body is inferred to be segmented, with possible segment boundaries at ~ 47°54.7'N, 47°56.8'N, and 48°00.5'N (Figure 1; see Van Ark et al., 2007; Carbotte et al., 2012, in this issue). At the seafloor, offsets in the faults bounding the axial rift and local constrictions in the bow-form topography of the axial rift shoulders define a morphological segmentation of the axis that is coincident with the segmentation of the magma lens (Figure 2).

The new seismic studies also provide information on the structure of the upper crust, which bears on how the volcanic layer is constructed and, indirectly, on hydrothermal flow and alteration within the upper crust. Seismic Layer 2A, believed to correspond with all or part of the lava section of the crust, is well imaged along the central portion of Endeavour: it is 330 m thick on average, thickening to the northern and southern ends of the segment (Van Ark et al., 2007). While Layer 2A is thicker on the ridge flanks (average thickness of 550 m), no clear pattern of off-axis thickening is observed. Based on interpretations of seismic data, accumulation of the extrusive layer appears to be largely confined to the axial region at this ridge, although direct imaging shows that recent volcanism occurs on the ridge flanks as well (recent work of author Gill). The existing data indicate a 10–20% increase in seismic velocities within a few kilometers of the axis. The increases in velocities are attributed to crack closure and porosity infilling with precipitation of alteration minerals linked to ridge-axis hydrothermal flow (Cudrack and Clowes, 1993; Van Ark et al., 2007; Nedimović et al., 2008). Following this rapid near-axis change, seismic Layer 2A velocities increase gradually over several million years due to ongoing low-temperature hydrothermal alteration on the ridge flanks (Rohr, 1994; Nedimović et al., 2008).

ENDEAVOUR PETROLOGY: CHEMICAL HETEROGENEITY AT SMALL SCALES AND COMPLEX MELT DELIVERY

Mid-ocean ridge basalts have been chemically classified into three broad groups, which depend on the degree of partial melting of the upper mantle and mixing processes: (1) normal mid-ocean ridge basalts (N-MORBs) that are believed to tap depleted upper mantle sources (i.e., depleted in the incompatible elements Cs, Rb, Ba, U, Th, Nb, K, and the light rare earth elements), (2) enriched MORBS (E-MORBS) generally originating in more fertile mantle (enriched in those incompatible elements), and (3) transitional MORBS (T-MORBS) that may result from mixing of N- and E-MORBs during upward migration of melts and/or within magma chambers. In detail, however, the interpretation of basaltic sources and processes that impact the chemical evolution of melts must be based on co-registered, detailed chemical and isotopic analyses to tease out specific processes. To examine the relationships among melt sources, melt storage, eruptive history, and development of ridge morphology at Endeavour, more than 250 basalt samples have been analyzed for major elements. Sample locations include the axial rift and adjacent flanks, stretching from Sasquatch to ~ 4 km south of Mothra (Figure 3). A large subset of the samples has also been analyzed for volatiles, trace elements, Sr-Nd-Hf-Pb-He isotopes, and U-Th disequilibria (Woodcock et al., 2007; Harris et al., 2008; Gill and Michael, 2008). The submersible *Alvin* and numerous robotic vehicles collected the basalts, and their positions were co-registered with the most recent high-resolution, near-bottom bathymetric maps generated by integrating sonar data collected by autonomous vehicles from MBARI (Clague et al., 2008) and the National Deep Submergence Facility (*ABE*). In concert, these analyses provide new insights into chemical heterogeneities at < 1 km scales and indicate that rift-bounding faults may play important roles in delivery of melts to the seafloor (Gill and Michael, 2008; Harris et al., 2008).

Recent work by Gill shows that basalt types within the Endeavour system have an along-axis range in differentiation that is similar to the EPR at 9°N; however, what sets Endeavour apart is the wide range of compositions independent of differentiation. At Endeavour, the basalts are most mafic (> 7.5% MgO) in the northern axial valley where the ridge is most shallow (Figure 3). Here, the hottest (most MgO-rich) magmas and the principal melt focusing for Endeavour occur at ~ 48°N, adjacent to Summit Volcano on the north end of the western flank (Gill and Michael, 2008). Lavas that span the chemical range for this segment extend southward along the axial valley for 2–3 km from this shallowest point, and they generally drop to ~ 7 wt % MgO between the High Rise and Main Endeavour hydrothermal fields.

Basalts on the east flanks of Endeavour are chemically homogeneous. In contrast, the westernmost west flank consists mostly of older small volcanic constructional highs of T-MORB pillow lava, surrounded by later sheet-to-lobate E-MORB flows (recent work by author Gill). An important new observation arising from this study is that the asymmetry in shape and distribution of surface basalt chemistry between the two flanks precludes a simple split-volcano hypothesis, indicating substantial off-axis magmatism on both sides of the axial valley that is not well resolved by seismic studies.

Trace element chemistry and isotopic analyses indicate a complex melt evolution history. There are threefold ranges in K/Ti and La/Yb ratios for N-MORB to E-MORBs that correlate as expected with subtle variations in all isotope ratios. However, both maximum and minimum isotope ratios occur at intermediate K/Ti, so that T-MORBs are not just mixtures of N-MORB and E-MORBs. The maxima ratios, especially in Pb isotopes, are associated with Ti and Nb enrichments. They differ from the enrichment pattern in the southern Juan de Fuca Ridge and East Pacific Rise, but are similar to the pattern in the Middle Valley and Explorer segments to the north. This diversity in incompatible trace element and isotope ratios has been combined with bathymetry and geology to identify "chemo-stratigraphic units" that may correspond to separate episodes of eruption, filling of crustal magma lenses, and mantle melting (Woodcock et al., 2007; Gill and Michael, 2008).

In detail, all basalt types occur within the axial rift valley where about half are E-MORB, half T-MORB, and < 10% N-MORB. The greatest geochemical diversity is near the base of the western wall where all basalt types occur within tens of meters of one another. This fault is also the western terminus of the current axial magma chamber and is the main structural control for fluid flow that feeds the southern hydrothermal fields (Delaney et al., 1992; Kelley et al., 2001b; Glickson et al., 2007). It has also been the locus of past seismic swarms (Wilcock et al., 2002). Surprisingly, both magmas and fluids appear to rise along fractures within this fault system (Gill and Michael, 2008). Because magma types there are so diverse, they either skirted the axial magma chamber (AMC) or the Endeavour AMCs are short-lived relative to the frequency of magmatism near the wall.

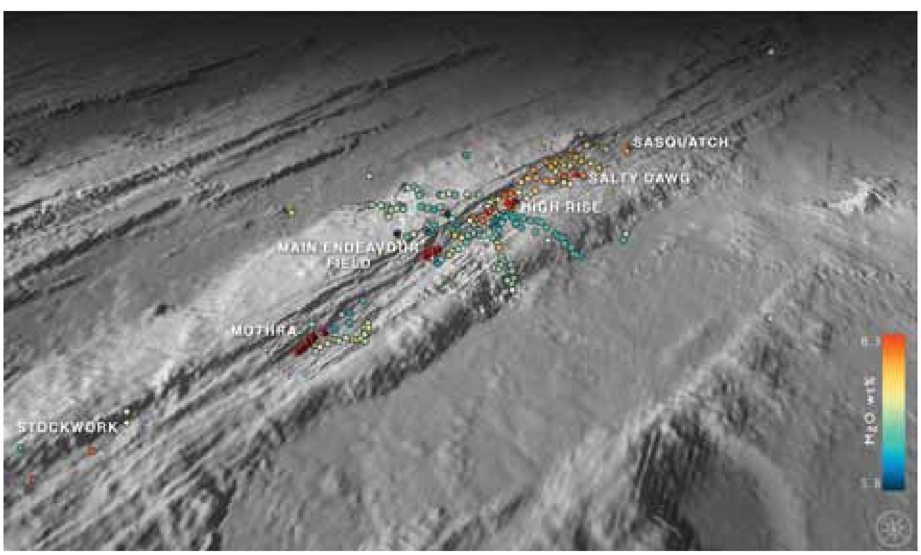

Figure 3. Gray-scale bathymetric map showing the location of basalt samples collected on myriad submersible and ROV dive programs, with colored circles indicating the ranges in MgO wt % from recent work by author Gill. The most primitive (mafic: > 7.5% MgO) rocks, with highest melt temperatures are in the north where vent fields are more closely spaced. Sasquatch vent fluids also have the highest CO_2 concentrations (not affected by diking events), while Mothra, to the south, historically has had the lowest CO_2 concentrations (though there has been limited sampling at both fields; Proskurowski et al., 2004).

SEGMENTATION, VENT FIELDS, AND RECHARGE

A major driver for choosing Endeavour initially as a Ridge 2000 ISS was because it is one of the most hydrothermally active areas along the global MOR, with numerous active and inactive chimneys densely concentrated over 15 km of ridge axis (Figure 1). At the inception of the Ridge 2000 Program, it was believed that there were five major, discrete vent fields with spacing between fields increasing from about 1.5 km in the north to 3 km to the south. However, it is now clear that numerous other smaller black-smoker sites, and abundant areas of diffuse flow, occur along the > 15 km segment hosting the major vent fields (Figure 1; Delaney et al., 1992; Robigou et al., 1993; Kelley et al., 2001a,b; Glickson et al., 2007). Each of the major high-temperature fields extends over several hundred meters along axis, and each hosts multiple sulfide structures that are large compared to those at many slow- and fast-spreading ridges (Figures 1 and 4; Table 2; Delaney et al., 1992, 1997; Robigou et al., 1993; Kelley et al., 2001a,b; Glickson et al., 2007; Kelley and Shank, 2010).

Vent field abundances within Endeavour Segment increase to the north, and the distances between them decrease in the same direction. Their spacing is closest at the shallowest portion of the segment and where MgO basalt chemistry indicates melts are the hottest (i.e., AMC depth minimum; Figures 2 and 3). The Main Endeavour and High Rise fields are the most robustly venting, have the largest chimney structures, and historically have had the highest vent temperatures (Delaney et al., 1992). Venting has been long-lived at many of the fields (e.g., High Rise, MEF, Mothra) as evidenced by the massive sizes of the active chimneys (some are 50 m across and 45 m tall) and by extinct massive sulfide deposits that are 500 m in length (Figures 4 and 5). Recent dating of sulfides using $^{226}Ra/Ba$ ratios shows that the MEF has been active for at least ~ 2,400 years (Jamieson et al., 2011).

In addition to the largest fields, there are also smaller sites of black smoker activity that include a small venting area south of Salty Dawg, called Vesta, and the Raven field, just north of the MEF (Figure 1). Less commonly, there are also present and past sites of black smoker activity on the western and eastern axial rift walls. For example, the Cirque site, located southwest of Salty Dawg at a water depth of ~ 2,130 m, contains weakly venting 4–5 m tall black smokers that in 1995 were venting 31°C fluids (Figure 1). In 2006, extinct sulfides were recovered near the summit of the eastern valley wall northeast of the Mothra hydrothermal field. Numerous small extinct chimneys rise through the talus slope along the western rift wall at Mothra and within the Stockwork area (Kelley et al., 2001a; Glickson et al., 2006).

Although the fields have been well studied with respect to vent fluid chemistry and to a lesser extent sulfide chemistry (e.g., Butterfield et al., 1994; Tivey et al., 1999; Lilley et al., 2003; Proskurowski et al., 2004; Kristall et al., 2006), only Mothra has been well characterized with respect to its geology: it is the only field within the segment for which a detailed geologic-tectonic base map has been produced (Glickson et al.,

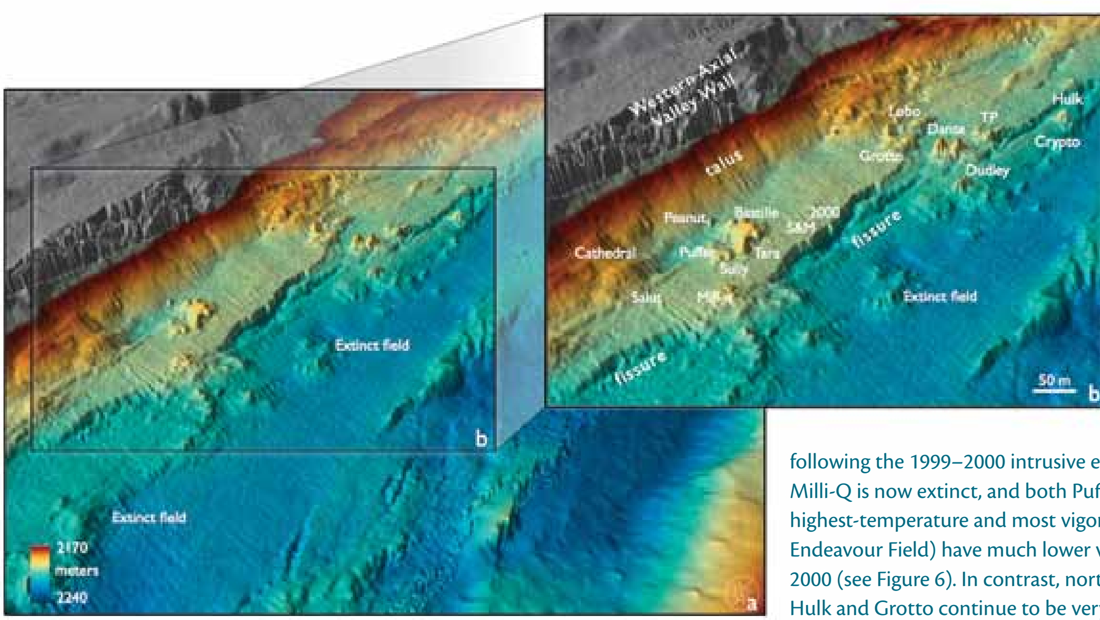

Figure 4. High-resolution (~ 5 m) bathymetric map of the Endeavour Integrated Study Site "bull's-eye," Main Endeavour Field. The bathymetry was collected in 2005 as part of a joint project between the University of Washington, the W.M. Keck Foundation, and NEPTUNE Canada using the autonomous vehicle *ABE*. Venting in the southern cluster of chimneys, known as the Bastille complex, has been waning following the 1999–2000 intrusive event. For example, the structure Milli-Q is now extinct, and both Puffer and Sully (historically the two highest-temperature and most vigorously venting structures in Main Endeavour Field) have much lower venting temperatures than in 2000 (see Figure 6). In contrast, northern complex structures such as Hulk and Grotto continue to be very active.

2007). Vent locations and some fault information exist for MEF and High Rise (i.e., Delaney et al., 1992, for MEF; Robigou et al., 1993, for High Rise), but these older maps do not include the 500 m long extinct sulfide deposit ~ 150 m east of MEF. This extensive, linear deposit of massive oxidized sulfide and small chimney mounds shows that venting jumped to the present location of the MEF, probably during a single diking/fissuring event, which then captured reorganized hydrothermal flow (Lilley et al., 2000; Kelley et al., 2002). In addition, following seismic swarms in 1999–2000, many of these fields changed dramatically, highlighting the need for detailed geological-tectonic maps to be completed. Based on results of recent MBARI autonomous underwater vehicle mapping along the axis of the rift, it is clear that the number of chimneys falls off rapidly to the south and north of the five main vent fields (Clague et al., 2008).

A crustal magma body(s) underlies all of the major active high-temperature fields at Endeavour (Figure 2; Carbotte et al., 2006, and 2012, in this issue; Van Ark et al., 2007). High Rise, Salty Dawg, and Sasquatch are all within the central portion of the shallowest lens segment from 47°56.8' and 48°00.5'N, while MEF is located above a zone of complex reflectivity at the southern end of this segment (Figure 2). Hydrothermal flow is focused along normal faults, trending at ~ 020 within the axial rift and inner walls (Delaney et al., 1992; Kelley et al., 2001b; Glickson et al., 2007). Earthquake focal mechanisms indicate a well-developed graben structure just north of MEF and show a

Table 2. Summary of Endeavour Segment Vent Field Characteristics

Field	Location	Extent-Activity
Sasquatch[1] Discovered in 2000 by Deborah Kelley and John Delaney	• 47°59.85'N, 129°4.0'W • In center of axial valley	• ~ 10, < 1–10 m tall, fragile sulfide chimneys with an areal extent of only ~ 20 x 20 m • Extinct chimneys (up to 20 m tall) • Fluid temperatures up to 287°C • Rapid growth up to 10 m in one year
Salty Dawg (SD)[1] Discovered in 1995 by John Delaney, Deborah Kelley, and Marvin Lilley	• 47°58.9'N, 129°04.6'W • Near eastern axial valley wall	• > 150 m in length, with core of field hosting 35 m long band of massive continuous sulfides • Largest structure Grendl reaches 25 m across and 25 m high • Field contains at least 25 sulfide structures with flanges common, fluid temperatures up to 305°C • Intense hydrothermal plume encountered in 2005 above field (source unclear)[2] • Diffuse sites to west on axial valley wall include Cirque (sulfides) and Dune (tubeworms)
High Rise (HRF)[2–4] Discovered in 1988 by John Delaney and Véronique Robigou	• 47°58.00'N, 129°05.50'W • Near center of valley on summit and sides of elongate horst	• > 10 large structures, currently site of most vigorous hydrothermal activity • Largest structure Godzilla rose 45 m above the seafloor, but collapsed in 1995–1996 • Similar to SD and MEF • Flanges are common • Current site of most intense hydrothermal and seismic activity • Clam Bed diffuse + smoker site is ~ 0.5 km to the south
Main Endeavour Field (MEF)[5,6] Discovered in 1982 by Margaret Leinen, John Delaney, and Paul Johnson	• 47°57'N, 129°06'W • Near western valley wall along major north-south trending fissure/fault	• >17 large, multi-flanged edifices that up until ~ 2005 had > 100 black smoker chimneys • New chimneys initiated post 1999, but since then southern complex (Bastille) has been significantly waning • Fluid temperatures up to 402°C • White smoker complex Cathedral formed ~ 1999–2000 (see http://media.marine-geo.org/video/video-cathedral-vent-complex-2000) • Proximal diffuse flow sites common • Significantly perturbed by 1999–2000 events
Mothra[7,8] Discovered in 1996 by John Delaney, Deborah Kelley, and Marvin Lilley	• 47°55.2'N, 129°06.3'W • Near western valley wall	• Composed of six clusters of chimneys reaching up to 24 m in height, spaced ~ 600 m along strike and ~ 200 m across strike • >> tens of active and inactive chimneys, typically tall, slender and lacking pronounced flanges, numerous sites of diffuse flow • Temperatures up to 320°C • Smokers not perturbed by 1999–2000 events though diffuse flow was affected[9]
Stockwork Discovered in 2005 by Deborah Kelley	• 47°54.00'N, 129°07.45'W • Along western axial valley wall	• 8 m tall extinct structures at base of wall (see http://media.marine-geo.org/video/upflow-zone-western-wall-endeavour-segment-2007) • Continuous exposure of upflow zone 200 m across, 100 m high on wall with massive sulfide, sulfide breccia, well-lithified metaliferous sediments • CTD results indicate weakly venting system immediately to northeast

[1]Glickson et al., 2006; [2]Kelley et al., 2001b; [3]Kellogg and McDuff, 2010; [4]Robigou et al., 1993; [5]Stakes and Moore, 1991; [6]Tivey and Delaney, 1986; [7]Delaney et al., 1992; [8]Kelley et al., 2001a; [9]Glickson et al., 2007; [10]Wilcock, 2004.

transition from normal faulting above the mid-crustal magma chambers to reverse faulting on either flank (Wilcock et al., 2009). Seismicity dramatically drops off just south of MEF, and there is an abrupt change in seismic characteristics between the Main Endeavour and High Rise fields that approximately aligns with the beginning of the northern segment as defined by Van Ark et al. (2007; Figure 2). Based on these observations, we hypothesize that significant fluid drawdown around the margins of the MEF (which is required to feed the vigorous and distributed venting) cools the crust, resulting in maintenance of the discrete, small magma chamber beneath this segment. This interpretation is also supported by thermal blanket measurements, which show depressed heat flow values (< 50 mW m^{-2}) in an aureole around the northern complex and part of the Bastille complex and elevated values near the core of the complexes (> 500 mW m^{-2}; Johnson et al., 2010; Hautala et al., 2012, in this issue). A deeper lens segment underlies Mothra to the south, with a strong reflector at about 2.5 km beneath the spreading axis (Figure 2; Glickson et al., 2007; Van Ark et al., 2007). It is important to note that although segmentation appears to play an important role in the geometry of hydrothermal cells beneath this ridge (Figure 2), the relationship among potential magma lens segmentation, chemistry, and vent properties has not been explored in detail.

Prior to 2005, Mothra was the southernmost site of known venting; however, in 2005 a fossilized upflow zone was discovered exposed along the western valley wall coincident with a series of extinct chimneys and weak plume anomalies (Figure 1). The upflow zone is a massive, continuous exposure, 200 m across and 100 m high, composed of variably altered and mineralized truncated pillow flows interspersed with lenses of massive sulfide that include breccias with monomineralic blocks of chalcopyrite and copper salt minerals (see http://media.marine-geo.org/video/upflow-zone-western-wall-endeavour-segment-2007). It represents a rare opportunity to gain insights into the chemistry, structure, and gradients within a submarine upflow zone. This zone of hydrothermal activity is directly above the most southern strong reflector defined by Van Ark et al. (2007) ~ 4 km south of Mothra (Figure 2), again indicating a direct relationship among segmentation, magma chamber development, and hydrothermal flow.

In addition to the myriad sites of black smoker activity, Endeavour also hosts numerous sites of diffuse flow both proximal and distal to the high-temperature fields. The discrete distal sites from north to south include Cirque, Dune, Clam Bed, Beach, and Quebec. Clam Bed, south of High Rise, is now a site of limited black smoker activity, perhaps in response to the increase in seismic activity at this site in 2005. In contrast to diffuse sites at the EPR, which are sparse and only ~ 10 m x 10 m across, diffuse sites at Endeavour are numerous and commonly reach ~ 20 m x 50 m across or more (Tables 1

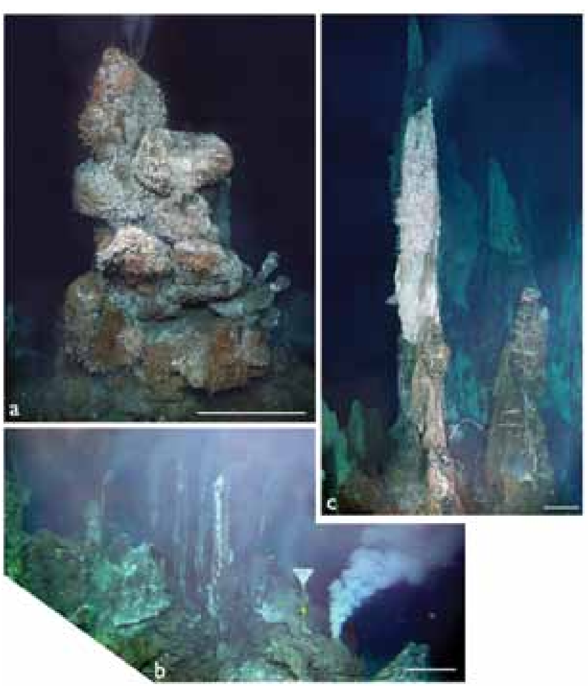

Figure 5. Hydrothermal edifices within the Endeavour vent system. (a) The Bastille structure, rising > 15 m above the seafloor, is typical of structures in the Main Endeavour, High Rise, and Salty Dawg hydrothermal fields, exhibiting numerous active flanges and black smoker orifices at its summit. Mixing of hydrothermal fluids and seawater in the porous outer walls supports dense communities of limpets, palm worms, scale worms, and tubeworms. This image shows one of the small pinnacles that form the summit of Bastille. The scale bar in all images is ~ 1 m. (b) The Cathedral complex in the southern portion of Main Endeavour Field is located on a talus slope along the western axial valley wall. Discovered in 2000, it is the only white smoker system on Endeavour (see http://media.marine-geo.org/video/video-cathedral-vent-complex-2000). It is for the most part extinct now and was likely a short-lived system resulting from the 1999 injection event. Mixing of seawater and hydrothermal fluids within the talus debris likely resulted in deposition of metals beneath the seafloor and egress of some of the lowest-pH fluids measured at Endeavour. (c) Tall, steep-sided structures typify black smoker deposits in the Mothra hydrothermal field, where they rise up to 24 m above the surrounding seafloor. This photomosaic is looking north, showing the 305°C venting structure Finn (left) and 287°C edifice Roane (right). Both chimneys were truncated in 1998 as part of the University of Washington Edifice Rex program (Delaney et al., 2001; Kristall et al., 2006). Finn has regrown a ~ 7 m tall section since then, with the new growth highly colonized by vibrant tubeworm communities (see http://media.marine-geo.org/video/black-smoker-finn-2005). A piece of Finn recovered in 1999 hosted the 121°C organisms cultured by Kashefi and Lovely (2003). The experiment in Roane consists of a microbial incubator inserted into the structure to examine the in situ conditions under which life thrives, survives, and expires within these extreme environments.

and 2). The higher frequency and abundance of both sulfide structures and diffuse-flow sites at Endeavour versus the EPR likely reflect the relative stability of heat sources and longer periods between eruptive events at Endeavour that maintain permeability pathways. In contrast, the higher frequency of eruptive events at the EPR leads to disruption of flow paths and/or covering of hydrothermal flow sites by lava (see Fornari et al., 2012, in this issue).

DIKING EVENTS, SEISMICITY, AND HYDROTHERMAL FLOW

The 20-year SOSUS earthquake catalog (Dziak et al., 2011) shows that Endeavour Segment lies in a region of elevated background seismicity that likely results from the reorganization of plate boundaries in the region. The reorganization is due to the presence of an unstable triple junction at the northern end of the Juan de Fuca Ridge, which formed when the Explorer Plate detached from the Juan de Fuca Plate along the Nootka Transform Fault. In addition to the elevated background level of seismicity, Endeavour has been punctuated by three major seismic swarm events during the last two decades. Two elevated periods of seismic activity were recorded in June 1999 and January 2000 (Lilley et al., 2003; Bohnenstiehl et al., 2004), and another in February 2005 (Hooft et al., 2010). The 1999 activity lasted 5–11 days and spanned the along-axis region of the shallow magma chamber reflectors, with a centroid position of 47°49'N (Johnson et al., 2000). Seismic activity migrated 12 km along axis at a rate of 1.1 km hr^{-1} (Bohnenstiehl et al., 2004). The January 2000 swarm was more limited in extent, of shorter duration, and did not show migration. In contrast to the 1999 and 2000 swarms, the February 2005 swarm began at the overlapping spreading center on the northern end of Endeavour Segment (see http://media.marine-geo.org/video/earthquakes-endeavour-2012). It was the first event to be recorded by in situ short-period seismometers deployed in small boreholes and "seismonuments" (i.e., rectangular cement casings with holes in which short-period seismometers are placed to better couple the sensors to the seafloor) at Endeavour as part of the Keck observatory effort (Wilcock et al., 2009; Hooft et al., 2010). In concert, these events perturbed the hydrology, chemistry, and biology of the Endeavour system, which had been relatively stable since the discovery of vents there in 1982 (Delaney et al., 1992).

1999–2000 Diking Event

The MEF was affected most strongly by the melt pulse and seismic swarms in 1999–2000, with dramatic increases in chimney growth, vent fluid temperatures, volatile concentrations, and flocculent output (Lilley et al., 2003; Seewald et al., 2003; Seyfried et al., 2003). Prior to 1999, there had been a long-standing chemical gradient between the northern and southern portions of the MEF that was interpreted to reflect feeding by two distinct upflow limbs (Figure 2; Butterfield et al., 1994; Delaney et al., 1997; Kelley et al., 2002). Fluid chemistry showed well-defined variation in salinity, carbon ($CO_2 + CH_4$), and temperature from north to south, with the highest salinity, lowest temperature fields occurring at Sasquatch and Mothra (~ 300°C, 710 mmol kg^{-1} Cl; Lilley et al., 1993; Butterfield et al., 1994; Delaney et al., 1997; Kelley et al., 2001a, 2002; Lilley et al., 2003; Glickson et al., 2007). The MEF hosted the long-standing record (two decades) for the highest vent fluid temperatures on the segment (up to 402°C; Delaney et al., 1984), with many of the structures in the southern Bastille complex exhibiting both boiling and supercritical condensation (Butterfield et al., 1994; Kelley et al., 2002; Lilley et al., 2003). However, beginning June 8, 1999, a diking event and resultant seismic swarm disrupted this gradient (Lilley et al., 2003) and resulted in significant increases in gas concentrations and profound changes in venting temperature, intensity, and chemistry (Figure 6; Lilley et al., 2003). The southern Bastille complex, which was venting 380°C and nearly fresh fluids (with respect to salinity), is now dying, with numerous chimneys only weakly venting; temperatures dropped to 230°C by 2007.

The 1999 event also caused dramatic increases in CO_2 concentrations and other magmatic gases and produced elevated H_2 concentrations through increased high-temperature water/rock reactions (Figure 6; Lilley et al., 2003). Many chimneys within the MEF increased by 15°C, boiling was extremely common, and some vents emitted fluids that were nearly fresh (Lilley et al., 2003). Measurements of vent fluid temperatures at Main Endeavour Field and the Clam Bed site showed a tenfold increase in fluid output for at least 80 days following the event (Johnson et al., 2000). In concert, the dramatic and large increase in CO_2 concentrations, heavier isotope values for $\delta^{13}CO_2$ (–6.07‰; Figure 6) and radiocarbon dead CO_2 in black smoker fluids, along with lateral migration of seismic events, indicate that the 1999 event was the result of a lateral dike injection (Johnson et al., 2000; Lilley et al., 2003; Bohnenstiehl et al., 2004; Proskurowski et al., 2004). Pressure transients measured in Integrated Ocean Drilling Program (IODP) boreholes east of Endeavour Segment also support this interpretation (Davis et al., 2001). Modeling of the transients by Davis et al. (2001) suggested a dike injection 40 km in length with a depth extent of 3 km.

The differences between the variability of gas concentrations in the Bastille complex and the northern portion of the MEF have continued through at least 2008. Sully in the south and Hulk in the north are hallmark vent structures that exemplify these differences. Although less than 300 m apart (Figure 4), the fluids venting from these two structures have followed significantly different paths since 1999. These differences may indicate that the Bastille complex and the northern complex are fed by different source fluids upwelling along limbs of convection cells from the south and north, respectively, which are affected by segmentation along the ridge (Figure 2). Carbon dioxide concentrations at Sully are approximately half those prior to the 1999 event (see http://media.marine-geo.org/video/vigorous-hydothermal-flow-sully-2005), while those at Hulk are about 1.5 times higher than pre-1999 values (Figure 6). Hydrogen concentrations at Sully are about a factor of 10 less than those of 1995, while at Hulk there is significant variability, but no overall trend toward lower concentrations.

The most striking behavior in gas composition between the two sites has been that of CH_4. In the summer of 1999 (about six months post event), the CH_4 concentration at Sully had dropped to about half the pre-1999 value. This decline continued into 2000, increased slightly in 2002, and then declined again until 2004, when CH_4 values reached 20% of the pre-1999 values. Since 2004, there has been a steady increase in CH_4 concentration; in 2008, the concentration had recovered to 66% of the pre-1999 value (Figure 6). Unfortunately, Sully has not been sampled since 2008. Methane concentrations at Hulk are variable through time, but are not significantly different than the pre-1999 values. These observations add further support to the idea that the northern and southern sections of the MEF are fed by separate upflow zones.

The CH_4 concentrations at Endeavour are remarkable for a bare-rock vent system. Methane values in the vent fluids are distinctly elevated compared to unsedimented MORs and associated $\delta^{13}CH_4$ values are light (–48.4 to –55.0‰; Lilley et al., 1993). The high CH_4 concentrations are associated with elevated ammonia values, leading to the conclusion that organic material in sediment buried within the volcanic edifice is being decomposed (Lilley et al., 1993; You et al., 1994). The dramatic decline in CH_4 concentrations at Sully may reflect increased thermogenesis rates of the buried organic carbon induced by the intruded dike. This explanation, however, cannot account for the recent concentration increases (Figure 6). Perhaps the most parsimonious explanation is that the dike disrupted the existing hydrothermal upflow zone beneath the southern portion of the MEF so that the fluids contacted less organic-bearing sediment for a time and the original flow path is now being reestablished.

Field observations at High Rise field show that this area is now the most vigorously venting area. In 2004, High Rise had the highest heat flux of any vent field surveyed, and in 2006, it created the most substantial plume within the valley (Kellogg, 2011). Robotic vehicle and submersible studies show that Sasquatch appears to have been reactivated since 2000, while Mothra has remained stable since its discovery in 1996.

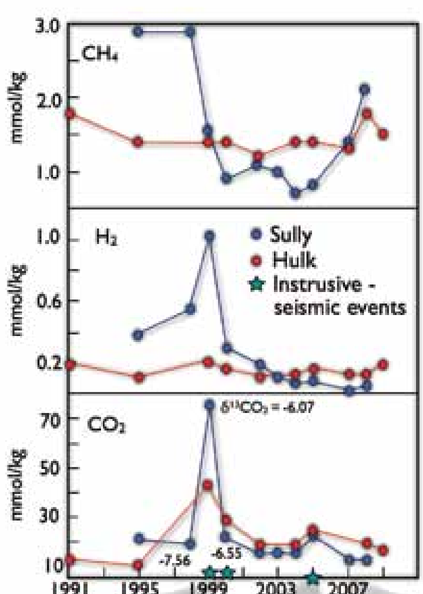

Figure 6. Volatile chemistry for the hydrothermal edifices Sully (blue dots) and Hulk (red dots) located in Main Endeavour Field. As illustrated, the hydrothermal systems in the Bastille complex, where Sully is located, and the northern complex, which hosts Hulk, have continued to have distinct chemical-thermal properties both prior to and following the 1999–2000 events. The implication from these results is that the Bastille complex is fed by a different upflow limb of a convection cell than the northern complex (as illustrated in Figure 2). The appearance of isotopically heavy and radiocarbon dead CO_2 ($\delta^{13}CO_2$) following the 1999 seismic event showed that the earthquake event likely represented injection of melt during a diking event (Proskurowski et al., 2004). Also shown is the evolution of macrofaunal communities on Sully, which has dramatically dropped in temperature since 2000 when it was venting 380°C fluids. Green stars indicate years of seismic swarm events.

Seismicity from 2003 to 2004

From 2003 to 2004, the Keck network located 14,000 earthquakes on Endeavour Segment, of which ~ 4,000 occurred in the inferred position of the high-temperature portion of the reaction zone beneath the hydrothermal fields and just above the AMC reflector (Figure 2; Wilcock et al., 2009). The majority of the earthquakes lie in an arcuate band that extends from the High Rise field to just south of the MEF. There is a remarkable correlation between the rate of seismicity beneath individual vent fields and their heat flux measured in the summer of 2004 (Wilcock et al., 2007; Kellogg, 2011). This correlation suggests that the earthquakes are intimately linked to the processes of hydrothermal heat extraction, similar to findings at the EPR (Fornari et al., 2012, in this issue). Earlier microearthquake studies at Endeavour led to the hypotheses that extensional tectonic earthquakes are critical to maintaining open hydrothermal pathways (McClain et al., 1993) or that the axial earthquakes were a manifestation of thermal stresses induced by hydrothermal cooling (Wilcock et al., 2002).

Relative relocations and focal mechanisms for the Keck data suggest that the normal faults forming the axial valley graben extend down to near the axial magma chamber between MEF and High Rise (Wilcock et al., 2009). The presence of earthquakes with compressional mechanisms to either side of the graben faults is consistent with a magma lens that is inflating. This interpretation led to the hypothesis that the high heat fluxes from High Rise and MEF are driven by ongoing magma inflation that not only replenishes the magmatic heat source, but also cracks the carapace that would otherwise insulate the axial magma chamber (Wilcock et al., 2009).

2005 Diking Event

In late January and late February 2005, the SOSUS arrays and the Keck network recorded two complex swarm sequences. Each swarm involved a north-to-south progression of seismicity over several days between distinct clusters near West Valley and Endeavour Seamount, on the northern Endeavour Segment, and in Endeavour Valley along the inferred extension of the West Valley propagator (see http://media.marine-geo.org/video/earthquakes-endeavour-2012; Weekly et al., 2008; Hooft et al., 2010). The second swarm sequence was larger and led to an event response, which found no evidence for an eruption or water-column perturbation (Dziak et al., 2007). The earthquake patterns recorded by the Keck network suggest that each sequence may have involved magmatic intrusions on the northern Endeavour Segment and West Valley propagator, as well as deformation within the overlapping spreading center. IODP borehole pressure records to the east of Endeavour suggest that the primary deformation associated with the late February sequence resulted from a dike intrusion on the northern Endeavour Segment (Hooft et al., 2010). Interestingly, the migration of earthquakes suggests that the dike propagated southward toward the center of the segment from a magma source to the north, which is possibly associated with Endeavour Seamount at the east end of the Heck seamount chain (Weekly et al., 2008).

Both swarms triggered increased rates of seismicity beneath the vent fields that were delayed about two days from the onset of seismicity on the northern Endeavour Segment. For the January swarm, the triggered seismicity was concentrated between Salty Dawg and High Rise (Weekly et al., 2008). The February swarm was concentrated further south between High Rise and the MEF and coincided with a thermal perturbation to a diffuse vent site in the Mothra field. Hooft et al. (2010) show that the delayed response in the vent fields is consistent with along-axis diffusion of a hydrostatic pressure anomaly associated with pore volume changes induced by the intrusion.

Immediately following the swarm sequences and lasting until the end of the Keck deployment in 2006, seismicity almost ceased at both ends of Endeavour Segment and decreased to ~ 25% of pre-swarm levels beneath the vent fields. Since the 1999 and 2000 swarms ruptured Endeavour Segment from the vent fields to the south, it appears that the 2004 swarm marks the end of a six-year episodic spreading event that cumulatively ruptured the entire segment and relieved the extensional stresses and magmatic pressures generating earthquakes.

While MEF is waning, water-column measurements show that High Rise, as of 2005, had the highest heat flux, and the temperatures of some chimneys had increased (Kellogg, 2011). Only two dives have been made at Salty Dawg since 2000, but a significant plume was detected in 2005 above the field that cannot have been sourced from either High Rise or Sasquatch (Kellogg and McDuff, 2010): some vent fluid temperatures in 2006 increased from a previous visit in 2000. Activity at Sasquatch has also increased since 2005; new chimneys have developed, while others have undergone dramatic growth (10 m in one year). In contrast, no changes in either vent fluid chemistry or black smoker temperatures were measured at Mothra from 1996 to 2007; only weak seismic activity has been recorded beneath this field. Lower CO_2 values are measured in vent fluids at Mothra compared with the vents to the north, but no clear links between other vent fluid properties and magma lens properties have been established for this site.

MICROBIOLOGY IN A VOLCANIC SYSTEM INFLUENCED BY SEDIMENTS

Microbial taxonomic and functional gene analyses of active sulfide structures and diffuse vent fluids at Endeavour Segment show that the microbial communities transition from a mix of bacteria and archaea at the structure's exterior to predominantly archaea in the interior (Shrenk et al., 2003). The archaea in the interiors of active sulfide structures are dominated by Desulfurococcales, with more modest concentrations of Thermococcales, and few to no Methanococcales (Schrenk et al., 2003; Zhou et al., 2009; Ver Eecke et al., 2009). Desulfurococcales included hyperthermophilic Fe(III) oxide reducers (Kashefi and Lovley, 2003; Ver Eecke et al., 2009) as well as one of the most-heat-tolerant-organisms known, which was cultured at 121°C. This organism was recovered from one-year-old new sulfide growth from the active chimney Finn in the Mothra field (Kashefi and Lovley, 2003). The higher proportion of Fe(III) oxide reducers and the absence of methanogens support the idea that H_2 concentrations are too low for methanogens. The reduction potential is only mildly reducing at Endeavour, which correlates with findings at other similar sites (Takai and Nakamura, 2010; Flores et al., 2011). In sulfide material from the black smoker edifice Dudley in the MEF, *Epsilonproteobacteria* comprise more than half of the bacteria clones (Zhou et al., 2009). Functional genes from a Mothra sulfide sample show that microbial communities are mainly fueled by sulfur oxidation coupled to CO_2 fixation via the Calvin cycle (Xie et al., 2011). This observation is in keeping with the predominant CO_2 fixation role of *Epsilonproteobacteria*. The first evidence of nitrogen (N_2) fixation at vents was found in a key N_2 fixation gene (*nif*H) in diffuse fluids near Puffer in the MEF (Mehta et al., 2003). This result indicates that nitrogen reduction is also occurring in the subseafloor at Endeavour. Hydrogen concentrations are 50–80% lower than predicted in diffuse vent fluids, suggesting that there is considerable microbial H_2 oxidation within the subseafloor (Wankel et al., 2011).

Studies of the role of microbial communities on the weathering of hydrothermal vent deposits at Endeavour show that community diversity decreases with decreasing reactivity of the sulfide component and increasing presence of alteration products (Rogers et al., 2003). The surfaces of inactive sulfide mineral assemblages were colonized solely by bacteria and not by archaea (Edwards et al., 2003). Results of biofilm and molecular analyses indicate that these weathered minerals are predominantly colonized by Fe-oxidizing bacteria, which preferentially form in pyrrhotite-rich regions (Rogers et al., 2003; Toner et al., 2009). The results indicate that mineral-oxidizing bacteria play a prominent role in weathering of seafloor sulfide deposits (Edwards et al., 2003).

In hydrothermal plumes at Endeavour, the concentration of exopolymer-rich particles and bacteria increase with aging of the plume, indicating that plumes stimulate in situ aggregate formation that supports populations of attached bacteria (Shackelford and Cowen, 2006). The neutrally buoyant portion of Endeavour plumes are rich in NH_4^+ (up to 177 nM), and autotrophic ammonia-oxidizing bacteria have been shown to account for > 93% of the total net NH_4^+ removal (Lam et al., 2008). Oxidation was heavily influenced by the presence of organic-rich particles where these ammonia-oxidizing bacteria were commonly associated (40–68%) and contributed up to 10.8% of the total microbial community within the plume.

FUTURE STUDIES: BRINGING THE INTERNET AND POWER TO ENDEAVOUR

In part because of the dynamic nature of the Endeavour system and our inability to be there to observe rapid changes that have profound impacts on thermal, chemical, and biological fluxes from the seafloor, the concept of the Northeast Pacific Time-Series Underwater Experiment (NEPTUNE) arose. This concept of a high-power and high-bandwidth underwater cabled observatory was first explored as early as 1987 (Delaney et al., 1988). Over a decade later, this project was further developed with the hope that a Canadian system would cover the northern one-third of the Juan de Fuca Plate and the US system would cover the central and southern two-thirds of the plate. In 2000, the Ocean Sciences Division of the National Science Foundation (NSF) put forth a proposal for Major Research and Equipment Facility Construction (MREFC) funds from Congress to incorporate the NEPTUNE cabled observing systems concept into an even broader ocean science program that included: (1) high-latitude measurements of heat fluxes and greenhouse gas exchange at the air-sea interface, and (2) focused inquiries into critical coastal environments where populations are stressing nearshore oceanic systems. The program, named the Ocean Observatories Initiative (OOI), was developed in response to interest in the global ocean from across the oceanographic community.

In 2003, representatives of the ocean science community met at an NSF-sponsored cabled observatory workshop and designated the Northeast Pacific as the site for the first regional cabled ocean observatory in recognition that a representative suite of global ocean processes occur in this area. Also in 2003, NEPTUNE Canada, led by the University of Victoria, announced receipt of federal, provincial, and private funding to complete planning and implementation of its network on the northern portion of the Juan de Fuca Plate with a significant focus on Endeavour Segment (http://neptunecanada.ca). In 2006, based on continued science planning linked to engineering design and development, NEPTUNE US passed the OOI Conceptual Design Review, and in 2007, NEPTUNE US was renamed Regional Scale Nodes (RSN) within the OOI (Figure 7).

Both NEPTUNE Canada and the RSN are now in the water; the Canadian system will be fully installed in 2012 and the RSN in 2014 (Figure 7). In concert, these two high-power (10 kW) and high-bandwidth (10 Gbs) expandable systems will be the first plate-scale experiment, with a total of 1,700 km of fiber-optic cable, hundreds of seafloor sensors, and an array of instrumented water column moorings with instrumented wire crawlers that reach to depths of 3,000 m. In part, this visionary experiment began with development of the RIDGE Program in the late 1980s—nearly three decades later the ocean sciences community is on the verge, for the first time, of being able to monitor and respond to events in real time at multiple sites on the Juan de Fuca Ridge. The cabled experiments on both Endeavour Segment and Axial Seamount will provide unprecedented access to these environments, the ability to conduct controlled perturbation experiments, and direct links to a global community of viewers and participants.

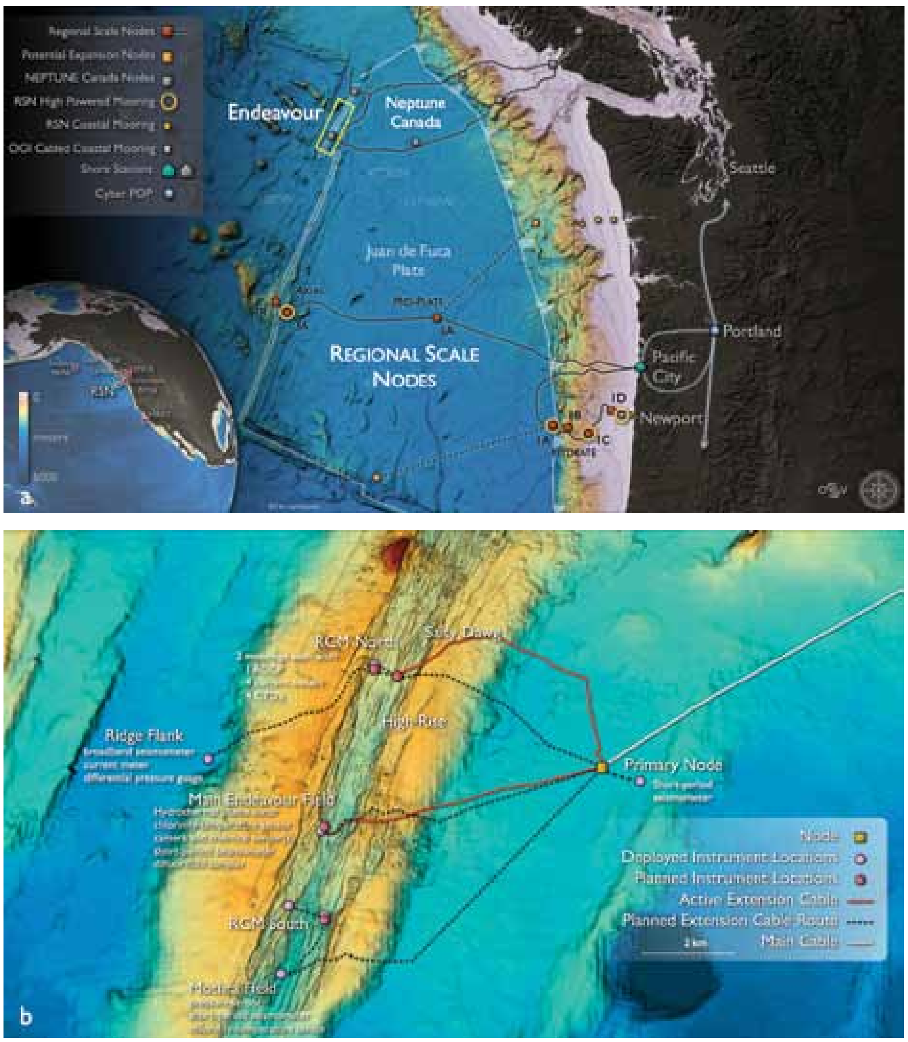

Figure 7. (a) Location of the cabled component of the National Science Foundation Ocean Observatories Initiative, including the Regional Scale Nodes and the companion system deployed as part of NEPTUNE Canada. (b) Installed and planned cable and sensor installation at the Endeavour node of the Canadian NEPTUNE high-power and high-bandwidth cabled observatory. Full installation will be completed in 2012 (http://www.neptunecanada.ca). The University of Washington is installing the US companion system at Axial Seamount as part of the National Science Foundation Ocean Observatory Initiative (http://www.interactiveoceans.washington.edu/story/Observatories+Index; http://www.oceanobservatories.org/infrastructure/ooi-components/regional-scale-nodes) and will be operational in 2013, with commissioning in 2014.

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