Fluid flow through seamounts and implications for global mass fluxes

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ABSTRACT

Seamounts contribute to globally significant hydrothermal fluxes, but the dynamics and impacts of fluid flow through these features are poorly understood. Numerical models of coupled heat and fluid flow illustrate how seamounts induce local convection in the oceanic crust. We consider idealized axisymmetric seamounts and calculate mass and heat fluxes by using a coupled heat- and fluid-flow model. By using P. Wessel's global database of ~15,000 seamounts identified through satellite gravimetry, we estimate that the mass flux associated with seamounts is ~10^{14} kg/yr, a number comparable to estimated regional mass fluxes through mid-ocean ridges and flanks. In addition, the seamount-generated advective heat flux may be locally significant well beyond the 65 Ma average age at which advective lithospheric heat loss on ridge flanks ends. These flows may be important for facilitating geochemical exchange between the crust and ocean and may affect subseafloor microbial ecosystems.

Keywords: fluid flow, heat flow, seamounts, numerical model, mass flux.

INTRODUCTION

Estimates of seafloor heat transfer based on the observed deficit between heat-flow determinations and models of conductive lithospheric cooling indicate that fluid flow is responsible for 34% of the global oceanic heat flux and is thermally significant, on average, to 65 Ma (Parsons and Sclater, 1977; Stein and Stein, 1994). Processes responsible for limiting advective heat flux between the oceanic crust and the ocean include increasing accumulations of low-permeability sediments that cap relatively high permeability basement, decreasing basal heat input available to drive flow, and decreasing crustal permeability with increasing crustal age (e.g., Anderson and Hobart, 1976; Sclater et al., 1980).

Several factors make seamounts ideally suited to overcome these flow-limiting processes. (1) Bathymetric relief associated with seamounts generates thermal buoyancy forces in excess of those present in flat seafloor. (2) Seamount edifices are constructed mainly of extrusive basalt that is likely to have relatively high permeability. (3) Seamounts tend to remain relatively sediment free much longer than the surrounding seafloor, thereby providing areas of exposed basement where fluid can exchange with the ocean unencumbered by low-permeability sediments.

Seafloor heat-flow measurements are highly sensitive to hydrothermal circulation in the underlying crust, but such measurements are relatively rare across seamounts because the bare-rock environment is inhospitable to instrument penetration and because many earlier studies tried to avoid the confounding influence of hydrothermal circulation on lithospheric heat transport. However, several studies have documented seamounts that are hydrologically active and that are stimulating fluid flow in the surrounding oceanic crust (Villinger et al., 2002; Lister, 1972; Fisher et al., 2003a, 2003b; Harris et al., 2000a, 2000b).

In this paper we describe numerical experiments that elucidate patterns of local fluid flow through seamounts and explore the potential significance of mass and heat fluxes associated with circulation through seamounts on a global basis. Fluid flow through seamounts differs fundamentally from circulation on ridge flanks, thought to be responsible for much of the global marine heat-flow anomaly. Ridge-flank circulation extracts heat advectively from most of the seafloor through large-scale lateral flow on average, to a mean crustal age of 65 Ma (e.g., Stein and Stein, 1994), whereas flow through seamounts has mainly a local to regional influence, and occurs at a temperature close to that of bottom water. Seamount circulation may continue within some of the oldest seafloor, where it can constitute a significant fraction of lithospheric heat loss. Although several recent studies have examined ridge-flank discharge through basement highs (e.g., Mottl et al., 1998; Cowen et al., 2003; Kelley et al., 2001), those systems involve water-rock reactions at temperatures considerably higher than those modeled herein.

GLOBAL DISTRIBUTION OF SEAMOUNTS

Wessel (2001) catalogued ~14,700 seamounts between lat. 72°N and 72°S by using the gridded vertical-gravity-gradient field derived from altimetry data, and we use this data set in our calculations. Seamount heights, $h(r)$, are modeled as axisymmetric Gaussian cones taking the form (Craig and Sandwell, 1988)

$$h(r) = A \exp\left(\frac{-r^2}{2R^2}\right), \quad (1)$$

where r is the radial coordinate, A is the height of the seamount above the surrounding seafloor, and R is the characteristic radius at an elevation of 0.6A. Wessel (2001) estimated the height and radius for each seamount from peak amplitudes and distance to the zero crossing in the vertical gravity gradient field, respectively. Catalogued seamount dimensions are 2–7.5 km in height and 2–50 km in radius; a typical height is 2 km, and radius is 10 km (Fig. 1). Histograms of seamount geometry are long tailed and well characterized by power-law distri-

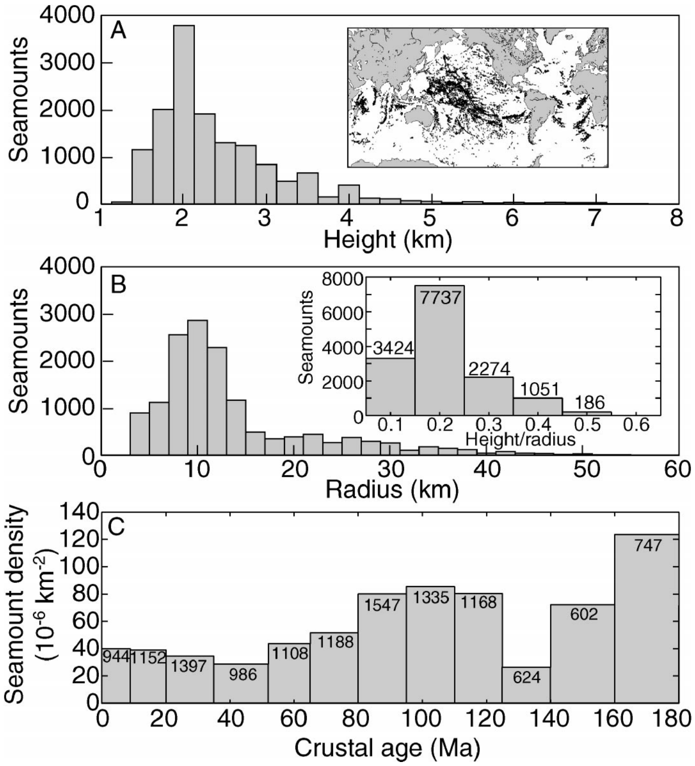

Figure 1. Geometries and global distribution of seamounts (data from Wessel, 2001). A: Histogram of seamount heights. Inset shows global distribution of seamounts. B: Histogram of seamount radii. Inset shows histogram of aspect ratios. C: Histogram of spatial density of seamounts. Number in each column represents number of seamounts in that age bin (Wessel, 2001).

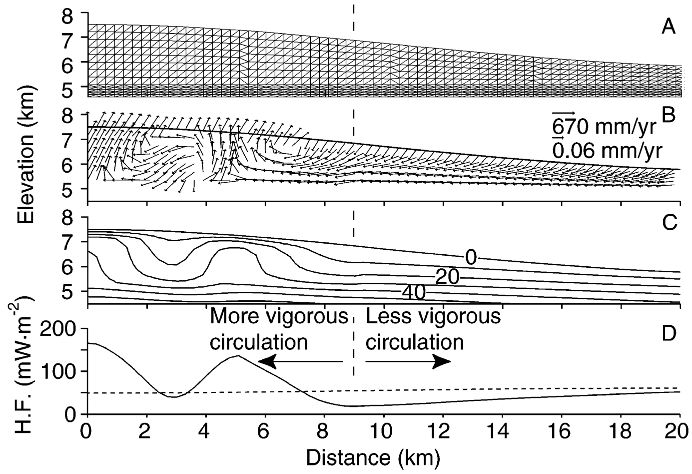

Figure 2. Results of coupled heat and fluid flow for seamount having aspect ratio (height/width) of 0.2, typical of global population (see Fig. 1), horizontal and vertical permeability of 10^{-12} and 10^{-13} m^2, respectively, and basal heat flow of 60 $mW \cdot m^{-2}$. A: Finite-element mesh used for this set of simulations. Vertical exaggeration is 1.2. B: Fluid-flow vectors. Vectors are logarithmically scaled. Vast majority of fluid and advective heat flow occurs on edifice and immediately surrounding area; fluxes on seamount flanks are much smaller. C: Isotherms with contour interval of 10 °C. D: Seafloor heat flow. Dashed line shows conductive heat flow (H.F.) in absence of fluid circulation. Solid line shows modeled heat flow.

butions, such that the actual number of seamounts may be on the order of 100,000, most being too small to be detected by altimetry data (Wessel, 2001). Seamounts are common features and are found on oceanic crust of all ages and in all of the world's oceans (Fig. 1).

FLUID-FLOW MODEL

We simulate fluid flow through seamounts by using a finite-element coupled-heat-and-fluid-flow algorithm (Zyvoloski et al., 1997). This algorithm solves equations appropriate for porous media that approximate fractured rock at a large scale. Fluid properties (density, enthalpy, and viscosity) vary with temperature and pressure (Harvey et al., 1997). Seamounts are parameterized in terms of their height and radius (equation 1) by using radial coordinates (Fig. 2). The seafloor is assigned hydrostatic pressure and a constant temperature of 2 °C. The bottom and distal boundaries of the model are no flow, and the mesh extends to a radius of 60 km to avoid edge effects. A constant basal heat flux is used. The model domain is composed of three units, a low-permeability lower basement (10^{-19} m^2), a higher-permeability upper basement 500 m thick, and a seamount edifice. Our models are idealized in geometry and use a uniform permeability for the upper basement and edifice, as appropriate for an order-of-magnitude analysis.

We tested a range of edifice and upper basement permeabilities, seamount aspect ratios, and basal heat fluxes. For the examples discussed in this paper, horizontal and vertical permeabilities for the edifice and upper-basement aquifer are 10^{-12} and 10^{-13} m^2, respectively. These permeabilities are near the low end of those observed in young oceanic crust (Fisher, 1998; Fisher and Becker, 2002; Davis and Becker, 2002) and thus should provide conservative estimates of fluid fluxes. In our models, mass flux scales roughly linearly with permeability; increasing or decreasing the permeability by an order of magnitude results in an order of magnitude higher or lower mass flux, respectively. The global seamount population is dominated by features with an aspect ratio of 0.2 (Fig. 1), but simulated fluid velocities are relatively insensitive to observed seamount aspect ratios. The simulations described here are based on a height and radius of 2 and 10 km, respectively, but we have completed sensitivity analyses using a range of aspect ratios and permeabilities (Fig. DR1[1]), and results cited herein are robust to a reasonable range of parameters.

Fluid circulates vigorously through the seamounts in our simulations, driven by horizontal temperature and density gradients (Fig. 2). In the absence of hydrothermal convection, isotherms would be warped upward under the seamount, because the seafloor is isothermal (2 °C) and conductive heat flow at the seafloor is only slightly reduced across the seamount due to bathymetric refraction. However, fluid recharge over a broad region on the flank of the seamount (Fig. 2B) depresses isotherms, and discharge focused across the top of the edifice raises isotherms. The resulting heat-flow profile exhibits a broad low heat flow on the distal flank of the seamount associated with recharge, a local positive anomaly at $r = 5$ km resulting from locally enhanced discharge, and a broad positive anomaly at the central part of the seamount. In these examples, seamount permeability is sufficiently high to allow shallower, cellular convection superimposed on a deeper, wider flow system. These heat-flow patterns are similar to those observed near a seamount on the young flank of the East Pacific Rise, where sediment cover is sparse (Villinger et al., 2002). Simulations based on the same crustal properties and heat input, but lacking a seamount edifice, resulted in fluid circulation, at rates several orders of magnitude lower, that does not produce measurable thermal anomalies.

Our initial set of simulations did not include the effects of low-permeability sediment cover, but sediments should play a role in inhibiting recharge on seamount flanks. To investigate this effect we

[1]GSA Data Repository item 2004118, Figure DR1, normalized mass flux as a function of seamount aspect ratio and horizontal permeability, is available online at www.geosociety.org/pubs/ft2004.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

TABLE 1. EFFECT OF SEDIMENT COVER ON CIRCULATION THROUGH SEAMOUNTS

Effective seamount height (km)	Radius to sediment (km)	Power (W)	Mass flux ($kg \cdot yr^{-1}$)
2.00	–	1.3×10^5	1.9×10^{10}
1.75	21.0	1.5×10^5	2.6×10^{10}
1.00	17.1	9.1×10^4	1.7×10^{10}
0.50	12.0	9.3×10^4	1.1×10^{10}

completed additional simulations with low-permeability (10^{-19} m^2) sediment covering a fraction of the seamount flank, thereby obstructing a part of the recharge area. We chose this low permeability to maximize the influence of the sediment. Simulation output was evaluated to quantify the importance of seamount height and radius in the presence of sediments (Table 1; Fig. 3). Sediment decreases the area of recharge and thus limits the potential mass and heat flux, but also increases the temperature of the basement fluid, promoting convection and increasing flow velocities. Because these effects are somewhat offsetting and flow is most vigorous near the crown of the seamount, the total advected heat and mass flux are relatively insensitive to the extent of sediment cover.

RESULTS AND DISCUSSION

We estimate global heat and mass fluxes associated with seamount circulation by grouping seamounts into age bins (Fig. 1) and varying the basal heat flux to be appropriate for seafloor age according to the model predictions of Global Depth and Heat Flow 1 (Stein and Stein, 1994). These seamount circulation estimates are compared to previous global estimates of advective power and heat flux associated with ridge-flank circulation. Seamounts occupy only ~1% of the ridge-flank area, and total heat loss through seamounts on ridge flanks is commensurately small, ~1% of the total to 65 Ma (Fig. 4A). However, although global heat-flow measurements on ridge flanks indicate that advective lithospheric heat loss ceases on average at 65 Ma (Stein and Stein, 1994), seamounts are capable of driving thermally significant fluid flow well beyond this age (Fig. 4B), increasing their impact at the global scale. For old crustal ages (older than 65 Ma), the average advectively disturbed heat flow due to seamount circulation is small (<10 $mW \cdot m^{-2}$), but variability remains large (Fig. 4B), suggesting that this form of circulation should be apparent in field observations. If this variability is widespread, as we suspect, fluid flow associated with seamounts may confound attempts to image variations in lithospheric heat flow associated with hotspots or plate aging. Unfortunately, global estimates of mass flux as a function of crustal age are not well known because these estimates are highly sensitive to the circulating fluid temperature, a poorly constrained parameter (e.g., Mottl and Wheat, 1994; Schultz and Elderfield, 1997). Comparisons of global mass flux estimates with those predicted by our models indicate substantial mass flux through seamounts for all ages.

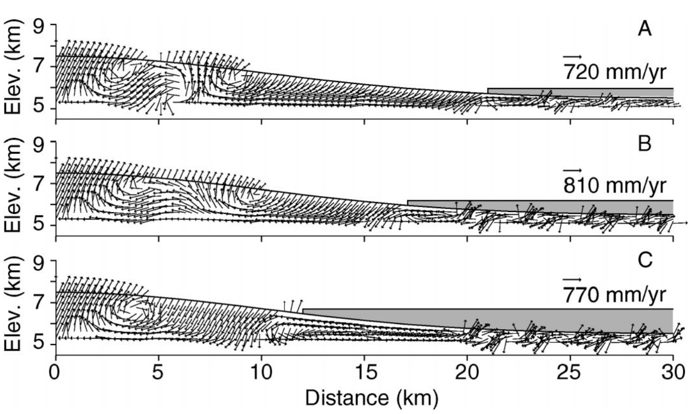

Figure 3. Effect of sediment cover on fluid circulation through seamounts. Seamount parameters are as in Figure 2. Sediment (shaded area) is assigned permeability of 10^{-19} m^2. Effective seamount height: (A) 1.5 km, (B) 1.0 km, and (C) 0.5 km.

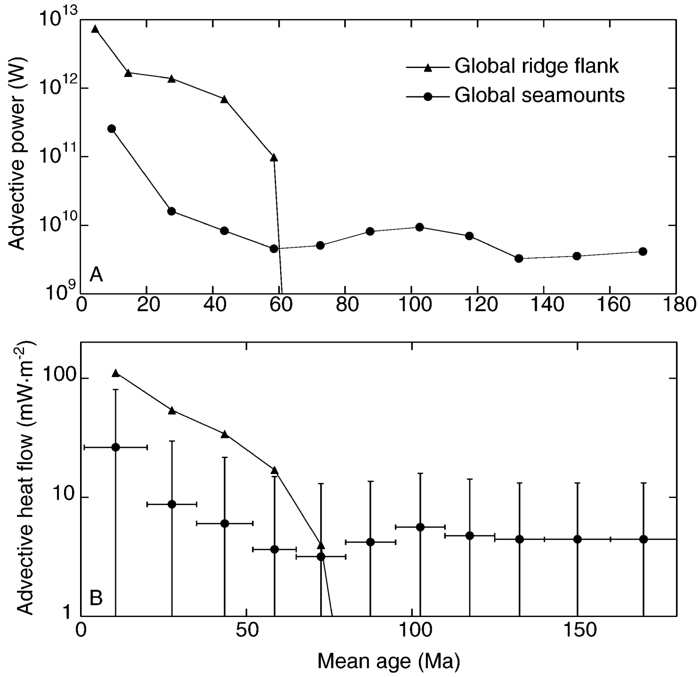

Figure 4. Power (A) and heat flux (B) through seamounts as function of crustal age. Triangles represent estimates of global power. Circles show extrapolated modeling results for seamounts. Horizontal bars indicate age range, and vertical bars indicate area weighted root-mean-square variability relative to no-flow case.

Extrapolation of modeling results to the global population of 12,798 mapped seamounts with assigned ages suggests a total mass flux of 5.0×10^{14} kg/yr. This value is an order of magnitude less than that estimated to occur through ridge flanks, but is somewhat larger than that estimated through ridge crests (Table 2). This estimate is based on the conservative assumption of relatively low seamount permeability and neglects as many as 85,000 additional seamounts that are not resolved by satellite gravimetry (Wessel, 2001).

Given the diverse origin and likely variability of seamount morphology and hydrogeologic properties, the biggest limitation of this analysis is our assumption of uniform permeability. However, in the absence of information on the distribution of permeability in seamounts, these initial simulations were completed with a simple representation. Our interpretation of a significant global mass flux through seamounts is robust, particularly considering many other conservative assumptions inherent in this analysis. Determining the distribution of permeability in seamounts requires direct testing, and future models can be refined to include parameters and constraints based on new observations.

The large fluid fluxes simulated in this study suggest that seamounts play an important role in the exchange of fluid and heat be-

TABLE 2. ESTIMATES OF MARINE HEAT AND MASS FLUXES

Environment	Power (W)	Mass flux ($kg \cdot yr^{-1}$)
Ridge axis* (younger than 1 Ma)	$1.8–3.3 \times 10^{12}$	$3.7–8.5 \times 10^{13}$
Ridge flank* (older than 1 Ma)	$7.7–9.3 \times 10^{12}$	$1.2–2.4 \times 10^{15}$
Seamounts (180–1 Ma)	4.1×10^{11}	5.0×10^{14}

*Numbers represent ranges of values from Stein and Stein (1994), Schultz and Elderfield (1997), and Mottl (2003).

tween the crust and ocean. On young seafloor, seamount circulation is superimposed on the more regionally extensive ridge-flank circulation responsible for the bulk of the global heat-flow anomaly and chemical mass transport between seawater and the crust. On crust older than 65 Ma, the average age at which advective lithospheric heat loss ends, seamounts may locally stimulate fluid flow. In some settings, old crust continues to host vigorous circulation systems, on the basis of the observed redistribution of heat (Noel, 1985; Detrick et al., 1986; Von Herzen, 2004), and seamount circulation may allow these deeper systems to exchange mass, heat, and solutes with the overlying ocean. This circulation is likely to advect nutrients that help to maintain vast microbial ecosystems in the upper oceanic crust (e.g., Edwards et al., 2003; Fisk et al., 2000; Holden et al., 1998; Kelley, 2002; Cowen et al., 2003). Confirmation of these processes requires field programs to collect coupled swath, seismic, and thermal data to evaluate the relationship between fluid flow and seamounts at a range of crustal ages, and additional coupled modeling that includes a range of permeability distributions.

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