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## Hunting for Hydrothermal Vents Along the Galápagos Spreading Center

Rachel M. Haymon

*University of California - Santa Barbara*

Edward T. Baker

Joseph A. Resing

Scott M. White

*University of South Carolina - Columbia*, [swhite@geol.sc.edu](mailto:swhite@geol.sc.edu)

Ken C. Macdonald

*University of California - Santa Barbara*

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BY RACHEL M. HAYMON, EDWARD T. BAKER, JOSEPH A. RESING,  
SCOTT M. WHITE, KEN C. MACDONALD, AND THE GALAPAGOS TEAM

# Hunting for Hydrothermal Vents

## Along the Galápagos Spreading Center

...searching for hydrothermal vents in the vastness  
of the deep ocean floor is not as easy as one might  
think. This is the story of how we did it.

In 1972, at a location in the eastern equatorial Pacific ~ 200 miles north-east of the Galápagos Islands, a young graduate student researcher was using surplus US Navy sonobuoys to listen to the portion of the global mid-ocean ridge known as the Galápagos Spreading Center (GSC) (Figure 1). The global mid-ocean ridge is a giant volcanic seam where Earth's lithospheric plates repeatedly rip apart and erupt lava to form new seafloor in a process known as seafloor spreading. Ken Macdonald was listening for the sounds of ripping and volcanic eruptions produced by seafloor spreading, and he was quite excited when he heard a swarm of such sounds (80 earthquakes per hour!) through his headphones. When he went out on the deck of the ship, he saw many dead fish floating on the sea surface, and quickly realized that these were *benthic* fish, which live near the seafloor at great depth. He logically concluded that the fish had been killed by the seafloor events producing the sounds detected by his sonobuoys, and he published a paper in 1974 to propose that the crest of the GSC near 86°W had experienced a volcanic eruption (Macdonald and Mudie, 1974).

Five years after the earthquake swarm, a US team diving in the *Alvin* submersible, led by John Corliss, discovered the first deep-sea hydrothermal vents on the GSC crest at the location of Macdonald's volcanic eruption (Corliss et al., 1979). Remarkably, these warm springs teemed with benthic life, and were inhabited by many types of animals that were heretofore unknown to science. The exotic animals were being nourished primarily by chemosynthetic microbes using vent-fluid chemicals, rather than sunlight, as an energy source. Thus the

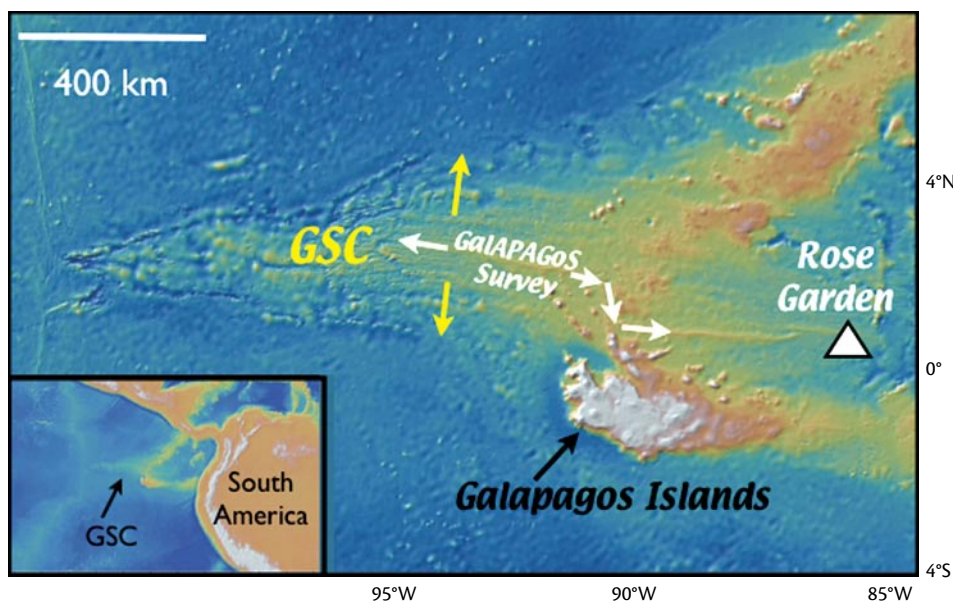


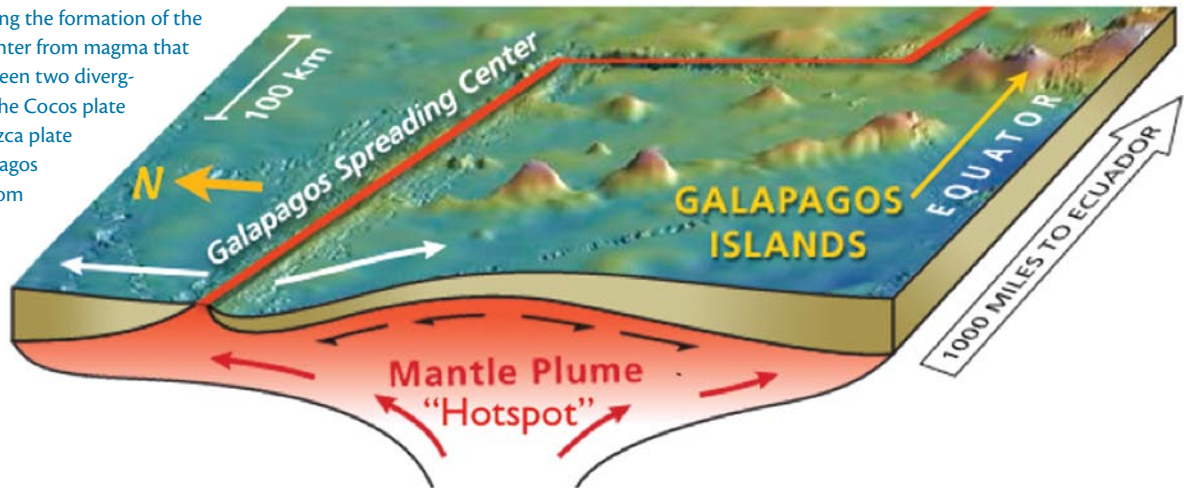
Figure 1. Location of the Galápagos Spreading Center (GSC) and the Galápagos Islands in the eastern equatorial Pacific. The GSC is the boundary between the Cocos and Nazca Plates; yellow arrows show directions of relative plate motion and seafloor spreading. The first hydrothermal vents to be found in the deep sea on the global mid-ocean ridge were discovered in 1977 at the Rose Garden site (white triangle). White arrows mark the portion of the GSC surveyed during the 2005–2006 GalAPAGoS Expedition, which was jointly funded by the US National Science Foundation (Marine Geology and Geophysics Program) and National Oceanic and Atmospheric Administration (Ocean Exploration Program). The GalAPAGoS surveys spanned the portion of the GSC overlying the mantle hotspot that feeds magma to the volcanoes of the Galápagos Islands.

GSC hydrothermal vent communities became the first known examples of light-independent ecosystems. Shortly thereafter, also in 1979, submersible divers exploring the crest of the East Pacific Rise came upon much hotter ( $380 \pm 30^\circ\text{C}$ ) hydrothermal vents (Spiess et al., 1980). These astonishing “black smokers” were blasting plumes of scalding fluid, blackened by tiny metal-sulfide mineral particles, into the deep ocean through tall mineral “chimney” conduits.

The discoveries of deep-sea hydrothermal vents and animal communities were among the most thrilling marine revelations of the latter twentieth century. Subsequent seafloor exploration demonstrated that submarine hydro-

thermal activity is a global-scale process profoundly affecting the chemical, biological, and physical properties of our planet (Humphris et al., 1995, and references therein). Furthermore, marine hydrothermal systems may be the crucible from which microbial life on Earth arose (Reysenbach and Shock, 2002; Knoll, 2004; and references therein). Although these great discoveries began on the GSC at a site known as “Rose Garden” (near 86°W; Figure 1), nearly three decades later the rest of the GSC remained largely unexplored for hydrothermal activity. On the eastern GSC near Rose Garden, only a few hydrothermal vents had been located, and none were hot black smokers.

Figure 2. Sketch illustrating the formation of the Galápagos Spreading Center from magma that rises into the crack between two diverging lithospheric plates (the Cocos plate to the north and the Nazca plate to the south). The Galápagos hotspot feeds magma from much deeper mantle sources to the Galápagos Islands and Galápagos Spreading Center.



Below the GSC, a much deeper mantle magma source, a so-called “hotspot,” is feeding the profuse volcanism that has built the Galápagos Islands (Sinton et al., 2003, and references therein) (Figure 2). About one-fifth of the global mid-ocean

ridge overlies hotspots (Ito et al., 2003); however, their impacts on mid-ocean ridge volcanism and hot-spring activity are not known. Some scientists have argued that the excess melt from hotspots is likely to produce a greater abundance of mid-ocean ridge hydrothermal vents and biota, and many black smokers, while others have predicted the opposite (e.g., Chen, 2003; Chen and Lin, 2004). Do hotspots enhance or reduce the global magnitude of high-temperature chemical exchange between the mid-ocean ridge and the oceans? If mid-ocean ridge/hotspot intersections are “hydrothermal deserts” offering few oases for vent biota, are hotspots significant biogeographical barriers to the dispersal of these organisms along the mid-ocean ridge? In December 2005–January 2006, we set out to explore for hydrothermal vents along the GSC above the Galápagos hotspot because it is an ideal place to find out how a hotspot affects the types and abundances of hot springs, animals, and volcanic features of the mid-ocean ridge. We hoped the GSC would provide some clues to our major questions about

the global impact of hotspots on seafloor hydrothermal activity.

But, searching for hydrothermal vents in the vastness of the deep ocean floor is not as easy as one might think. This is the story of how we did it.

## THE GALAPAGOS SURVEYS

The size of the area that we set out to explore is approximately the size of the California coastal zone from San Francisco to Los Angeles (Figure 1). None of this *terra incognita* had ever been seen before by human eyes. Hydrothermal vents on the mid-ocean ridge typically cover areas of seafloor no bigger than a football field, and individual black smokers and animal clusters cover areas smaller than the average living room (Haymon et al., 1991; Haymon, 2005; Humphris et al., 1995). To hunt for these rather small features within such a large search area, we conducted a sequence of sonar, hydrothermal plume, and photographic surveys designed to zoom in on the locations of the hydrothermal vents. These combined surveys along the GSC crest from

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RACHEL M. HAYMON (*haymon@geol.ucsb.edu*) is Professor, Department of Earth Science and Marine Science Institute, University of California, Santa Barbara, CA, USA. EDWARD T. BAKER is Supervisory Oceanographer, NOAA Vents Program, Pacific Marine Environmental Laboratory, National Oceanic and Atmospheric Administration, Seattle, WA, USA. JOSEPH A. RESING is Chemical Oceanographer, NOAA Vents Program, Pacific Marine Environmental Laboratory, National Oceanic and Atmospheric Administration, Seattle, WA, USA. SCOTT M. WHITE is Assistant Professor, Department of Geological Sciences, University of South Carolina, Columbia, SC, USA. KEN C. MACDONALD is Professor, Department of Earth Science and Marine Science Institute, University of California, Santa Barbara, CA, USA.

95°W to 89.5°W (Figure 1) were accomplished during the six-week GalAPAGoS (*Galápagos Acoustical, Plume, And Geobiological Surveys*) Expedition on R/V *Thomas G. Thompson* (<http://oceanexplorer.noaa.gov/explorations/05galapagos/welcome.html>).

We began by making a continuous bathymetric map along the GSC crest from 89.5°W to 95°W (Figure 3). To do this, we used the Simrad EM300 30 kHz multibeam sonar system mounted on the ship's hull. Multibeam sonar systems map wide swaths of seafloor bathymetry using an array of many narrow sound beams. At ship speeds of 8–9 knots, we were able to complete this initial bathymetric survey in less than two days. Within hours after the end of the survey, we produced new bathymetric maps of the GSC crest with 50-m pixel resolution, which is more than four times better resolution than maps made previously with lower frequency (12- and 15-kHz) multibeam sonar systems. The new maps permitted recognition of seafloor features that were  $\geq 5$  m tall and at least 250 m (i.e., three pixels) across. We used the EM300 maps to accurately locate the GSC summit axial zone, where our chances of finding hydrothermal vents would likely be greatest.

Next, we towed a DSL 120a near-bottom 120 kHz side-scan sonar system (Figure 3) along the axial zone at a speed of  $\sim 1.5$  knots and an altitude of  $\sim 110$ – $125$  m above the seafloor. The DSL 120a sonar produced  $\sim 1$ -km-wide swaths of acoustic backscatter data with  $\sim 2$ -m pixel resolution, and phase bathymetry with  $\sim 5$ -m pixel resolution. In these near-bottom sonar images and maps, our eyes were able to recognize individual seafloor features

only 10–50 m (2–25 pixels) across and 1–2 m high, as determined from subsequent comparison with video images of the same features.

The DSL 120a sonar system also was used as a platform for optical and chemical sensors designed to detect hydrothermal plume signals at altitudes of 50–300 m above the seafloor. These sensors detected light scattering from plume particles, temperature anomalies, conductivity anomalies, Eh variations, and dissolved iron, manganese, and methane. Some of the plume sensors were mounted on the sonar system

itself, while others were attached to the tow cable above the sonar sled and to a wire dangling beneath (Figure 3). Data from some of these instruments were transmitted up the tow cable to the ship so that we could monitor plume signals during the DSL 120a tows. Other instruments recorded data that were quickly downloaded at the end of a deployment.

Thus, we simultaneously conducted near-bottom, high-resolution sonar mapping and hydrothermal plume surveys continuously along the GSC axial zone for almost 600 km, from east of the hotspot center (89.5°W)

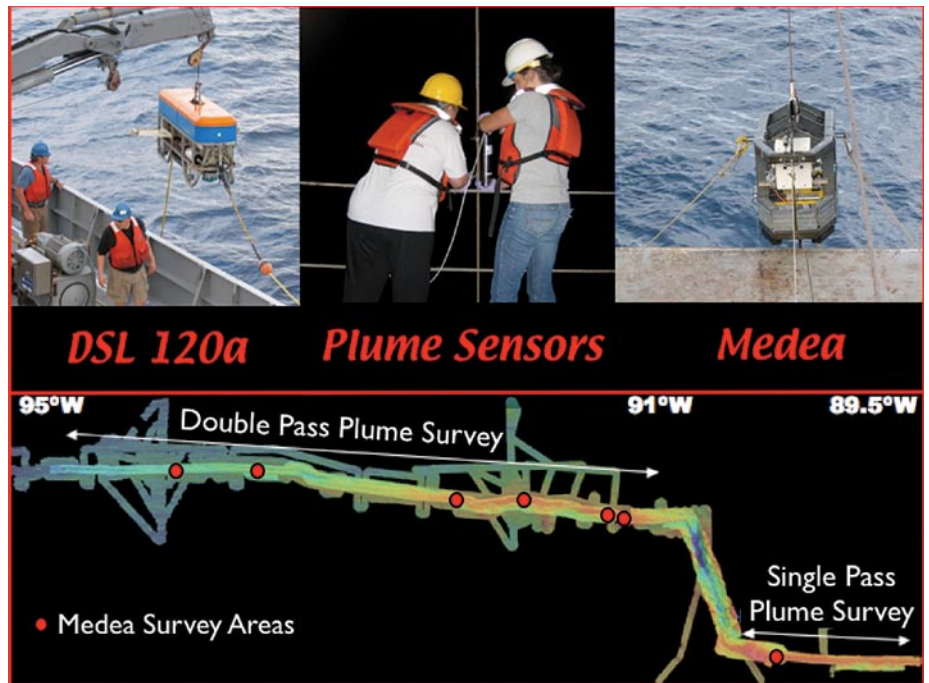


Figure 3. The GalAPAGoS Expedition team mapped GSC hydrothermal vent plumes and homed in on their seafloor sources using a sequence of “nested” surveys. The first step was to map the bathymetry of the GSC with a 30-kHz multibeam sonar system (shown superimposed over lighter-shaded 12-kHz multibeam bathymetry in the lower figure panel; map depths are color-coded, with red = most shallow and dark blue = most deep). Then, the team mapped the GSC summit in greater detail using the towed DSL 120a near-bottom side-scan sonar system (upper left), and simultaneously mapped hydrothermal plumes in the bottom waters using sensors mounted on the sonar sled, on the tow cable, and on a wire beneath the sled (upper middle). Last came towing of the near-bottom *Medea* camera sled (upper right) at the locations shown by red dots (lower panel) to visually locate and image hydrothermal vents on the seafloor beneath the detected plumes (see Figure 4). GalAPAGoS team members Sharon Walker, left, and Kayla Pettit, right, are shown attaching plume sensors to the DSL 120a tow cable.

to the western edge of hotspot influence (95°W) (Figures 1 and 3). During the DSL 120a surveys, we detected significant hydrothermal plumes in eight areas. We subsequently searched beneath several of the plumes to find their seafloor hydrothermal vent sources, using a towed, near-bottom camera system called *Medea* (Figure 3).

For the GalAPAGoS Expedition, the *Medea* sled was equipped with powerful lights, color video and still cameras, an altimeter, plume sensors, a scanning sonar, and thrusters. Camera images were streamed to the ship in real time through the fiber-optic tow cable. To illuminate the seafloor adequately, the sled had to be towed only 5–10 m above bottom, and at this altitude the field of view for the camera was not more than 10 m across. To maneuver without either hitting the bottom or kiting the sled upward, the towing speed had to be slower than the average person can walk (less than a quarter of a knot). Because we covered ground slowly and had a lim-

ited field of view, we had to focus our brief *Medea* searches within small areas where the vents were most likely to be found. To select small target areas for our searches, we used the excellent fine-scale bathymetry and backscatter images from the EM300 and DSL 120a surveys

## DISCOVERY OF BLACK SMOKERS ON THE GALÁPAGOS SPREADING CENTER

and our knowledge about typical geologic settings of mid-ocean ridge crest hydrothermal vents.

On December 11, 2007, as the DSL120a sonar was towed at 120 m above the ridge crest near 92°W, the oxygen, methane, iron, manganese, and particle sensors on the sonar platform simultaneously registered very large signals as they passed through the plume of a black smoker. We were very excited, and could hardly wait to go back and visually hunt for the smoker on the seabed. When we reached the end of the DSL 120a line on December 13, we removed the sonar sled from the cable, and replaced it with the *Medea* camera sled. Meanwhile, near the site where the plume was detected, we collected some plume water samples with a Niskin bottle cast. The strong rotten-egg smell of hydrogen sulfide emitted by the water samples indicated

of the plume source. Plumes are blown away from vents on the seafloor by bottom currents and tidal flows, and they can drift thousands of meters from their seafloor sources over the course of a day. With the limited field of view and slow towing speed of *Medea*, we knew it would be challenging to cover enough territory to sight the smoker on the seabed. It would be a bit like walking slowly through the forest at night with a small flashlight, looking for mushrooms.

On the night of December 14, we first lowered *Medea* into a trough on the GSC crest, thinking that the vent might be along a fissure on the floor of a collapsed lava pond. On this lowering of *Medea*, the altimeter, which detects the depth of the seafloor beneath the sled, failed to function. In the few brief minutes that the video camera transmitted pictures, before we brought *Medea* back aboard to replace the altimeter, we saw that lava flows in the floor of the fissure were older flows on which some light-colored carbonate sediment had accumulated. No animals were seen, and the oxygen and light-scattering sensors on *Medea* did not show any plume signal. We decided then to try a different spot for the second lowering.

When we replaced the altimeter and sent *Medea* back down three hours later, it was to the top of an elongated, east-west-oriented “axial volcanic ridge” (AVR) located just south of the lava pond where we put *Medea* on the first lowering. On the second lowering, we towed *Medea* slowly along this elongated volcanic construction, following a fissure along the top. The lava flows on the AVR top exhibited little carbonate sediment accumulation on the rock surfaces, and looked considerably younger than

On the ocean floor, the end of all our exploring is nowhere in sight, and what we know about the place is eclipsed by what we have yet to discover.

that we had sampled the plume near its source. We put *Medea* close to the bottom for a look-see on the evening of December 14.

Although we knew where the chemical signal from the plume was strong, this did not tell us the seafloor location

the flows in the trough to the north. Did these young-looking lava flows lie above rock that was still hot? On the AVR top, we saw more biota than previously, especially near the fissure along the AVR summit. Because animals are attracted to food sources at hydrothermal vents, we were encouraged by these hopeful signs. We continued to search slightly downslope from the fissure, on the south slope of the AVR. We noticed that lava surfaces at this location appeared to be coated with brown sediment. From previous experience diving around black smokers, we recognized the coating to be fine-grained iron oxide particles from black smoker plumes. Such coatings usually are observed only very close to a black smoker vent. We marked the location of the brown sediment on our map, and continued our traverse into the trough on the south side of the AVR.

Like the northern trough, the southern trough was floored with older lava on which no animals were to be seen. We therefore abandoned the trough and towed *Medea* back to the top of the AVR. We then traveled along the AVR summit fissure back toward the area of coated lava flows. More animals appeared, and cloudy water emerged from the fissure. We knew we must be close . . . we began to see brown sediment coating the lava flows, and wisps of smoke drifted into view. Then the smoke became thicker. Our *Medea* winch operator used the vehicle's thrusters to swing it from side-to-side, looking for the smoker. Then, in the forward-looking video camera, we could see the black smoker chimney! In just three and a half hours after lowering *Medea* back down to the seafloor, we had sleuthed our way to the first black smoker ever to be found on the

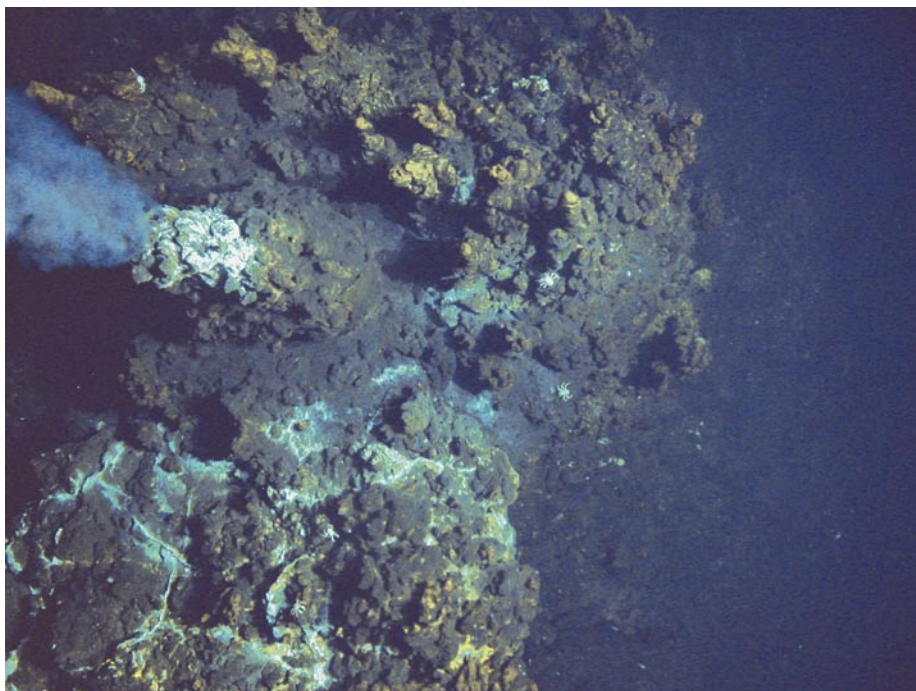


Figure 4. *Medea* image of the first black smoker (“Plumeria”) ever found on the GSC. Field of view in this image is ~ 5 m. This vent is one of 21 active black smoker chimneys located within the Iguanas-Pinguinos vent field, which extends for several kilometers along the top of an axial volcanic ridge near 92°W.

GSC (Figure 4). We named this smoker “Plumeria” (after the tropical flower by that name), and continued our search along and near the AVR summit fissure. Soon we came upon a cluster of six 12–14-m-high chimneys pouring out massive quantities of black smoke (title page photo). We named these smokers the “Iguanas” vents, after the famous marine iguanas of the Galápagos Islands.

On the morning of December 15, tired but joyful with discovery, we brought *Medea* back aboard. Our success in finding the smokers came from piecing together all the clues from plume sensors, water samples, seafloor bathymetry, and video images of biota and seafloor terrain. Locating the smokers relied on decades of collective vent-hunting experience among the science team, and

on the technical skills of the team and the ship's crew.

Almost 30 years after vents were first found on the GSC we finally were able to show that black smokers do exist here, and are the most common expression of hydrothermal venting that we found on the GSC where it passes over the Galápagos hotspot. By the end of the GalAPAGoS Expedition, we had located with *Medea* a total of 26 actively smoking chimneys on the GSC crest grouped in two fields (Figure 5). One field is slightly west of the center of hotspot influence (Iguanas-Pinguinos Field, where Plumeria Vent was found) and the other field is at the western periphery of hotspot influence (Navidad Field). In addition, we found dozens of recently active chimneys (i.e., intact, unweath-

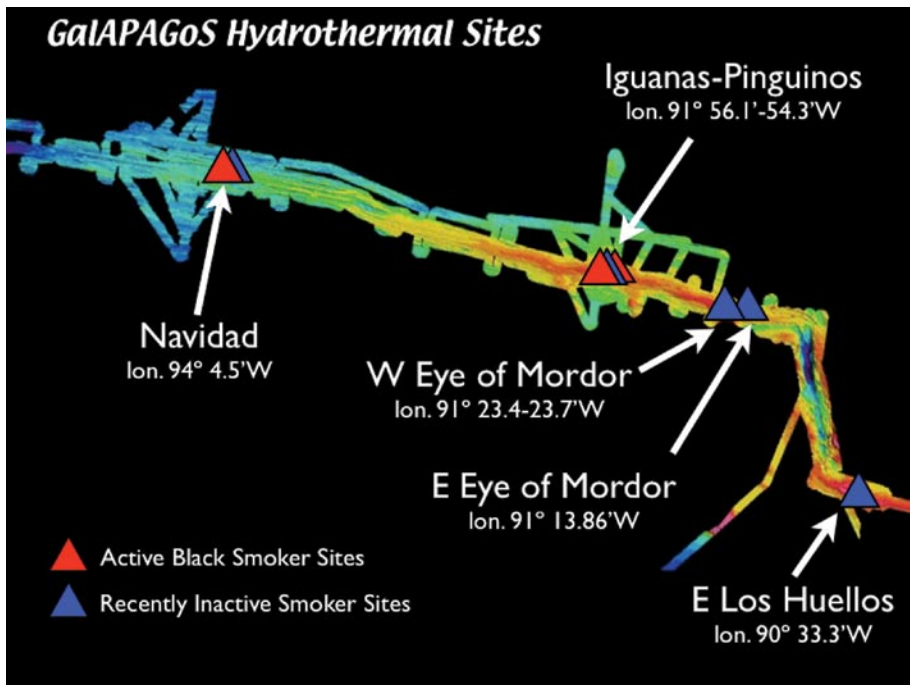


Figure 5. Multibeam bathymetry map showing the areas where active (red triangles) and recently inactive (blue triangles) high-temperature hydrothermal vents were imaged with *Medea* during the GalAPAGoS Expedition. Map depths are color-coded, with red = most shallow and dark blue = most deep. GalAPAGoS EM300 bathymetry is superimposed here over lighter-shaded 12-kHz bathymetry collected by others prior to our 2005–2006 expedition. In total, 26 active black smoker chimneys and dozens of recently inactive chimneys were seen in the limited time available for *Medea* searches.

ered chimneys no longer visibly venting warm water) located within the active fields, and we also found several such chimneys in three other areas near the center of hotspot influence (Figure 5). However, our plume surveys detected significantly fewer active high-temperature vents than expected for a normal mid-ocean ridge spreading at a rate comparable to the GSC (Baker et al., 2006). The Galápagos hotspot is likely responsible for the observed reduction in high-temperature vents along the GSC—but how? A possible answer to this question is suggested by the characteristics of the hydrothermal vents and biota revealed in *Medea* images.

Surprisingly, live hydrothermal vent

animals were relatively sparse throughout the survey area, and all of the hydrothermal vents appeared to be in late stages of development; in other words, chimneys were either *mature* (tall structures with highly focused, vigorous flow through orifices at the top), *waning* (tall but with diffuse flow from the top), or *inactive* (tall but no longer emitting visible fluid). In addition, the lava flows hosting the vents appeared to be of geologically similar age (we estimate the flows to be only tens to hundreds of years old, based on extent of visible glassiness and amount of sediment cover). The similarity in lava age and vent maturity at vent sites throughout the hotspot-influenced GSC suggests an

intriguing new hypothesis: perhaps hotspot-affected mid-ocean ridges exhibit pulses of volcanic and hydrothermal activity, followed by periods of quiescence, as a consequence of their interaction with hotspots. If true, there may have been much more activity back when Ken Macdonald listened to an eruption at Rose Garden than there was at the time of the GalAPAGoS Expedition. How can we test this interesting idea?

### WE MUST KEEP EXPLORING!

If GSC hydrothermal activity waxes and wanes in time due to interaction with the hotspot, then during waxing times when there are many vents the hydrothermal animals will have an abundance of nearby habitat, and will be able to disperse their genes easily from vent to vent. Conversely, during waning times when vents are few and far between, the animal communities will be isolated and unable to disperse their genes along the ridge. The genetic similarity or divergence of vent organisms living on opposite sides of the hotspot may show whether or not the hydrothermal communities are in genetic communication or isolation, and may thus reveal whether or not there are times when hydrothermal communities are more abundant and closely spaced. If the hotspot-influenced GSC is chronically deficient in vents, then the animals at Rose Garden to the east and Navidad Field more than 400 km farther to the west will be as genetically distinct as Charles Darwin's finches are on the isolated islands of the Galápagos archipelago. In addition, we can collect and possibly radiometrically date the lava flows and mineral deposits from the GalAPAGoS vent sites, to see if they really are nearly the same age and there-



fore possibly could be products of a near-contemporaneous pulse of eruption and hydrothermal venting throughout the hotspot-affected portion of the GSC. We also can spend more time searching for GSC vents to see whether new sites are similar to the vents that we located during the GalAPAGoS Expedition, and to determine whether the characteristics of new sites also are consistent with the hypothesis of hotspot-modulated episodic hydrothermal venting. And finally, we can explore other hotspot-influenced portions of the global mid-ocean ridge.

The global mid-ocean ridge system is ~ 65,000 km long. Less than 1% of its length has been visually explored from a submersible or remotely operated camera system, and the percentage of observed area shrinks drastically as one moves away from the ridge summit. A director of a famous oceanographic institution recently commented to the first author of this article that: “The age of ocean exploration is over; the future lies in ocean monitoring.” The age of exploration is far from over! The director had never once visited the seafloor himself to behold its vastness and unknown wonders. T.S. Eliot memorably wrote: “We shall not cease from exploration, and the end of all our exploring will be to arrive where we started and know the place for the first time.” On the ocean floor, the end of all our exploring is nowhere in sight, and what we know about the place is eclipsed by what we have yet to discover.

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## REFERENCES

- Baker, E.T., J.A. Resing, S.L. Walker, G.T. Lebon, K. Nakamura, R.M. Haymon, S.M. White, and K.C. Macdonald. 2006. Hydrothermal plume mapping along the hotspot-affected Galápagos Spreading Center finds high-temperature vent sites are anomalously scarce. *Eos Transactions, American Geophysical Union* 87(52), Fall Meeting Supplement, Abstract V14A-06.
- Chen, Y.J., 2003, Influence of the Iceland mantle plume on crustal accretion at the inflated Reykjanes Ridge: Magma lens and low hydrothermal activity? *Journal of Geophysical Research* 108:2,524–2,536.
- Chen, Y.J., and J. Lin. 2004. High sensitivity of ocean ridge thermal structure to changes in magma supply: the Galápagos Spreading Center. *Earth and Planetary Science Letters* 221:263–273.
- Corliss, J.B., J. Dymond, L.I. Gordon, J.M. Edmond,

- R.P. Von Herzen, R.D. Ballard, K.E. Green, D.L. Williams, A. Bainbridge, K. Crane, and T.J. Van Andel. 1979. Submarine thermal springs on the Galápagos rift. *Science* 203:1,073–1,082.
- 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 and Planetary Science Letters* 104:513–534.
- Haymon, R.M. 2005. Hydrothermal vents at mid-ocean ridges. Pp. 388–395 in *Encyclopedia of Geology*, Book 5. R. Selley, L.R. Cocks, and I. Plimer, eds, Elsevier, Oxford.
- Humphris, S.E., R.A. Zierenberg, L.S. Mullineaux, and R. E. Thomson, eds. 1995. *Seafloor Hydrothermal Systems*. American Geophysical Union Geophysical Monograph 91, American Geophysical Union, Washington, DC, 466 pp.
- Ito, G., J. Lin, and D. Graham. 2003. Dynamics of mantle plume-mid-ocean ridge interaction. *Reviews of Geophysics* 41:1,017–1,040.
- Knoll, A.H. 2004. *Life on a Young Planet: The First Three Billion Years of Evolution on Earth*. Princeton University Press, Princeton, NJ, 304 pp.
- Macdonald, K. C., and J.D. Mудie. 1974. Microearthquakes on the Galápagos spreading center and the seismicity of fast-spreading ridges. *Geophysical Journal of the Royal Astronomical Society* 36:245–247.
- Reysenbach, A.L., and E. Shock. 2002. Merging genomes with geochemistry in hydrothermal ecosystems. *Science* 296:1,077–1,082.
- Sinton, J., R. Detrick, J.P. Canales, G. Ito, and M. Behn. 2003. Morphology and segmentation of the western Galápagos Spreading Center, 90.5°–98°W: Plume-ridge interaction at an intermediate spreading ridge. *Geochemistry, Geophysics, and Geosystems* 4:8,515–8,540, doi:10.1029/2003GC000609.
- Spiess, F.N., K.C. Macdonald, T. Atwater, R. Ballard, A. Carranza, D. Cordoba, C. Cox, V.-M. Diaz-Garcia, J. Francheteau, J. Guerrero, J. Hawkins, R. Haymon, and others. 1980. East Pacific Rise: Hot springs and geophysical experiments. *Science* 207:1,421–1,433.