Heat flow on the Hawaiian Swell and lithospheric reheating

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Most oceanic volcanic centres caused by hotspot activity are surrounded by sea floor that is unusually shallow for its age[1,2]. There is increasing evidence that swells found on older sea floor, like the Hawaiian Swell, have formed from a broad-scale reheating and thinning of the lithosphere as it passes over a mantle hotspot[3,4]. If the formation and subsequent disappearance of these swells are controlled by thermal processes, they should have an above-normal heat flux. We present here the results from 95 new heat flow measurements on the Hawaiian Swell. Along the older part of the swell the heat flow is 20–25% higher than the normal heat flow for crust of this age. This anomaly is consistent with the observed swell uplift. The shape and amplitude of the heat flow anomaly require that the reheating be largely confined to the lower half of the lithosphere.

The Hawaiian Swell is a broad, elongate region of anomalously shallow depths surrounding the youngest portion of the Hawaiian–Emperor seamount chain (Fig. 1). The swell has a maximum width of ~1,200 km and extends more than 2,700 km WNW along the length of the Hawaiian chain. Southeast of Oahu the swell rises ~1.5 km above the surrounding sea floor. The height of the swell gradually decreases to the northwest along the older portion of the island chain. While various models have been proposed for the origin of the Hawaiian Swell[5–7] it has also been argued[3,4] that the swell forms as a result of a broad-scale reheating of the lithosphere by the Hawaiian hotspot. The main evidence for this model is that the disappearance of the swell seems to follow a predictable thermal subsidence curve[3]. If the lithosphere has been reheated, the swell should have an above-normal heat flux with the size and location of the heat flow anomaly depending on the manner in which the lithosphere is reheated[4].

To test this hypothesis we recently obtained 95 reliable heat flow measurements at eight well-sedimented sites along the Hawaiian Swell (Fig. 1)[8]. The measurements were made with the Woods Hole Oceanographic Institution's digital heat flow instrument using thermistors externally mounted on either a piston core or a multipenetration pogo probe. Thermal conductivity measurements using the needle probe method[9] were made on sediment samples recovered in piston cores at each site and a single mean conductivity determined for each area. The mean heat flow at each site, weighted according to the errors in individual heat flow measurements, is given in Table 1 and compared with the normal heat flow expected for crust of this age in Fig. 2.

The heat flow measurements at each site are remarkably uniform. The 95% confidence limits on the weighted site means are $<\pm 4\ \text{mW m}^{-2}$ (0.1 h.f.u.) at all but one site. The near-normal heat flow on the youngest part of the swell precludes any significant reheating of the upper part of the lithosphere. However, the gradual increase in heat flow over the older part of the swell is consistent with reheating of the lower part of the lithosphere as it will take several million years for these relatively deep temperature changes to diffuse upwards. While part of the increase in heat flow between sites C and E is attributable to the ~10 Myr age offset across the Molokai fracture zone (Fig. 1), the heat flow at sites F, G and H is still 7–12 mW m^{-2} higher than the expected heat flow for crust of this age. This anomaly, which is ~20–25% of the normal background heat flux, is clearly resolvable with the present data.

To determine if this heat flow anomaly is consistent with the amount of reheating required to uplift the swell, the expected heat flow for a simple reheating model has been calculated. The reheating process is assumed to begin at the lithosphere's base and proceed upwards, raising all lithospheric temperatures below a depth L to $T_{\rm m}$, the assumed temperature of the asthenosphere. The initial temperature above depth L remains unchanged. While other forms of reheating are possible, this model puts the added heat as deep as possible and satisfies the constraint that no large heat flow anomaly is associated with the youngest part of the swell. In this model, the sea floor depth and heat flow at any point along the swell are completely determined by the geotherm (age) of the lithosphere when reheated, the initial height of the swell and the time since reheating[8]. If we assume an age of 90 Myr for the lithosphere around Hawaii and a plate model geotherm for the lithosphere[10], then lithospheric thicknesses after reheating of 37–45 km are required to explain the observed swell uplift (corrected for the isostatic loading of

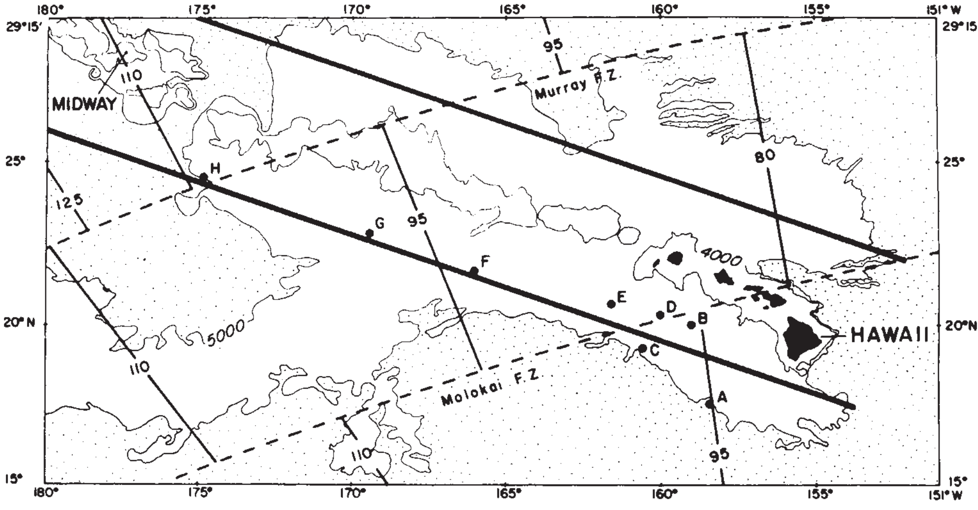

Fig. 1 Bathymetric map of the central Pacific with contours in metres. Isochrons (in Myr) and fracture zones (dashed lines) adapted from ref. 12. The extent of Hawaiian Swell is approximately indicated by the 5,000-m contour. ●, Heat flow site locations. Average depths along thick, black lines are plotted in Fig. 3.

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Table 1 Summary of heat flow data on the Hawaiian Swell

Site	Location	N	$\bar{K}$ (Wm^{-1} K^{-1})	$\bar{Q}$ (mW m^{-2})	s.d.	95% confidence limits (mW m^{-2})	t_c (Myr)	t_H (Myr)
A	17°40′ N 158°20′ W	11	0.73	52.9	3.3	±2.3	95	2.1
B	20°00′ N 159°00′ W	8	0.77	51.5	2.0	±1.8	96	3.8
C	19°20′ N 160°25′ W	18	0.77	54.5	3.5	±1.8	98	5.0
D	20°15′ N 160°02′ W	4	0.74	58.7	3.4	±6.2	86?	5.0
E	20°30′ N 161°30′ W	8	0.81	58.0	2.9	±2.6	88	6.8
F	21°45′ N 166°00′ W	10	0.86	57.4	4.5	±3.4	94	12.1
G	22°56′ N 169°36′ W	18	0.95	58.3	4.0	±2.1	97	16.3
H	24°41′ N 174°38′ W	18	0.96	58.8	4.5	±2.3	109?	22.5

N, number of gradient measurements. $\bar{K}$, mean site thermal conductivity (corrected to *in situ* conditions). $\bar{Q}$, weighted mean heat flow with sample standard deviation s.d. t_c, Estimated crustal age. t_H, Inferred time since reheating. Crustal ages were estimated using the isochron map in ref. 12. Time since reheating was determined by projecting the site locations onto a line joining Hawaii and Midway and assuming an age of 27 Myr for Midway[13].

100–200 m of sediment). These lithospheric thicknesses are about half the normal thickness of lithosphere of this age.

The predicted subsidence and anomalous heat flow for this range of values are shown in Fig. 3. The upper subsidence curve ($L = 37$ km) matches the data around Hawaii reasonably well, but seems too shallow over most of the rest of the swell. Inspection of the detailed bathymetry around the Hawaiian Islands[11] shows that there are two high spots on the swell, at 3 and 17 Myr, where smaller island chains (fracture zones?) crosscut the swell. Thus, the depths in these two areas may be anomalously shallow. The lower subsidence curve ($L = 45$ km) is a better fit over most of the swell. The heat flow anomaly observed on the swell also seems to be closer to the anomaly predicted by this lower subsidence curve, although the heat flow at the three oldest sites is less than predicted. This part of the swell actually formed when the hotspot was reheating slightly younger lithosphere (~80-Myr old) before it crossed the Molokai fracture zone (Fig. 1). When this is considered (dashed line in Fig. 3), the heat flow anomaly on this part of the Hawaiian Swell is probably large enough to be consistent with the observed swell uplift.

The main uncertainty in the present study is that reliable measurements of heat flow were not obtained on crust of the same age located off the swell, so the observed heat flow anomaly cannot easily be separated from any regional anomaly unrelated to the swell. The size of the observed anomaly is also small and close to the resolution of the data. Thus, although the present measurements are consistent with lithospheric reheating, the strongest evidence for this model remains the manner in which the swell subsides.

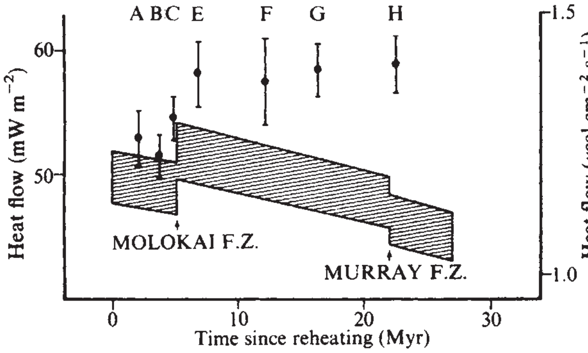

Fig. 2 Observed heat flow on the Hawaiian Swell with 95% confidence limits plotted against the time since each site passed over the Hawaiian hotspot. The shaded band is the normal heat flow expected for crust of this age estimated using a simple (age)$^{-1/2}$ relation with a scale factor of 11–12 h.f.u. (ref. 10). Assumed crustal ages and reheating times are given in Table 1. Site D was omitted from this plot because the heat flow is poorly determined (only four measurements) and the site is probably located on the Molokai fracture zone.

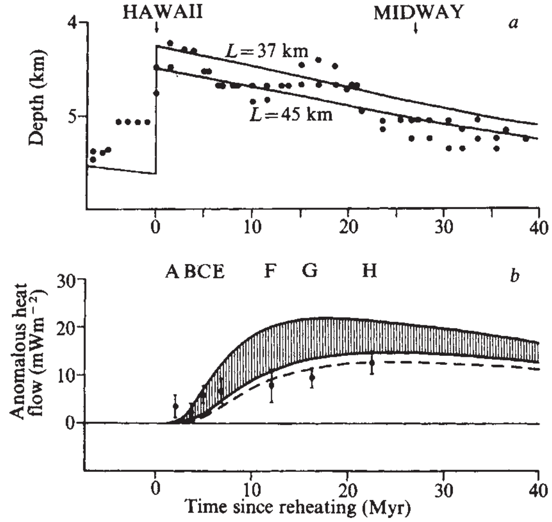

Fig. 3 *a*, Observed and predicted swell subsidence. Dots are 1°×1° averages of the depth of the crest of the Hawaiian Swell along the lines shown in Fig. 1. Solid curves are predicted subsidence for reheating model where L is the lithospheric thickness after reheating. *b*, Anomalous heat flow observed on the Hawaiian Swell compared with predicted heat flow for $L = 37$ km (upper solid curve) and $L = 45$ km (lower solid curve) assuming an age of 90 Myr before reheating. These curves represent the upper and lower bounds on the heat flow anomaly required to explain the observed swell uplift. The dashed line shows the effect on the lower bound of reheating 80-Myr old rather than 90-Myr lithosphere (see text for discussion).

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