Large heat and fluid fluxes driven through mid-plate outcrops on ocean crust

M. HUTNAK[1]*, A. T. FISHER[1], R. HARRIS[2], C. STEIN[3], K. WANG[4], G. SPINELLI[5], M. SCHINDLER[6], H. VILLINGER[7] AND E. SILVER[1]

[1]Department of Earth and Planetary Sciences and Institute for Geophysics and Planetary Physics, University of California Santa Cruz, Santa Cruz, California 95064, USA
[2]College of Ocean and Atmospheric Sciences, Oregon State University, Corvallis, Oregon 97331, USA
[3]Department of Earth and Environmental Sciences, University of Illinois at Chicago, Chicago, Illinois 60607, USA
[4]Pacific Geoscience Centre, Geological Survey of Canada, Sydney, BC, V8L 4B2, Canada
[5]Department of Earth and Environmental Science, New Mexico Tech, Socorro, New Mexico 87801, USA
[6]FB Federal Institute for Geosciences and Natural Resources (BGR), 30655 Hannover, Germany
[7]FB Geowissenschaften, Universität Bremen, Klagenfurter Strasse, 28359 Bremen, Germany
*e-mail: mhutnak@pmc.ucsc.edu

Published online: 1 August 2008; doi:10.1038/ngeo264

Hydrothermal circulation on the sea floor at mid-ocean ridge flanks extracts ∼30% of heat from the oceanic lithosphere on a global basis[1] and affects numerous tectonic, magmatic and biogeochemical processes[2–4]. However, the magnitude, mechanisms and implications of regional-scale fluid and heat flow on mid-ocean ridge flanks are poorly understood. Here we analyse swath-map, seismic and sea-floor heat-flux data to quantify the heat and fluid discharge through a few widely spaced basement outcrops on the Cocos Plate. Heat removed by conduction from a 14,500 square kilometre region of the sea floor is 60–90% lower than that predicted by lithospheric cooling models. This implies that a substantial portion of the heat is extracted by advection, which requires fluid discharge of 4–80 × 10^3 litres per second. The heat output of individual discharging outcrops is inferred to be comparable to that from black-smoker vent fields seen on mid-ocean ridges. Our analysis shows that hydrothermal circulation on mid-ocean ridge flanks through widely spaced outcrops can extract a large fraction of lithospheric heat. This circulation requires a very high crustal permeability at a regional scale. Focused flows of warm, nutrient-rich hydrothermal fluid may enhance sub-seafloor microbial habitats[5,6] and enable direct sampling of these systems.

Global estimates of heat, fluid and solute fluxes through mid-ocean ridge flanks have been made using thermal and chemical constraints[7], but regional fluxes and the properties and processes that control them are poorly understood because of a lack of collocated, high-resolution data sets. Basement outcrops can facilitate advective extraction of lithospheric heat by providing highly permeable conduits that enable fluids to bypass low-permeability sediments[8–11]. The driving forces that sustain outcrop-to-outcrop discharge are limited to tens to a few hundreds of kilopascals, based largely on the difference between fluid pressures at recharging (cool) and discharging (warm) zones in the crust. Modest driving forces and the long distances between recharge and discharge sites require high crustal permeability[9,11,12], consistent with borehole hydrogeological, tidal, and seismic analyses[13,14].

Previous studies of mid-ocean ridge-flank hydrothermal fluxes focused on individual features (local scale)[10,11,15] or composite data sets from many areas (global scale)[16], but no earlier studies have shown that widely spaced basement outcrops can mine a large fraction of lithospheric heat on a regional scale. Collocated seafloor bathymetric, seismic-reflection and heat-flux data from a large area of 18–24 million-year-old (Myr) sea floor of the eastern Pacific Ocean, on the Cocos Plate seaward of the Middle America Trench (Fig. 1), provide the foundation for a quantitative assessment of advective heat and fluid fluxes on a regional basis.

The methods used to collect and process swath-map, seismic and seafloor heat-flux data from this area are described in detail elsewhere[17]. Swath-mapping across a 50,000 km^2 region achieved 40% spatial coverage, and is overlain on complete bathymetric data coverage from satellite gravimetry[18] (Fig. 1a). Multichannel seismic reflection data were acquired along 3,000 km of profiles. Seafloor heat-flux data were acquired with a 3.5 m, 11-sensor, violin-bow multipenetration probe with *in situ* thermal conductivity and real-time data telemetry, and with three to five autonomous outrigger probes mounted on core barrels[8,17]. Heat-flux, seismic and nearby drill-core data[19] were combined to extrapolate surface thermal conditions to the sediment–basement interface to map spatial variations in upper basement temperatures (these interpretations and the complete heat-flux data set are provided as Supplementary Information, Table S1).

The Cocos Plate has a complex tectonic history in the survey area, where it comprises lithosphere generated at the fast-spreading East Pacific Rise (EPR) and the medium-spreading Cocos-Nazca Spreading Centre (CNS), separated by a plate suture[20] (Fig. 1b). Drilling and seismic data from this area show that sediment is typically 400–500 m thick, except where disrupted by seamounts and other basement outcrops, and comprises mainly pelagic and hemipelagic material[8,17,21]. Basement outcrops are unevenly distributed regionally. Outcrops are relatively common on EPR-generated sea floor northwest of the plate suture (Fig. 1), ranging in diameter from hundreds to thousands of metres (Table 1), and are typically separated by 20–50 km. In contrast,

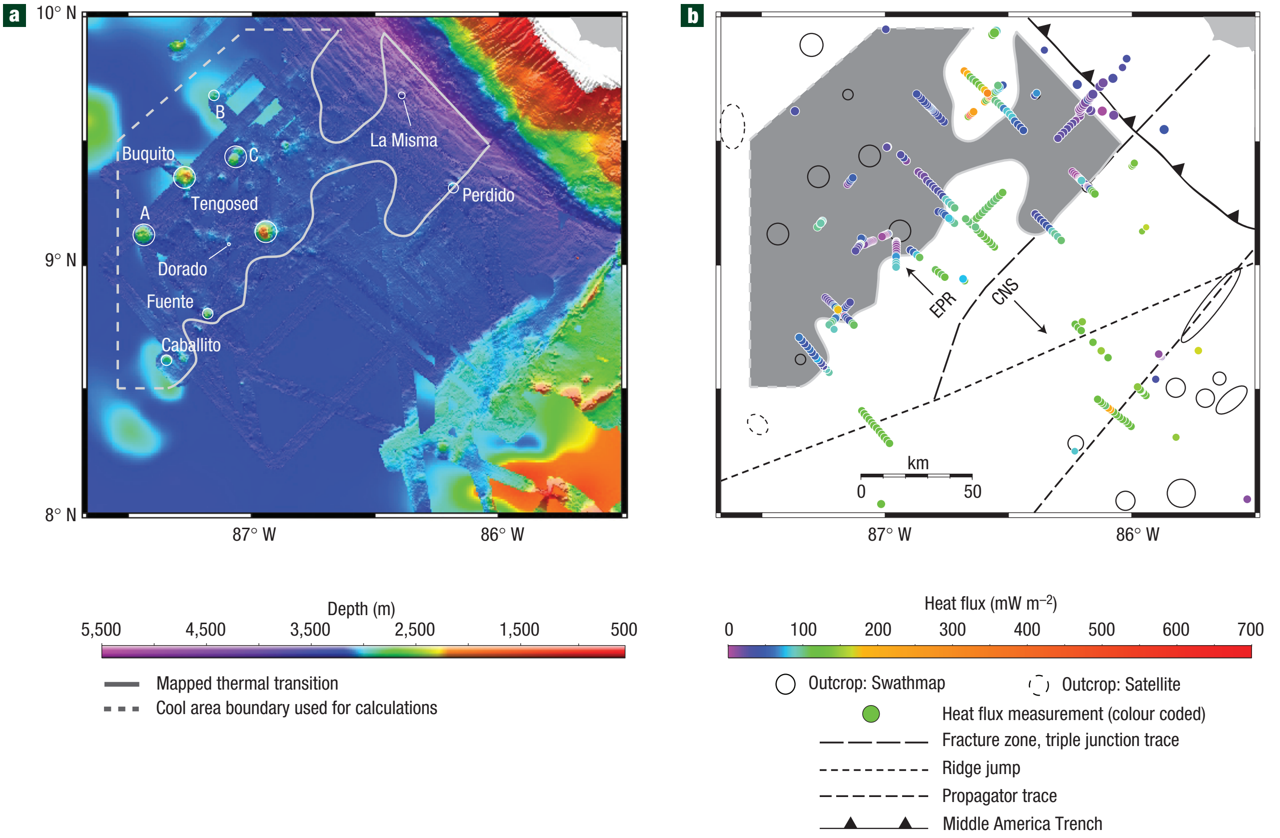

Figure 1 Regional bathymetry and heat flux. a, Bathymetry and mapped basement outcrops. Bathymetric data are from swath-mapping and satellite gravimetry. Circles correspond to outcrops. The dashed and solid grey line delineates the boundary between 14, 500 km^2 cooler and warmer parts of the plate. **b**, Cartoon illustrating the cool region (dark grey), heat flux (colour-coded circles), mapped basement outcrops (black ovals) and major tectonic boundaries. EPR = lithosphere generated at the East Pacific Rise. CNS = lithosphere generated at the Cocos-Nazca Spreading Centre. The plate suture between EPR- and CNS-generated lithosphere is defined by a triple junction trace and a fracture zone.

no basement outcrops are evident on CNS-generated sea floor southeast and adjacent to the plate suture, or on EPR-generated sea floor immediately to the west (Fig. 1).

'Warm' and 'cool' parts of the Cocos Plate are delineated by 327 high-quality heat-flux measurements collocated with seismic reflection profiles (Fig. 1), and augmented by scattered heat-flux data from earlier surveys[22]. The mean seafloor heat flux through the warm part of the plate is consistent with lithospheric reference models, 97–120 milliwatts per square metre for 18–24 Myr sea floor[1] (Figs 1 and 2a). In contrast, the seafloor heat flux through the cool part of the plate (area shaded grey in Fig. 1b) is typically 10–40 mW m^{-2}, just 10–40% of lithospheric predictions (Fig. 2a). The thermal transition between warm and cool areas is abrupt, only a few kilometres wide, consistent with advective heat extraction from the upper crust on the cool side of the plate[8,17].

Ten seamounts and other basement outcrops mapped within the cool part of the survey area collectively comprise ~260 km^2 of exposed basement (Fig. 1, Table 1). Heat-flux and seismic surveys oriented radially away from outcrops indicate that some enable hydrothermal recharge whereas others enable hydrothermal discharge[17] (Table 1). Fluid recharge is indicated by a decrease in seafloor heat flux and a downward sweeping of isotherms where sediment thins in proximity to an outcrop. In contrast, fluid discharge results in extremely high seafloor heat flux (sometimes more than 1 W m^{-2}) and an upward sweeping of isotherms adjacent to exposed basement. Data analysed in the present study, similar data collected from a younger mid-ocean ridge flank where recharge and discharge are guided by basement outcrops[9,23] and results of numerical models suggest that discharge is favoured through smaller outcrops[9,11,23], probably because it is easier to maintain warm conditions within smaller features during fluid ascent.

We define a 14, 500 km^2 area of cool, 21–24 Myr lithosphere on the EPR side of the Cocos Plate, with geographic boundaries comprising the trench to the northeast, a thermal transition to the southeast and the limits of high-resolution thermal surveys to the north and west. We infer that lithospheric heat advected from the cool part of the survey area is discharged through basement outcrops within this area[8,17]. The northern and western limits of the cool area are placed equidistant between basement outcrops within and outside the cool area; if heat advected from the cool area flowed through outcrops outside this area, then the regional advective heat loss and power output of each discharging outcrop would be greater than those indicated by the calculations that follow. In fact, scattered heat-flux measurements collected during earlier surveys[22] beyond the northern and western limits of the study area suggest that lithospheric cooling extends to a much larger region. This implies

Table 1 Summary of basement-outcrop characteristics

Outcrop*	Diameter (km)†	Height (m)‡	Heat-flux profiles§
Fuente	4.8	600	3-R, 1-D
Dorado	0.4	150	2-D
Tengosed	8.8	880	2-R
La Misma	2.8	40	1-C
Perdido	1.8	300	2-R
Caballito	3.0	50	ND
Buquito	8.2	1,100	ND
A	8	1,000	ND
B	4	250	ND
C	4	650	ND

*Outcrop locations shown in Fig. 1.

†Diameter of outcrop where basement penetrates sediment at the sea floor, to nearest 0.1 km for swath-mapped features and nearest 1 km for outcrops mapped by satellite (based on comparison of satellite- and swath-mapped features).

‡Height of outcrop above sea floor calculated from seismic two-way travel time, to nearest 10 m.

§Number of heat-flux profiles oriented radially around basement outcrops. Heat-flux data interpreted to indicate recharging (R), discharging (D) or conductive (C) conditions. The latter does not mean that the outcrop is not hydrogeologically active, only that existing data provide no evidence for advective heat extraction through an outcrop. ND = no thermal data.

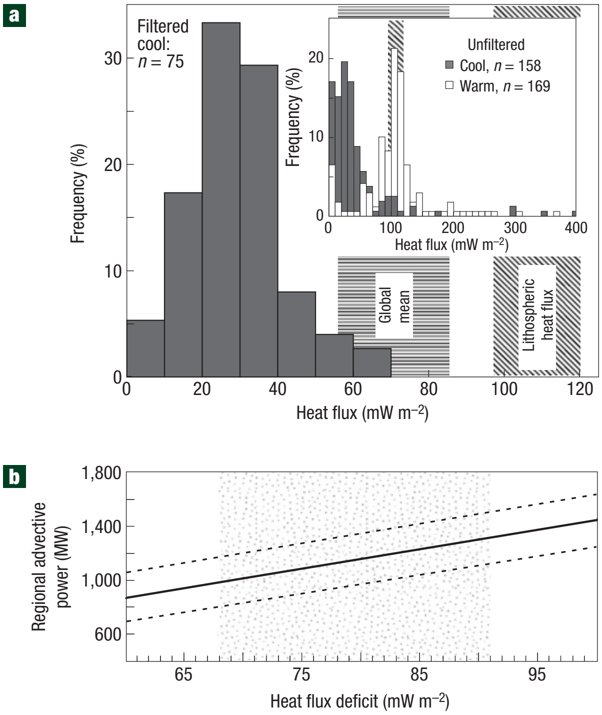

Figure 2 Heat-flux and power deficit. a, Heat-flux values. Inset: The complete dataset, separated into subsets located on 'warm' and 'cool' sides of the thermal transition. Main plot: Filtered data from the cool side of the plate, and the range of lithospheric predictions and global averages for sea floor of this age. The mean value is 29 ± 13 mW m^{-2}. **b**, Regional advective power based on the difference between lithospheric and observed heat flux on the cool side of plate. The stippled band shows the range of conductive heat-flux deficit based on lithospheric cooling models; the dashed lines show calculations based on the standard deviation of the observed heat flux.

that our calculations are conservative, and suggests that basement transmissive properties may be high across a large portion of this mid-ocean ridge flank.

To assess the magnitude of regional advective heat extraction from the cool part of the Cocos Plate, we exclude heat-flux measurements collected above and immediately adjacent to buried basement highs and outcrops (removing both anomalously high and low values influenced by conductive thermal refraction and the local influence of hydrothermal recharge and discharge), retaining values over areas of flat sea floor and basement, ≥1–2 km from the nearest outcrop, where the sediment thickness is typically 400–500 m. The mean of 75 filtered measurements from the cool part of the Cocos Plate is 29 ± 13 mW m^{-2} (± one standard deviation) (Fig. 2a). When integrated across the 14,500 km^2 of cool EPR-generated sea floor (ignoring the 260 km^2 of exposed basement comprising outcrops, 1.8% of this area), the regional power deficit is 800–1,400 MW (Fig. 2b). Heat-flux profiles oriented radially adjacent to five of the ten mapped basement outcrops in this area provide evidence for recharge through two, discharge through one (the smallest surveyed), one that both recharges and discharges and one that shows evidence for neither recharge nor discharge (Fig. 1, Table 1). Five other outcrops have not been sufficiently surveyed to assess their importance to hydrothermal circulation.

Assuming that recharge and discharge are distributed through all ten outcrops as suggested by our surveys, the mean advective power output of discharging outcrops is 200–350 MW. This is a conservative estimate; if more outcrops are recharging than inferred, then the mean power output of discharging outcrops is commensurately greater. This range of power output overlaps estimates made from plume and point studies of high-temperature vent fields on the southern cleft segment of the Juan de Fuca ridge (JdFR) and 21°N on the EPR (at the low end) and the Endeavour Main Field on the JdFR and 9° 50′ N on the EPR (at the high end)[24]. However, in contrast to these mid-ocean ridge–crest systems, the advection of lithospheric heat from the cool part of the Cocos Plate is conveyed by fluids that are only slightly warmer than bottom seawater.

The heat-flux values from the cool side of the Cocos Plate, when combined with seismic reflection and drilling data, indicate upper basement (advective fluid) temperatures of just 5–40 °C, requiring 4–80 × 10^3 l s^{-1} of fluid entering and exiting seafloor outcrops to account for the regional heat-flux deficit (Fig. 3). If this fluid flow is distributed evenly across the discharging outcrops, consistent with interpretations from the heat-flux surveys, then each of these features vents 1–20 × 10^3 l s^{-1} of cool hydrothermal fluid. This fluid flow rate is three orders of magnitude greater than that seeping from a well-studied basement outcrop on 3.5 Myr sea floor on the eastern flank of the Juan de Fuca ridge[10,15], where there is little or no regional heat-flux deficit owing to current hydrothermal activity.

Heat and fluid fluxes are unlikely to be distributed evenly across the surface of basement outcrops, but are probably concentrated along faults and other highly permeable pathways, as seen at other hydrothermal discharge sites[10,25,26]. The large magnitude of fluxes documented in the present study, and their likely focusing within small areas on a few outcrops, should generate detectable thermal anomalies in deep water near the sea floor[27,28]. The possibility of detectable chemical anomalies is less certain because cold recharging sea water must transit rapidly through the uppermost crust and has little opportunity to interact chemically with the host rock, making it chemically very similar to sea water[29].

Earlier studies used analytical and numerical calculations to assess the driving forces and crustal properties needed to sustain flow between basement outcrops separated by tens of kilometres on a young mid-ocean ridge flank[9,11,12], indicating basement permeability ranging from 10^{-11} m^2 to 10^{-10} m^2. In contrast to the current analysis, there was little impact of outcrop-to-outcrop fluid circulation on the regional seafloor

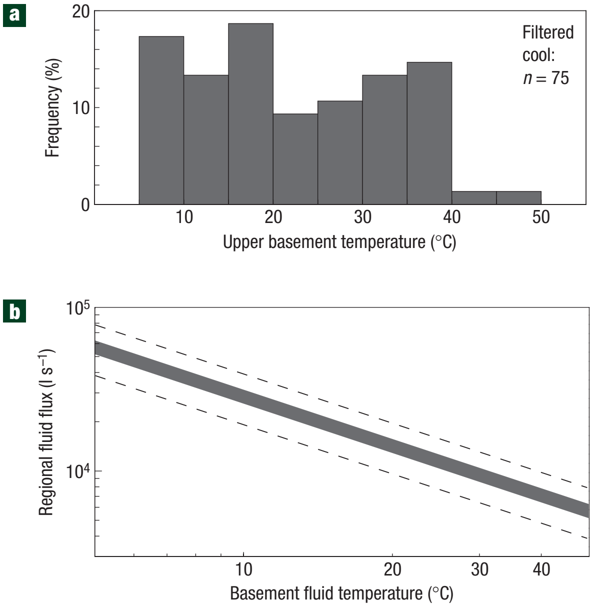

Figure 3 Fluid temperature and flux. a, Histogram of temperatures at the sediment–basement interface on the cool side of the plate, based on filtered heat-flux data (Fig. 2a) and collocated seismic data. **b**, Fluid flux required to advect the regional power deficit (Fig. 2b) based on the range of fluid (upper-basement) temperatures. The solid line indicates the range of power deficits shown with a solid line in Fig. 2b, whereas the dashed lines indicate ± one standard deviation of the mean heat flux on the cool side of plate.

heat flux in these earlier studies. The much greater fluid and heat flows documented in the present study, driven by even smaller pressure differences (because the difference in fluid temperature between recharge and discharge areas is smaller), imply commensurately greater basement permeability. Extracting a large fraction of lithospheric heat through widely spaced outcrops while maintaining cool basement temperatures (5–40 °C) below thick sediments probably requires regional basement permeabilities of 10^{-10}–10^{-9} m^2 (ref. 11), a value consistent with earlier regional estimates[15] (see the Supplementary Note and Supplementary Information, Fig. S1). This hypothesis can be tested, along with the existence of thermal plumes in bottom water fed by massive, low-temperature discharge, through carefully directed observational and modelling studies.

Large fluxes of relatively unaltered seawater through the upper oceanic crust bring oxygen, nitrate and other solutes to microbial ecosystems that live in pore spaces within and adjacent to primary fluid flow paths[3,5,6]. Our work shows that these fluxes of fluid, heat and solutes can continue to crustal ages beyond the 10–20 Myr commonly associated with the most vigorous biomass production[6]. Focused discharge sites on outcrops can provide hydrogeological windows into the sub-seafloor biosphere on mid-ocean ridge flanks, without drilling or other invasive methods, much as black-smoker vents enable access to the subsurface environment at mid-ocean ridges[30].

Received 25 March 2008; accepted 30 June 2008; published 1 August 2008.

References

1. Stein, C. & Stein, S. Constraints on hydrothermal heat flux through the oceanic lithosphere from global heat flow. *J. Geophys. Res.* **99**, 3081–3095 (1994).
2. Behn, M. D., Boettcher, M. S. & Hirth, G. The thermal structure of oceanic transform faults. *Geology* **35**, 307–310 (2007).
3. Huber, J. A., Butterfield, D. A., Johnson, H. P. & Baross, J. A. Microbial life in ridge flank crustal fluids. *Environ. Microbiol.* **88**, 88–99 (2006).
4. Peacock, S. M. & Wang, K. Seismic consequences of warm versus cool subduction metamorphism: Examples for southwest and northeast Japan. *Science* **286**, 937–939 (1999).
5. Santelli, C. M. *et al.* Abundance and diversity of microbial life in ocean crust. *Nature* **453**, 653–656 (2008).
6. Bach, W. & Edwards, K. J. Iron and sulfide oxidation within the basaltic ocean crust: Implications for chemolithoautotrophic microbial biomass production. *Geochim. Cosmochim. Acta* **67**, 3871–3887 (2003).
7. Elderfield, H. & Schultz, A. Mid-ocean ridge hydrothermal fluxes and the chemical composition of the ocean. *Annu. Rev. Earth Planet. Sci.* **24**, 191–224 (1996).
8. Fisher, A. T. *et al.* Abrupt thermal transition reveals hydrothermal boundary and role of seamounts within the Cocos Plate. *Geophys. Res. Lett.* **30**, 4-1–4-5 (2003).
9. Fisher, A. T. *et al.* Hydrothermal recharge and discharge across 50 km guided by seamounts on a young ridge flank. *Nature* **421**, 618–621 (2003).
10. Wheat, C. Geoffrey *et al.* Heat flow through a basaltic outcrop on a sedimented young ridge flank. *Geochem. Geophys. Geosyst.* **5**, doi:10.1029/2004GC000700 (2004).
11. Hutnak, M. *et al.* Hydrothermal recharge and discharge guided by basement outcrops on 0.7–3.6 Ma seafloor east of the Juan de Fuca Ridge: Observations and numerical models. *Geochem. Geophys. Geosyst.* **7**, doi:10.1029/2006GC001242 (2006).
12. Stein, J. S. & Fisher, A. T. Observations and models of lateral hydrothermal circulation on a young ridge flank: Reconciling thermal, numerical and chemical constraints. *Geochem. Geophys. Geosyst.* **4**, 1026doi:10.1029/2002GC000415 (2003).
13. Becker, K. & Fisher, A. Permeability of upper oceanic basement on the eastern flank of the Endeavor Ridge determined with drill-string packer experiments. *J. Geophys. Res.* **105**, 897–912 (2000).
14. Davis, E. E. & Becker, K. in *Hydrogeology of the Oceanic Lithosphere* (eds Davis, E. E. & Elderfield, H.) 225 (Cambridge Univ. Press, Cambridge, 2004).
15. Mottl, M. J. *et al.* Warm springs discovered on 3.5 Ma oceanic crust, eastern flank of the Juan de Fuca Ridge. *Geology* **26**, 51–54 (1998).
16. Stein, C. & Stein, S. A model for the global variation in oceanic depth and heat flow with lithospheric age. *Nature* **359**, 123–129 (1992).
17. Hutnak, M. *et al.* in *The Seismigenic Zone of Subduction Thrust Faults* (eds Dixon, T. & Moore, C.) 86 (Columbia Univ. Press, New York, 2007).
18. Smith, W. H. F. & Sandwell, D. T. Global sea floor topography from satellite altimetry and ship depth soundings. *Science* **277**, 1956–1962 (1997).
19. Kimura, G., Silver, E. & Blum, P. (eds) *Proc. Ocean Drilling Program, Initial Reports* (Ocean Drilling Program, College Station, Texas, 1997).
20. Barckhausen, U. *et al.* Revised tectonic boundaries in the Cocos Plate off Costa Rica: Implications for the segmentation of the convergent margin and for plate tectonic models. *J. Geophys. Res.* **106**, 19207–19220 (2001).
21. Silver, E. *et al.* An 8–10 Ma tectonic event on the Cocos Plate offshore Costa Rica: Result of Cocos Ridge collision?. *Geophys. Res. Lett.* **31**, doi:10.1029/2004GL020272 (2004).
22. Vacquier, V., Sclater, J. G. & Corry, C. E. Studies in the thermal state of the earth, the 21st paper: Heat-flow, Eastern Pacific. *Bull. Earthq. Res. Inst.* **45**, 1519–1535 (1967).
23. Zuehlsdorff, L. *et al. Proc. Ocean Drilling Program* 301 (Ocean Drilling Program, College Station, Texas, 2005).
24. Baker, E. T. Hydrothermal cooling of midocean ridge axes: Do measured and modeled heat fluxes agree? *Earth Planet. Sci. Lett.* **263**, 140–150 (2007).
25. Macdonald, K. C. in *Faulting and Magmatism at Mid-Ocean Ridges* Vol. 106 (eds Buck, W. R., Delaney, P. T., Karson, J. A. & Lagabrielle, Y.) 27 (American Geophysical Union, Washington DC, 1998).
26. Kelley, D. S. *et al.* An off-axis hydrothermal vent field near the Mid-Atlantic Ridge at 30° N. *Nature* **412**, 145–149 (2001).
27. Wheat, C. G., Mottl, M. J., Baker, E. T. & Feely, R. A. Chemical plumes from low-temperature hydrothermal venting on the eastern flank of the Juan de Fuca Ridge. *J. Geophys. Res.* **102**, 15433–15446 (1997).
28. Lavelle, J. W. & Wetzler, M. A. Diffuse venting and background contributions to chemical anomalies in a neutrally buoyant ocean hydrothermal plume. *J. Geophys. Res.* **104**, 3201–3209 (1999).
29. Wheat, C. G. & Mottl, M. J. Hydrothermal circulation, Juan de Fuca Ridge eastern flank: Factors controlling basement water composition. *J. Geophys. Res.* **99**, 2225–2237 (1994).
30. Kelley, D. S., Baross, J. A. & Delaney, J. R. Volcanoes, fluids, and life at mid-ocean ridge spreading centers. *Annu. Rev. Earth Planet. Sci.* **30**, 385–491 (2002).

Supplementary Information accompanies this paper on www.nature.com/naturegeoscience.

Acknowledgements

This research was supported by the US National Science Foundation, the Institute for Geophysics and Planetary Physics at the University of California and the Ocean Drilling Program. We thank the officers and crews of the R/V *Maurice Ewing* and R/V *Melville* and the scientific parties of the TicoFlux expeditions, who assisted with data collection.

Author contributions

Project planning was carried out by A.T.F., E.S., R.H, C.S. and K.W. Heat-flux data acquisition was overseen by A.T.F. Seismic data acquisition was overseen by E.S. Several autonomous outriggers were supplied by H.V. and M.S. Gear deployment was carried out by M.H., A.T.F., R.H, C.S., K.W., G.S., M.S. and E.S. Bathymetric data were processed by M.H. Seismic data processing was carried out by E.S. and M.H. Heat-flux data were processed by M.H., A.T.F., M.S. and R.H. Data analysis and compilation was carried out by M.H and A.T.F. All authors contributed to the writing of this manuscript.

Author information

Reprints and permission information is available online at http://npg.nature.com/reprintsandpermissions. Correspondence and requests for materials should be addressed to M.H.