Potential effects of hydrothermal circulation and magmatism on heat flow at hotspot swells

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ABSTRACT

The lack of high heat flow values at hotspots has been interpreted as showing that the mechanism forming the associated swells is not reheating of the lower half of oceanic lithosphere. Alternatively, it has recently been proposed that the hotspot surface heat flow signature is obscured by fluid circulation. We re-examine closely-spaced heat flow measurements near the Hawaii, Reunion, Crozet, Cape Verde, and Bermuda hotspots. We conclude that hydrothermal circulation may redistribute heat near the swell axes but it does not mask a large and spatially-broad heat flow anomaly. There may, however, be heat flow perturbations associated with the cooling of igneous intrusions emplaced during hotspot formation. Although such effects may raise heat flow at a few sites, the small heat flow anomalies indicate that the mechanisms producing hotspots do not significantly perturb the thermal state of the lithosphere.

INTRODUCTION

After the recognition that hotspots, regions of excess volcanism and higher elevation compared to surrounding areas, result from the rise of material through the mantle to the Earth's surface beneath both oceans and continents, marine geothermal measurements were among the first geophysical techniques used to assess their nature. Initially it was proposed that significant reheating of the bottom half of the lithosphere over a distance of ~300 km diameter was required to match the depth anomalies at hotspots (e.g. Crough, 1978). A consequence of this mechanism is unusually high surface heat flow, which should be measurable by established methodologies. The first detailed study of the Hawaiian hotspot found high mean heat flow (Von Herzen et al., 1982) but subsequent studies showed that the anomaly was over-estimated because the reference model predicted significantly lower heat flow than observed in unperturbed older lithosphere (Von Herzen et al., 1989; Stein and Stein, 1993). The conclusion was that lithospheric reheating is not a major factor in hotspot formation. Thus, possible mechanisms producing the swells, must be consistent with small or essentially zero heat flow anomalies, such as those expected for dynamic models (e.g. Ribe and Christensen, 1994).

However, it has been recently proposed (Harris et al., 2000a,b) that hydrothermal circulation may obscure the signal from the processes forming hotspots. Harris et al. (2000a) suggested that "fluid flow has the potential to obscure basal heat flow patterns associated with the Hawaiian hot spot" which would "not bode well for capturing the form and magnitude of this signature." Most hydrothermal circulation occurs in young oceanic crust (0 to ~65 Myr), resulting in lower measured heat flow compared to conductive cooling models of the lithosphere. Heat flow transferred by hydrothermal circulation in older oceanic lithosphere is thought to be much less (e.g., Stein and Stein, 1994; Von Herzen, 2004). However, as suggested above, if the overall rough basement and islands and seamounts associated with hotspots causes fluid flow to occur both in the igneous basement and perhaps in the relatively permeable volcaniclastic sediments then "capturing the maximum basal heat flux may be confounded by fluid flow" (Harris et al., 2000a). Evidence on the magnitude and extent of hydrothermal heat transfer may be provided by the detailed heat flow at the five hotspots on crust older than ~65 Myr.

In this paper we first examine heat flow anomalies near these hotspots. The anomalies are computed relative to the GDH1 reference model (Stein and Stein, 1992) and with crustal ages from Muller et al. (1997). Second, we examine which sites may be affected by hydrothermal circulation and thus mask higher heat flow. Last, we consider heat flow perturbations associated with the cooling of igneous structures associated with the hotspot processes, including the igneous material emplaced on the surface of pre-existing oceanic crust, and intruded sills at sub-crustal depths.

PREDICTIONS OF EXPECTED HEAT FLOW FROM HOTSPOTS

Although the depth in the Earth from which hotspots originate is still debated (e.g., Anderson, 2005; Sleep, 2003; Foulger, this volume; Garnero et al., this volume), a geophysical challenge is to separate the effects of mechanisms forming hotspots from shallower lithospheric processes, including the "normal" lithospheric cooling as the plate ages. Lithospheric interactions with the upward flow of magma, the absolute velocity of the plate, and near surface physical processes (including excess volcanism and hydrothermal circulation) complicate the task of understanding the deeper mantle processes leading to the formation of hotspots. Also, because heat is largely transferred by conduction through the lithosphere, excess heat loss associated with hotspot formation at a given location may occur long after the hotspot upwelling has ceased. Although hot spots are associated with anomalously shallow bathymetry, it is unclear if their surface heat flow is anomalously high. Depending on the answer to this question, different mechanisms have been proposed for hotspot formation.

Many mechanisms have been suggested to explain hotspot formation. An important observation to model is the anomalously shallow bathymetry and its subsequent subsidence (e.g., DeLaughter et al., 2005). For example, the reheating model requires significant upwelling of mantle material that rapidly thins the bottom half of the overlying plate (Crough 1978; 1983). For the dynamic plume model that incorporates a large viscosity contrast between the plume and overlying lithosphere, most reheating is at the base of the lithosphere (e.g., Liu and Chase, 1989; Ribe and Christensen, 1994). The compositional buoyancy model predicts shallower depths from relatively low density magmas emplaced either within the lithosphere or near its base (e.g., Robinson, 1988; Sleep, 1994; Phipps Morgan et al., 1995). Different amounts of reheating and excess heat flow with time since hotspot formation are expected from these different mechanisms. Hence heat flow data may help to discriminate between them.

For the Hawaiian chain, on the relatively fast moving Pacific plate, matching the observed uplift and subsequent subsidence by the reheating mechanism requires that the bottom third to half of the oceanic lithosphere is rapidly reheated to asthenospheric temperatures over a zone 300 km wide centered on the axis (Von Herzen et al., 1982). At the time reheating begins, the surface heat flow anomaly should be zero, but as the plate moves away from the upwelling the heating of the lower lithosphere propagates upward by conduction. The predicted anomaly gradually increases to a maximum of ~25 mW m^{-2} about 15 to 20 Myr after reheating, and then gradually decreases. The heat flow anomaly should be a maximum at the axis of the chain and decrease to zero over about 600 km normal to the axis (Figure 1a).

Although anomalously high heat flow was initially reported for the Hawaiian chain (Von Herzen et al., 1982), consistent with significant lithospheric reheating, subsequent data and analysis (Von Herzen et al., 1989; Stein and Stein, 1993) showed that the expected Gaussian distribution of anomalous heat flux orthogonal to the axis did not exist, and many of the apparent anomalies along axis result from comparing the data to reference thermal models that underestimate heat flow elsewhere. Thus, the implication is that heat flow data do not support swell formation by extensive lithospheric heating.

The small heat flow anomaly and absence of the pattern expected for lithospheric reheating at Hawaii and other marine hotspots (Reunion (Bonneville et al., 1997), Bermuda (Detrick et al., 1986), Cape Verde (Courtney and White, 1986) and Crozet (Courtney and Recq, 1986)) imply that uplift may result from the dynamic effects of rising plumes. Their thermal effects are concentrated at the base of the lithosphere and hence would raise surface heat flow at most slightly, given that tens of millions of years are required for the conduction of heat to the surface. For example, Ribe and Christensen (1994) predicted heat flow anomalies for Hawaii of less than 1 mW m^{-2} (Figure 1b). The heat flow anomaly associated with compositional buoyancy depends on whether the magma is near the base of the lithosphere (e.g., Sleep, 1994) or at relatively shallow depth in the lithosphere (e.g., Phipps Morgan et al., 1995).

DATA

Of the five oceanic hotspots (Hawaii, Reunion, Cape Verde, Bermuda, and Crozet) with closely-spaced "pogo"[1] heat flow measurements (Figure 2), Hawaii is the best studied (Von Herzen et al., 1982; 1989 and Harris et al., 2000a). The ~81 Ma hotspot track (e.g., Keller et al., 1995;

[1] (For "pogo" measurements, the equipment is initially lowered to the seafloor, and then after heat flow is determined at a location it is raised slightly above the seafloor and towed to other nearby sites, allowing for closely-space measurements typically for ~24 hours, before the equipment is returned to the ship. Hence, it is similar to jumping with a pogo stick.)

Clouard and Bonneville, 2005; Norton, this volume) presently has an absolute velocity in the hotspot frame of ~104 mm/yr (Gripp and Gordon, 2002). Heat flow measurements on ~84 to ~118 Ma crust show neither the expected anomalously high heat flow near the axis parallel to the relative motion of the hotspot track, nor a decrease from the center of the axis of the swell towards the edges (Figures 3a,b & 4a). The anomalies are ~5-10 mW m^{-2} higher than expected for similar age lithosphere (Von Herzen et al., 1989; Stein and Stein, 1992). These anomalies may reflect lithosphere, before perturbation by the hotspot processes, having a somewhat higher heat flow than typical, but still within the observed range of variability, for its age (DeLaughter et al., 2005).

Reunion is the location of most recent volcanism for a ~65 Ma hotspot track (e.g., Bonneville et al., 1997) with a present-day ~13 mm/yr absolute velocity in the hotspot reference frame (Gripp and Gordon, 2002). The heat flow measurements were made in the form of long (~200 and ~400 km) parallel profiles about 100 km apart extending westward from the Mascarene Ridge (perpendicular to the hotspot track) on crust affected by hotspot volcanism ~15-20 million years ago (Figure 2b). The crustal age is about 65 Myr west of the Mahanoro fracture zone. To the east, the crustal ages from Muller et al. (1997) are ~10-15 million years younger than those used by Bonneville et al. (1997) (derived from Dyment (1991)) to analyze their heat flow measurements. With the revised younger crustal ages, many measured heat flow values to the east of the Mahanoro fracture zone, which were initially interpreted as greater than the expected average by Bonneville et al. (1997), are now about that expected, thus suggesting no heat flow anomaly. The heat flow anomaly is largest west of the Mahanoro fracture zone (~6 mW m^{-2} for the northern profile, although it may be affected by hydrothermal circulation) and decreases towards the Mascarene Ridge. Hence, the expected increase in the heat flow anomaly towards the axis of the hotspot from a lithospheric reheating mechanism is not observed (Figure 3c,d).

Unlike the Hawaiian and Reunion hotspots with clear and long volcanic signatures, volcanism for Crozet on the Antarctic plate started at ~8 Ma and lacks a clear track (Figure 2c). The shallow Crozet Bank appears to have been emplaced on old, mechanically thick crust different from the adjacent Del Cano Rise, formed on or near the Southwest Indian Ridge before anomaly 24 time (Goslin and Diament, 1987; Recq et al., 1998). The Crozet Bank's eastern islands (Île de la Possession and Île de l'Est) are separated by the Indivat Basin from the western islands (Île des Pingouins, Île aux Cochons, and Îles des Apotres). The eastern islands are usually thought to be the oldest with the oldest dated volcanism at ~8 Ma, but detailed paleomagnetic work indicates that volcanism also occurred from 5-0.5 Ma on the eastern island of Possession (Camps et al., 2001). Also, the western island of Apotres has volcanism dated as old as 5.5 Ma (Giret et al., 2003). Both western and eastern islands have some Holocene volcanism. The relatively few heat flow measurements for the Crozet hotspot are all on ~68 Myr age crust extending southeast from the eastern islands (Courtney and Recq, 1986) and presumably into crust unperturbed by the hotspot activity. Of the three reliable multi-penetration sites, M4, with the shallowest seafloor, has a heat flow anomaly of ~14 mW m^{-2} (Figure 4b). The other two sites, M5 and M6, farther away from the volcanism, have heat flow approximately that expected for the crustal age. It is difficult to interpret one isolated measurement, M3, at the base of the shallowing volcanic construct of the archipelago, where the heat flow is ~35 mW m^{-2} above expected. This heat flow value will be discussed later in the paper.

Two additional heat flow surveys are on swells perturbing old crust. Cape Verde is on the African plate (Courtney and White, 1986) and Bermuda (Detrick et al., 1986) is on the North American plate (Figures 2d,e). Some characteristics of Cape Verde are similar to those of Crozet. Volcanism producing the islands is relatively recent on ~125 Ma crust. The easternmost islands formed ~10-20 Ma with the western ones younger than 8 Ma (Courtney and White, 1986). The absolute velocity in the hotspot reference frame for Cape Verde is somewhat higher (~21 mm/yr) than for Crozet (~6 mm/yr) (Gripp and Gordon, 2002). As with Crozet, the heat flow sites are located on a profile of approximately similar age crust extending from near the volcanic islands into crust unperturbed by the hotspot activity. Of the 7 sites with closely-spaced measurements (Figure 2d), site A was considered unreliable because of the difficulty penetrating the seafloor with the heat flow probe, the lack of measured thermal conductivity, and likelihood of bottom erosion to the seafloor (Courtney and White, 1986). We have included the values here using an estimated thermal conductivity of 1 W/(m K). The heat flow anomaly is relatively high (~9 mW m^{-2}) at site C, within a few hundred km of the maximum geoid high (Figure 4c).

Bermuda (Figure 2e), on the North American plate (with an absolute velocity of ~38 mm/yr in the hotspot reference frame (Gripp and Gordon, 2002)), is a shallow region without volcanism for ~33 Myr. Bermuda may be either a "one shot" hotspot or perhaps part of a track with a very large spatial gap in volcanism (e.g Vogt and Jung, this volume). Compared to the other four hotspot regions, the “pogo” measurements at Bermuda (Detrick et al., 1986) have a similar small maximum anomaly (~8 mW m^{-2}). Also, a heat flow value determined from a drill hole on the island of Bermuda (Hyndman et al., 1974) has a small (~5 mW m^{-2}) anomaly. The heat flow data do not display the broad anomaly pattern expected for significant thermal rejuvenation of the lithosphere (Figure 4d), although the mean heat flow values are systematically distributed with distance from Bermuda.

HYDROTHERMAL CIRCULATION

”Fluid flow has the potential to obscure basal heat flow patterns associated with the Hawaiian hot spot” (Harris et al., 2000a). Hydrothermal circulation is assumed to transfer relatively little heat in oceanic lithosphere older than ~65 Myr (e.g., Stein and Stein, 1994; Von Herzen, 2004), about the minimum crustal age in these surveys. However, even in old crust, a few areas have been interpreted as having hydrothermal circulation (e.g., Noel and Hounslow, 1988; Fisher and Von Herzen, 2005). Also, areas where isolated igneous basement peaks penetrate or are only shallowly buried by the sediment cover are thought to be the main flow path for fluids between the overlying ocean and the crystalline crust (e.g Harris et al., 2004). This effect has been observed on 3.5 Ma crust on the Juan de Fuca plate (Mottl et al., 1998) and inferred from heat flow measured on 83 Myr crust of the northwestern Atlantic (Embley et al., 1983). Studies suggest that pore water circulation removes heat from the surrounding area, extending a few to tens of kilometers distance from (near-) outcrops of basement rock (e.g., Stein and Stein, 1997; Fisher et al., 2003).

An additional factor for hotspots is that if hydrothermal circulation removes large amounts of heat near seamounts, significant pore water flow may also occur within the relatively highly permeable volcaniclastic sediments. The permeabilities of sediment obtained for the Canary Islands seafloor by Urgeles et al. (1999) are as high as $\sim 10^{-16}$ m^2. However, the mostly thick sediments at the hotspots we discuss should prevent any significant vertical flow of water (e.g. Spinelli et al., 2004) and thus any significant advective heat transfer. Slow horizontal pore water velocities may occur given this sediment permeability, but modeling of flow in oceanic crystalline basement suggests flow sufficient to transport significant amounts of heat requires higher permeabilities, at a minimum ~3 to ~5 orders of magnitude larger (Fisher et al., 2003; Stein and Fisher, 2003, Hutnak et al., 2006; A. Fisher, personal communication). For the sediments, Harris et al. (2000b) “found that horizontal permeabilities as large as 10^{-11} m^2 were needed to produce significant perturbations to the surface heat flow".

To test this hypothesis of significant hydrothermal circulation, we use the analysis of 58 high-quality closely-spaced heat flow measurements ("pogo" surveys) (Von Herzen, 2004). This approach used the correlation of heat flow variations with the shape of the basaltic basement and sediment cover to infer whether areas have hydrothermal circulation. Von Herzen (2004) classified the sites in four categories: (1) having hydrothermal circulation, (2) perhaps having hydrothermal circulation, (3) uncertain if all conductive, and (4) conductive heat transfer. 44 of the 58 "pogo" surveys are on or near the swells discussed in this manuscript (Figure 2). For the surveys associated with hotspots, Von Herzen (2004) suggested that 24 (~55%) have conductive heat flow, 8 (~18%) probably conductive heat flow, 8 (~18%) have convection, and 4 (~9%) probably have convection.

About 27% of the surveys near the swells were interpreted as having or probably having convection. Most are within ~200 km of the swell axes (Figures 3 and 4). These sites include five made close to the Hawaiian axis (Site #4, two sections of the Maro Reef profile, and two sections of the Oahu profile; Figure 2a), the two closest sites to Bermuda (#5 and #6), and site C from Cape Verde, about 40 km from the geoid high and closest to the youngest region of volcanism. Conversely, most heat flow sites off axis are apparently not affected by hydrothermal circulation. Thus it is doubtful that hydrothermal circulation masks a high and wide heat flow anomaly associated with lithospheric reheating mechanism for the formation of the swells, but it may occur near the swell axes.

VOLCANISM

Although magmatic activity is associated with the formation of hotspot swells, its thermal effects are typically not included in heat flux estimates. Crustal thickness at hotspots is significantly greater than for normal oceanic crust (e.g., White et al., 1992) although the conditions producing the melt have large uncertainties (e.g. Sallares and Calahorrano, this volume). The emplacement of the additional hot material at relatively shallow depths should have a thermal signature. While some excess crust is associated with the near-surface volcanism constructing the islands, some hotspots have a deeper sill structure intruded near the base of oceanic crust. Such sills are deduced from seismic data for Hawaii (ten Brink and Brocher, 1987) (Figures 5a and b) and the Marquesas (Caress et al., 1995; McNutt and Bonneville, 2000), but others do not appear to have obvious underplating (e.g., Crozet (Recq et al., 1998)). Next, we examine the heat flux associated with the cooling of the island/seamount chain and the underplated sill for Hawaii, and the implications for the other heat flow surveys on hotspots.

Total heat contribution

The contribution of the cooling magma to the geothermal budget in part depends on its production with time. We estimate the production rate at the Hawaiian hotspot from the magma cross section geometry (Figure 5b) and the absolute plate velocity of ~0.1 m/yr. Assuming that erosion of Oahu has reduced its initial volume by a factor ranging between 0.3-0.5, the mean magma volume generation/unit time (V) is about 3-6 m^3/s, comparable to other estimates of the rate of Hawaiian magmatism (Swanson, 1972; Shaw, 1973; Wadge, 1980).

The total thermal power (P) from the magma is its latent heat from solidification (PL) plus the cooling (PT). For the "island" region the total thermal power is given in equation (1) and values for the parameters from Table 1.

$$P = PL + PT = V\rho\,(L + c\,\Delta T) = 1\text{-}2\times10^4\ \mathrm{MW}. \qquad (1)$$

Additional heat comes from the deeper sill that has an average thickness of 2.5 km. We estimate the volume of the sill is about half that of the edifice of the islands before erosion. While the emplacement of the underplated material may consist of thinner sills that average to a lower effective initial temperature, for our calculations we assume a single sill initially at the solidus temperature (~1000°C above the intruded rock), to maximize its thermal effects. Thus, including the contribution of both the "island" and the sill, the total power is $1.5 – 3 \times 10^4$ MW (50% greater than that estimated in eqn. (1)). Another way of examining this issue is to calculate the power released from the cooling for a volume of magma, one square meter area with a thickness of 2.5 km. The total power, 8.25×10^{12} J, for the square meter area divided by about 10 million years of cooling produces an average heat flow of ~26 mW m^{-2} or three times that if the "island" and eroded material are included.

Table 1:
Physical properties assumed for the cooling magma.

Symbol	Term	Value
ρ	Density	3000 kg/m^3
c	Heat capacity	800 J/kg-K
k	Thermal conductivity	2.2 W/m-K
κ	Thermal diffusivity	8×10^{-7} m^2/s
L	Latent heat of melting	3×10^5 J/kg
ΔT	Temperature drop after solidification	1000 K

The Sill Model

The cooling of a magmatic underplated region should have a longer-term effect compared to the near surface volcanism. At midocean ridges, heat flow rapidly decreases from cooling lava (Johnson and Hutnak, 1997) and heat is quickly dissipated by seawater. Similarly, on land atmospheric cooling dissipates heat after an eruption. The surface heat flow from the underplated area with time is calculated assuming 1-D cooling of an infinitely extending horizontal sill, appropriate because of the large ratio of width to thickness such as observed near Oahu, Hawaii. The analytical solution for the surface heat flux (q) with time (t) is given in equation 5 from Von Herzen et al. (1989) (initially obtained from Carslaw and Jaeger, 1959) as:

$$q(t) = [k\Delta T/(\pi\kappa t)^{1/2}]\{\exp[-a^2/(4\kappa t)]-\exp[-b^2/(4\kappa t)]\} \quad (2)$$

where a and b are the depths of the upper and lower sill surfaces, respectively and the other parameters are from Table 1.

The deep sill structure found by ten Brink and Brocher (1987) is approximately 200 km wide with an average thickness of 2.5 km, and we presume it was formed by intruded magma associated with the hotspot. The heat flux over time is illustrated in Figure 5c, for values of the top (a) and the bottom (b) of the sill equal to 7 and 9.5 km, respectively relative to the seafloor depths away from the edifice. The surface heat flow for the deep sill is zero at emplacement and then rapidly increases to a maximum of ~75 mW m^{-2} at about 0.5 Myr after emplacement, but subsequently rapidly decreases with increasing age since emplacement. This model predicts excess heat flow of ~10 mW m^{-2} at ~3.5 Ma (near Oahu) but only ~2 mW m^{-2} at ~15 Ma (near Maro Reef). However, the observed heat flow anomalies (measured less that expected from GDH1 (Stein and Stein, 1992)) along the Oahu and Maro Reef profiles (Figure 6) to about 150 km from the islands are about the same value and similar to other measurements for the Hawaiian chain (~5-10 mW m^{-2}).

After correcting the heat flow values at Oahu and Maro Reef for "thermal blanketing" due to deposition of cold sediment (e.g. Von Herzen and Uyeda, 1963; Hutchison, 1985) the data are consistent with the suggestion that additional heat is derived from an intrusive body. The "corrected" heat flow (Harris et al., 2000a) at Oahu is anomalous by ~24 mW m^{-2} and at Maro by ~12 mW m^{-2}, approximately the expected difference in heat flow at these locations modeled by conductive cooling of the sill intrusion. However, the amount of the correction depends greatly on factors such as the sedimentation rate, thermal conductivity of the sediments, and assumed boundary conditions at the sediment/igneous crust interface. Most oceanic sites have too low sedimentation rates to require corrections, and for those with somewhat thicker sediment, the corrections are typically small, a few percent. In contrast, for the measurement sites closest to Oahu and Maro Reef, about two kilometers of sediment have been deposited in the "moat" formed by the "loading" of the islands on the crust. The calculated correction is large if the heat flow at the sediment/basement interface varies with normal conductive cooling of oceanic lithosphere, as assumed by Harris et al. (2000a). However, the correction is somewhat smaller if vigorous hydrothermal circulation occurs within the top of the igneous oceanic crust (Wang and Davis, 1992). Additional uncertainties for the calculation are introduced if significant hydrothermal circulation occurs within permeable near-surface volcaniclastic sediments. Thus for Oahu, a case can be made for or against additional heat from igneous intrusions depending on assumptions.

Magmatic activity may explain the higher heat flow at two sites near Crozet and perhaps one at Cape Verde. For Crozet, at station M3 the heat flow anomaly is ~35 mW m^{-2}, ~50 km from the Holocene volcanism on Île de l'Est, and at M4, the heat flow anomaly is ~15 mW m^{-2}, ~100 km distant (Figure 4b). The interpretation at M3 is problematic, since only one reliable measurement was made, but the site is clearly on the slope of the volcanic structure. At Cape Verde, station C, the

~10 mW m^{-2} heat flow anomaly is within about 100 km of Sao Vincent, an island with Holocene volcanism (Figure 2d).

DISCUSSION AND CONCLUSIONS

Reanalysis of closely-spaced heat flow surveys near five hotspots confirms that the heat flow anomalies are quite small, generally less than ~10 mW m^{-2}, and do not have the Gaussian-shaped distribution of values extending ~600 km away from the swell axis expected from the lithospheric reheating models. This finding accords with previous studies (Von Herzen et al., 1989; Stein and Stein, 1993; DeLaughter et al., 2005) showing that significant lithospheric reheating does not occur, and the upwelling plume of material must have a substantially smaller thermal imprint than the suggested 300 km diameter (e.g. Crough, 1978)

Issues with Hydrothermal Circulation

It seems possible that hydrothermal circulation may redistribute some heat within ~200 km of the swell axis. However, it does not mask a large and spatially-broad heat flow anomaly expected from reheating of a significant portion of lower lithosphere (e.g., Crough, 1978).

Hydrothermal circulation occurs at the two nearest sites to Bermuda's volcanic edifice. Unlike the four other hotspots with present-day volcanism, the most recent volcanic activity here is dated at ~33 Ma (Vogt and Jung, this volume). Bermuda does not appear to be associated with low mantle seismic velocities, as inferred at the other four active hotspots (e.g., Zhao, 2004; Dziewonski, 2005; Ritsema, 2005). The three sites with the highest heat flow anomalies are located near the base of the volcanic edifice (site 4) and the others (sites 5 and 6) higher on the structure (Figure 2c). The first is interpreted as having conductive heat transfer but the other two as "perhaps" having convection (Von Herzen, 2004). Hence, some higher than expected heat flow near the volcanic edifices may result from convection, rather than volcanic processes.

Heat flow and absolute plate velocity

The maximum heat flow anomalies for all five hotspots are about the same, yet the duration of the hotspot tracks and the absolute plate velocities and age are quite different. Maximum heat flow anomalies for the two long hotspot tracks of Hawaii and Reunion are approximately the same as observed at the volcanically active, more concentrated, "large volcanic highs" of Crozet and Cape Verde (Figure 2). Despite the large range of absolute plate velocities for these five hotspots (104 to 6 mm/yr) there is no clear trend of larger heat flow anomalies with decreasing absolute plate velocity, as might be expected if volcanic activity occurred over a longer period of time in one region.

Pogo surveys and the global heat flow data

We have examined how the heat flow on and off swells varies with lithospheric age and compared to the global dataset (Figure 7 top). Swell sites are these sites on the regions of shallow depths associated with the hotspots discussed in this paper. Off-swell sites include those away from the shallow depth regions, and others discussed in Von Herzen (2004). On average, “pogo” surveys have heat flow values similar to global averages for oceanic lithosphere.

Overall, the standard deviations for the “pogo” sites (Figure 7 bottom) are much lower than for widely-spaced measurements on similar age crust (Stein and Stein, 1994). There is a slight decrease in the standard deviations for the “pogo” surveys with increasing age. These observations suggest that although hydrothermal circulation transfers relatively little heat in old oceans, its effect is still slightly decreasing with age, even in Mesozoic crust. Von Herzen (2004) reached a similar conclusion based on the decreasing percentage with increasing age of “pogo” surveys on old oceanic lithosphere that were interpreted to have hydrothermal circulation.

Future Work

The obvious difficulty in interpreting the data for swells is the low density of heat flow measurements. For example, although the Hawaiian swell has the most extensive geothermal, geological, and geophysical data compared to other hotspots, it is still difficult to determine the extent and thermal effects of hotspot magmatism. It is interesting to note that a high measured heat flow anomaly for Hawaii occurs at the northeastern ends of the Oahu and Maro Reef profiles (Figure 6). These sites are on the relatively thinly-sedimented flexed arches that have been associated with relatively recent and extensive seafloor volcanism (Clague et al., 2002). Similarly, the highest heat flow for Crozet (M3, Figure 2c) is on the volcanic edifice near recent volcanism.

Additional work on hot spots would be useful. As far as we know, the Marquesas, has no "pogo" heat flow measurements. Seismic data from the Marquesas hotspot (Caress et al., 1995, Figure 4) indicate a similarly-shaped, but substantially larger, subcrustal intrusion compared to Hawaii, with ~10 km maximum thickness at the center, thinning to about 3-4 km at 150 km distance to either side. Given this intrusion and the recent age of the chain (less than 6 Ma (Desonie et al., 1993)), the Marquesas may be an excellent location for future study (Figure 5c).

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FIGURE CAPTIONS

Figure 1- Predicted heat flow anomalies from reheating and dynamic plume models. (a) The reheating model predicts heat flow anomalies up to ~25 mW m^{-2} (Von Herzen et al., 1982) in contrast to a (b) dynamic plume model of less than 1 mW m^{-2} (Ribe and Christensen, 1994). The location of heat flow measurements for Hawaii from Von Herzen et al. (1982; 1989) and Harris et al. (2000a) are shown in (a). In (b) the predicted surface heat flow from an upwelling plume (location indicated by the solid semicircle) beneath a moving plate is shown for up to 2400 km downstream of where the plume has passed (horizontal axis) and for up to 1600 km perpendicular (vertical axis) from the path of the plume.

Figure 2- Bathymetry and sites with closely-space heat flow measurements for (a) Hawaii, (b) Reunion, (c) Crozet, (d) Cape Verde, and (e) Bermuda. Von Herzen (2004) examined heat flow and bathymetry to infer if the sites have hydrothermal circulation (red), probably have hydrothermal circulation (orange), probably have conductive heat transfer (green), or have conductive heat transfer (blue). Most sites have conductive heat transfer. The associated numbers and letters next to the heat flow locations are the site names from the published heat flow papers. For (c) Crozet, the upper right

panel is an enlargement of the region with the islands indicated by the small box. The eastern islands (Po=Île de la Possession and E=Île de l'Est) are separated by the Indivat Basin (Ind. B.) from the western islands (Pi=Île des Pingouins, C=Île aux Cochons, and A=Îles des Apotres).

Figure 3- Heat flow anomaly with distance for profiles taken perpendicular to a hotspot track for Hawaii and Reunion (see locations from Figure 2a,b). While the heat flow may be ~5 mW m^{-2} greater than predicted by the GDH1 reference model, the heat flow anomaly does not show the expected Gaussian-type pattern from significant lithospheric reheating with a large maximum at the axis (0 km). Similarly, few sites show evidence of hydrothermal circulation (Von Herzen, 2004). Symbols same as Figure 2. Horizontal bar at left of Figure 3a,b represents mean heat flow anomaly on incoming Pacific plate before reaching hotspot.

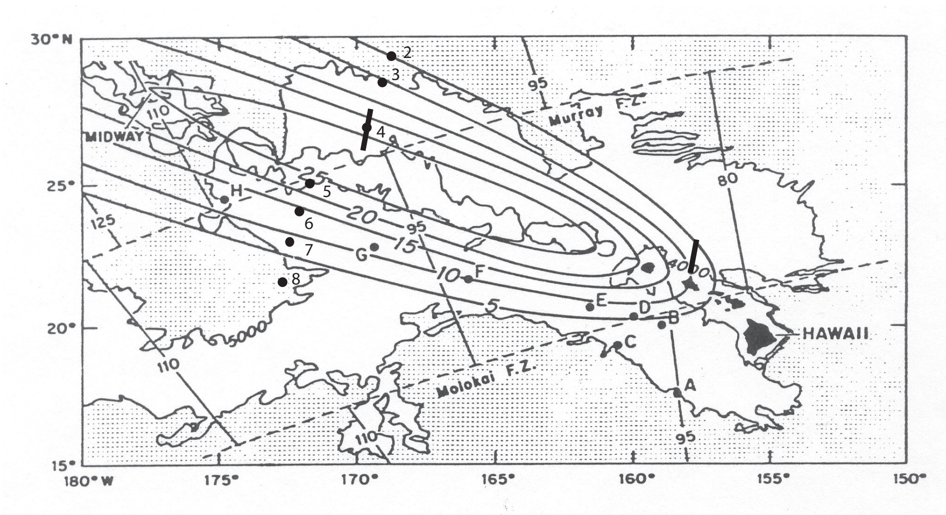
Figure 4- Heat flow anomaly with distance for profiles taken parallel to a hotspot track for Hawaii (A). Crozet (B), Cape Verde (C), and Bermuda (D) have no clear hotspot track so distances for the sites are measured from the local geoid maximum in the approximate direction of the heat flow sites. Symbols same as Figures 2 and 3. Horizontal bar at left of Figure 4a represents mean heat flow anomaly on incoming Pacific plate before reaching hotspot.

Figure 5- Sill intrusions and heat flow anomalies. (a) Location of seismic study across Oahu (solid line). (b) Cross section with volcanic sill and edifice above (from ten Brink and Brocher (1987)). (c) Heat flow anomaly expected for the observed sills (with an average thickness of 2.5 km) under Oahu and (with an average thickness of 5 km) under the Marquesas. Heat flow for Oahu is a maximum at about 0.75 Myr and decreases with increasing age.

Figure 6- Heat flow anomalies (top), measured and sediment-corrected heat flow (middle), and depth-converted seismic reflection profiles (bottom) for (left) Oahu and (right) Maro Reef. The top panels show the heat flow anomalies for the measured (solid circles) and sediment-corrected heat flow (purple triangles). Blue circles indicate no hydrothermal circulation is inferred, red circles indicate hydrothermal circulation is inferred and black circles have no determination (same as Figure 2). The middle panel shows the measured heat flow (open circles and sediment-corrected heat flow values (closed circles). The location of these Hawaiian measurements are shown in Figure 2a. The middle and lower panels are Figures 10 and 11 from Harris et al. (2000a))

Figure 7- Heat flow data with crustal age for the swell (triangles) and non-swell (squares) “pogo” surveys analyzed by Von Herzen (2004). (top) The average heat flow from each survey with age is similar to the observed global average heat flow (Stein, 2003). (bottom) The standard deviations of the “pogo” surveys are significantly less than the global average. Colors are the same as in Figures 2-4. Two sites from Von Herzen (2004) are not included in this figure. One located near a seamount has extremely high and variable heat flow (presumably due to fluid flow) and the other, in the Gulf of Mexico, has a large uncertainty in crustal age.

a)



b)

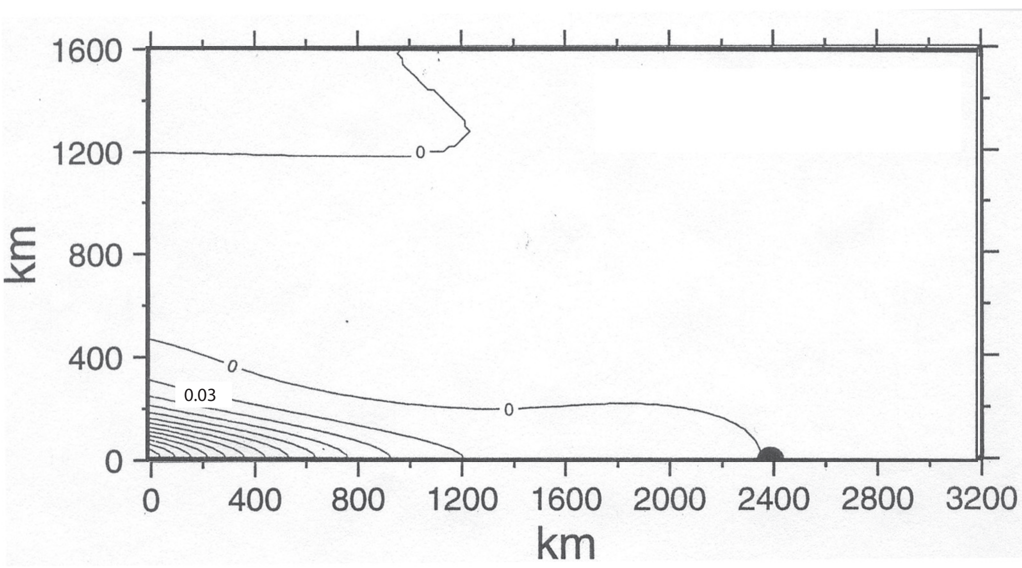


Figure 1
Stein and Von Herzen

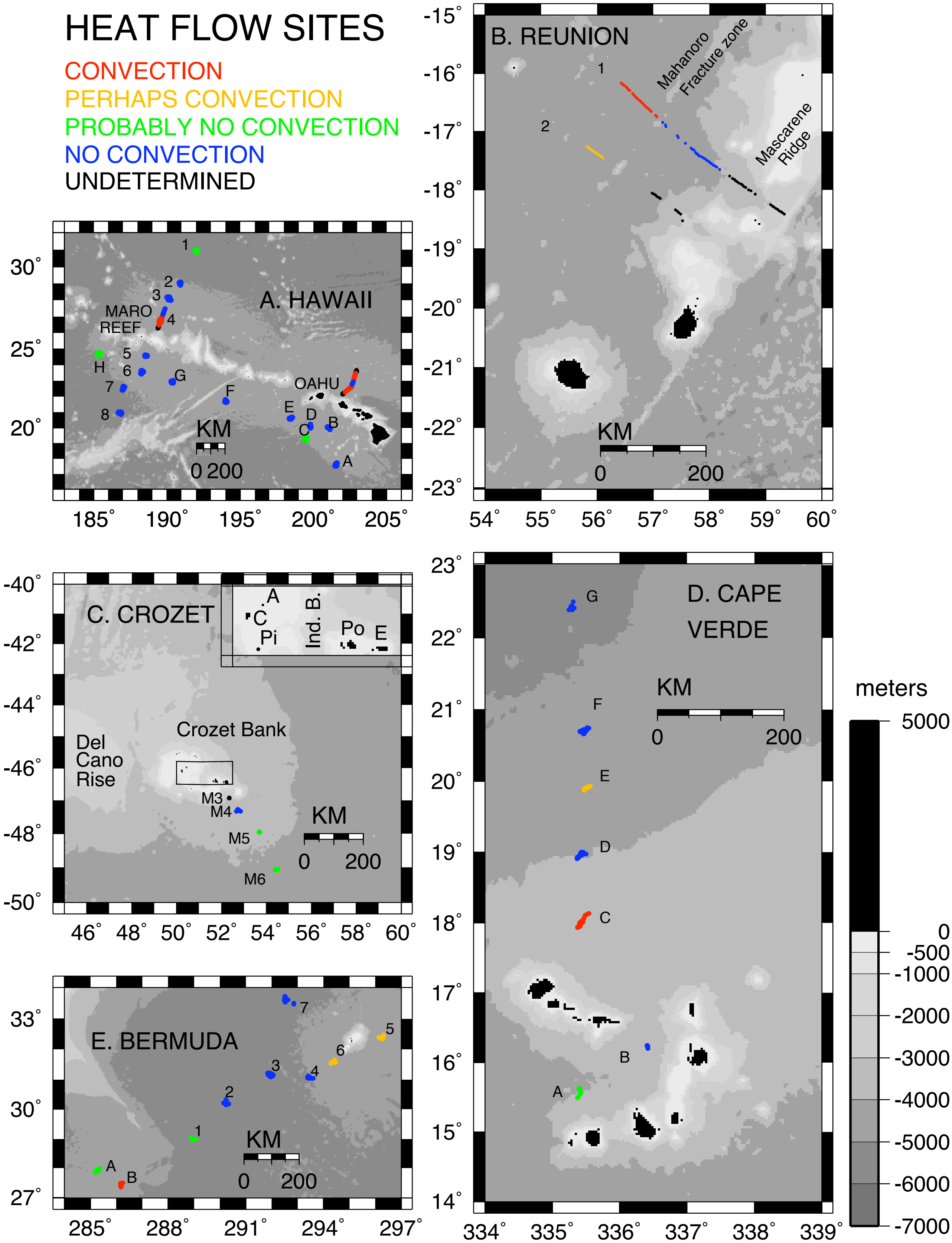


Figure 2 Stein & Von Herzen

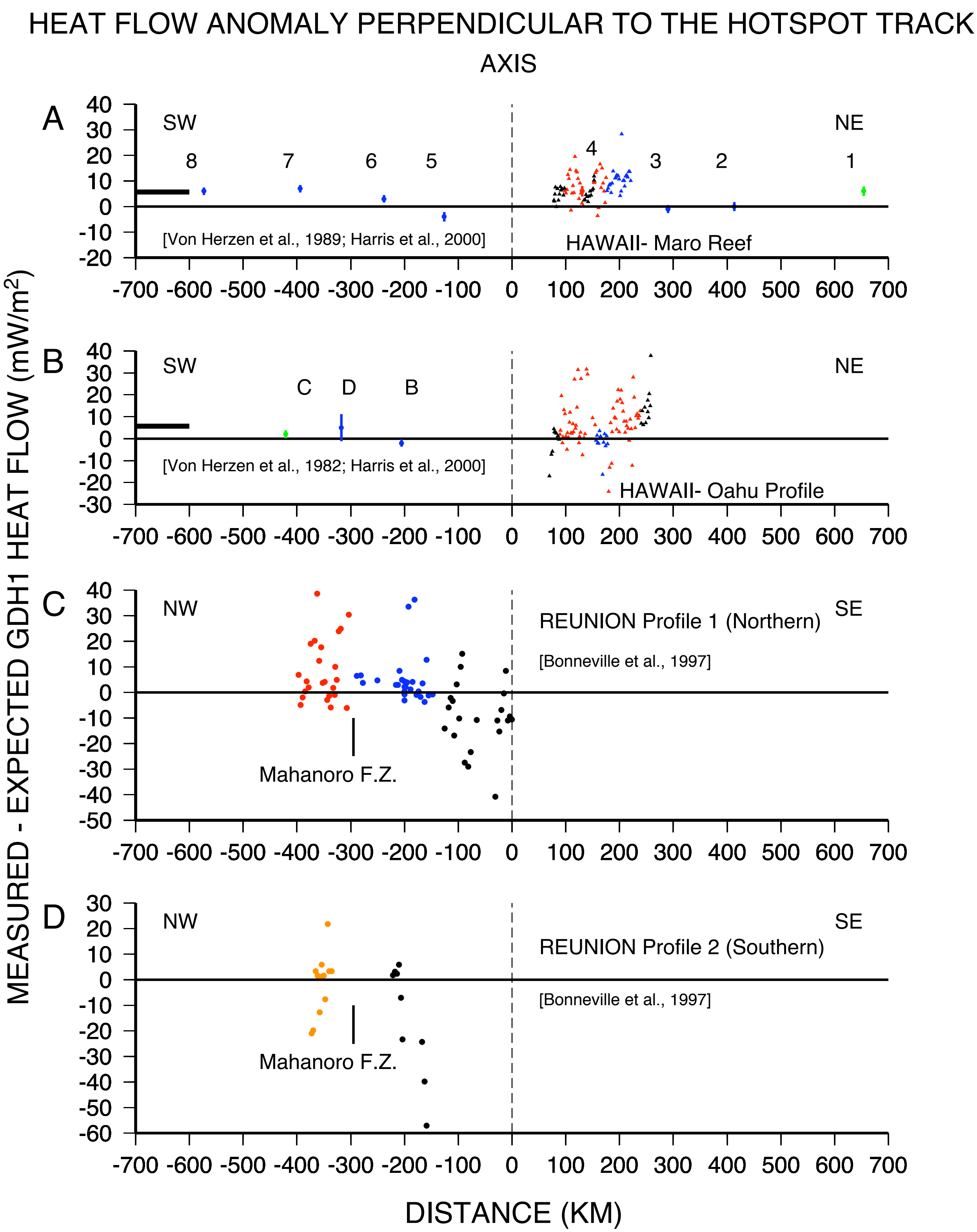


Figure 3
Stein & Von Herzen

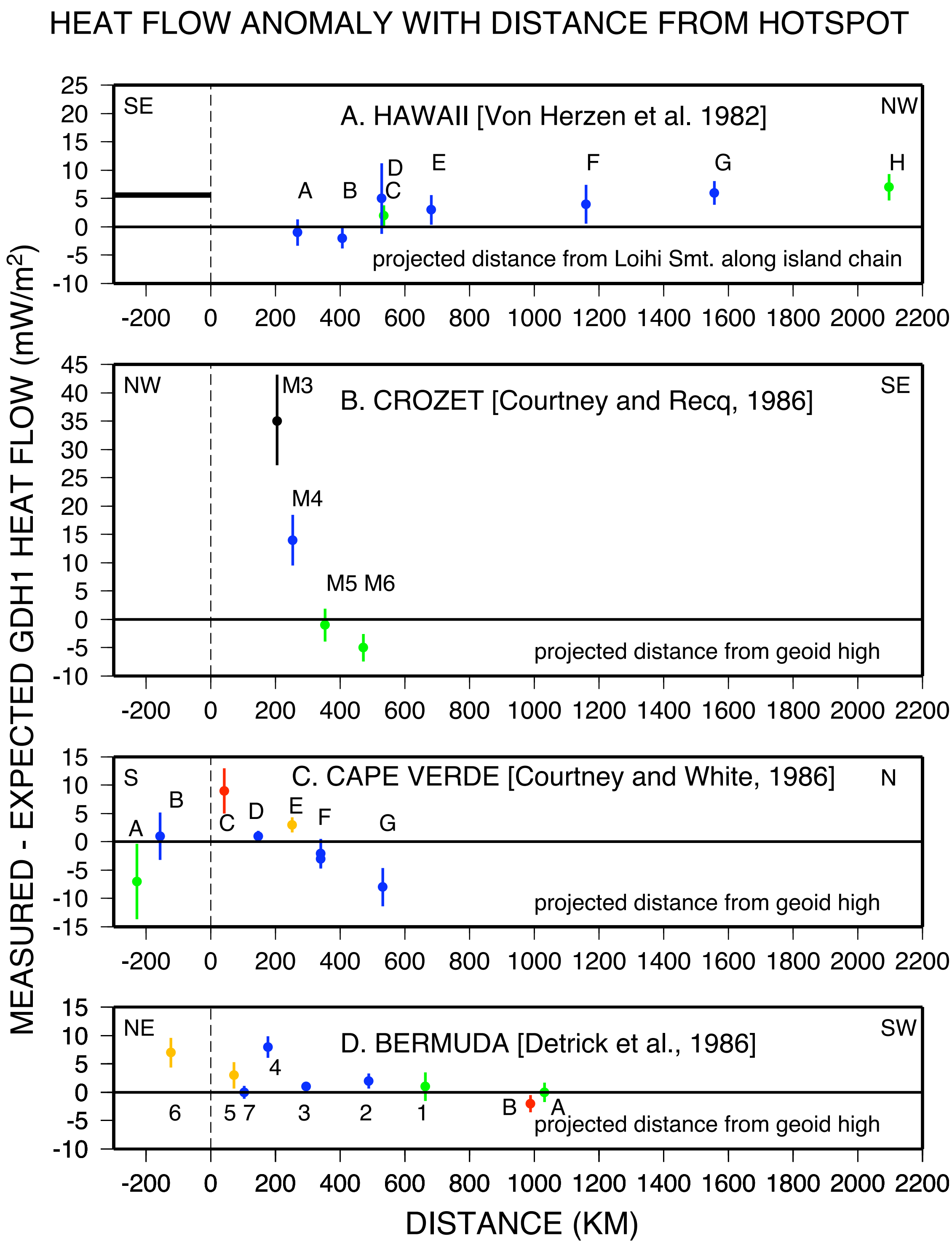


Figure 4
Stein & Von Herzen

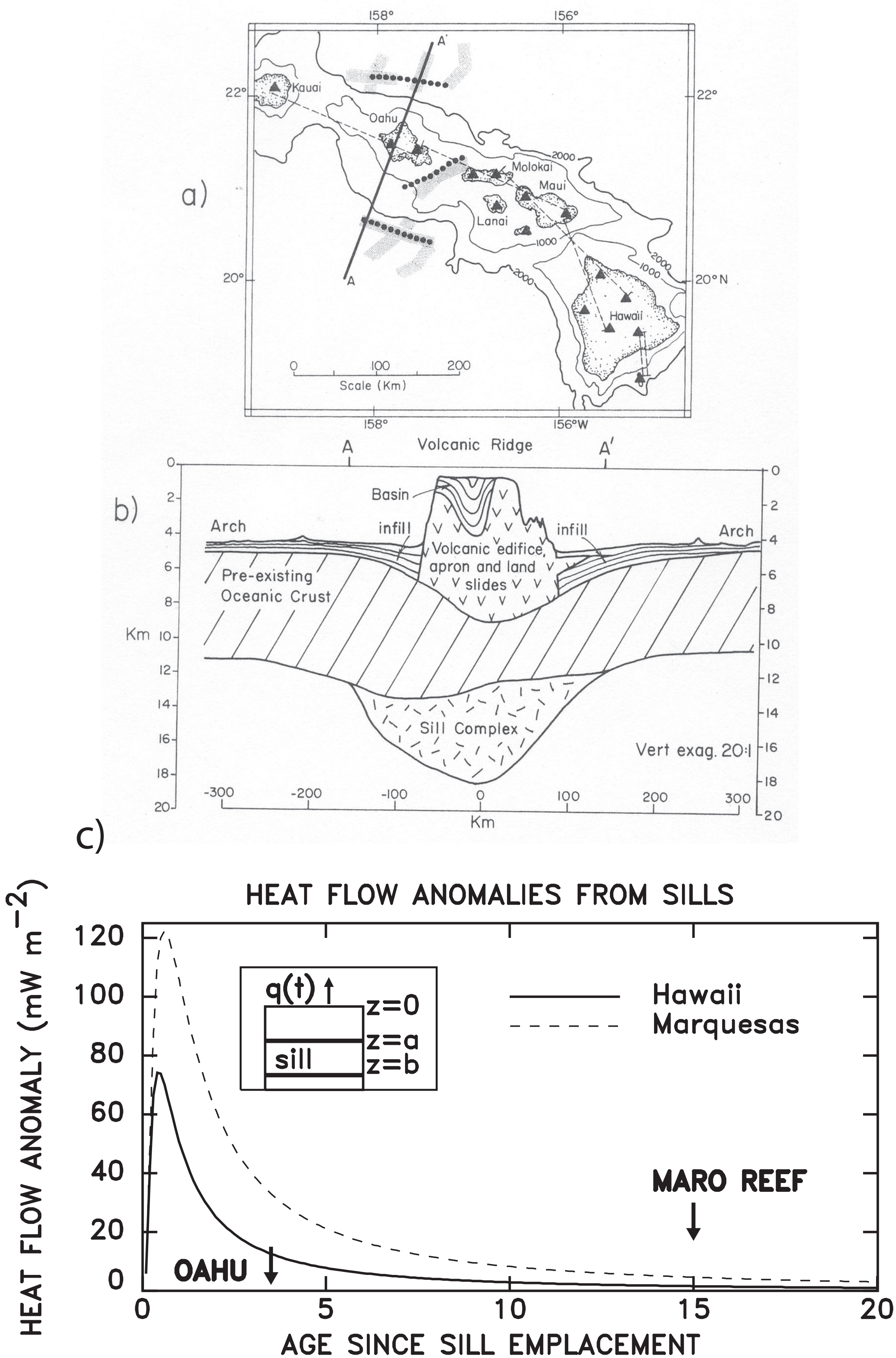


Figure 5
Stein and Von Herzen

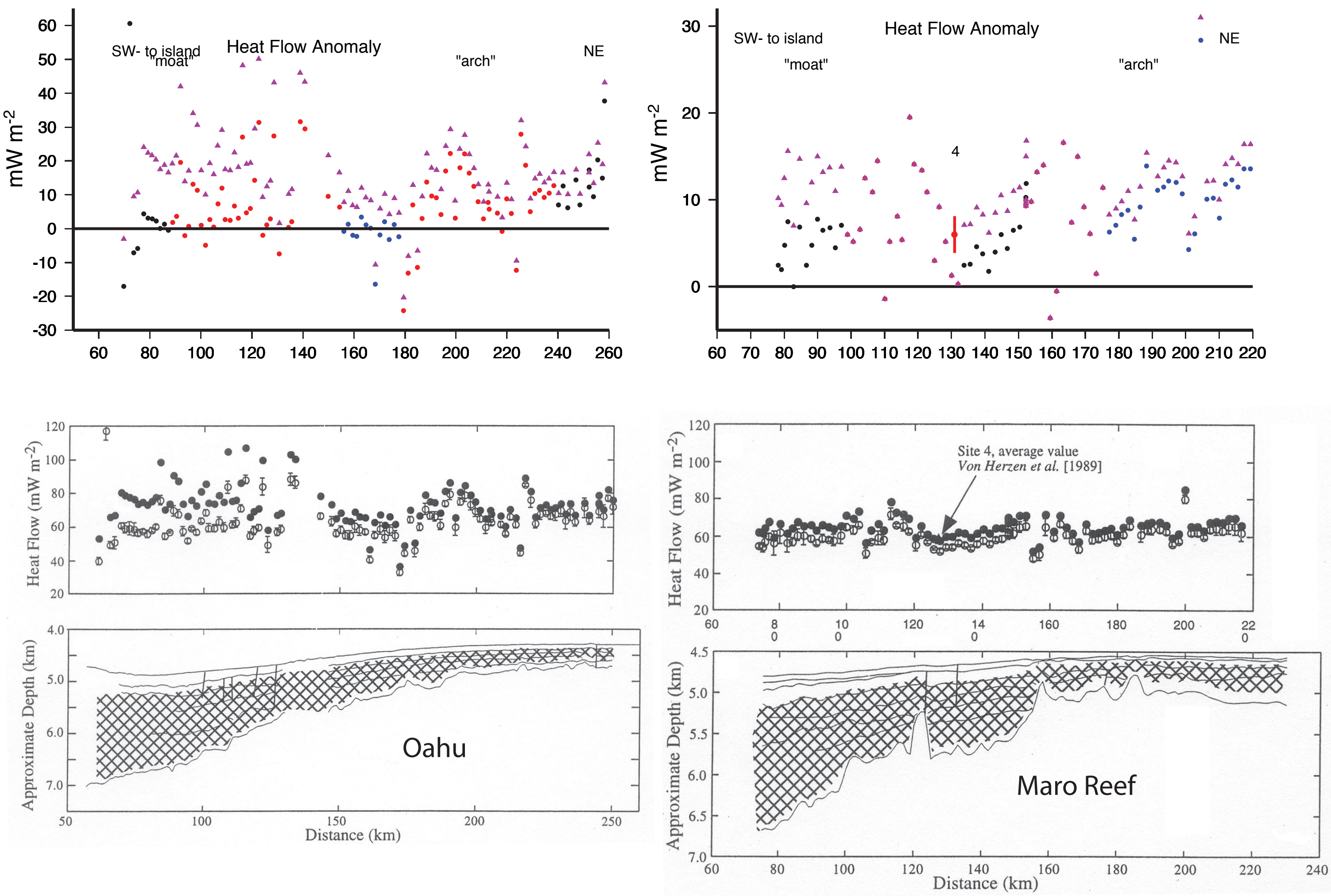


Figure 6- Stein and Von Herzen

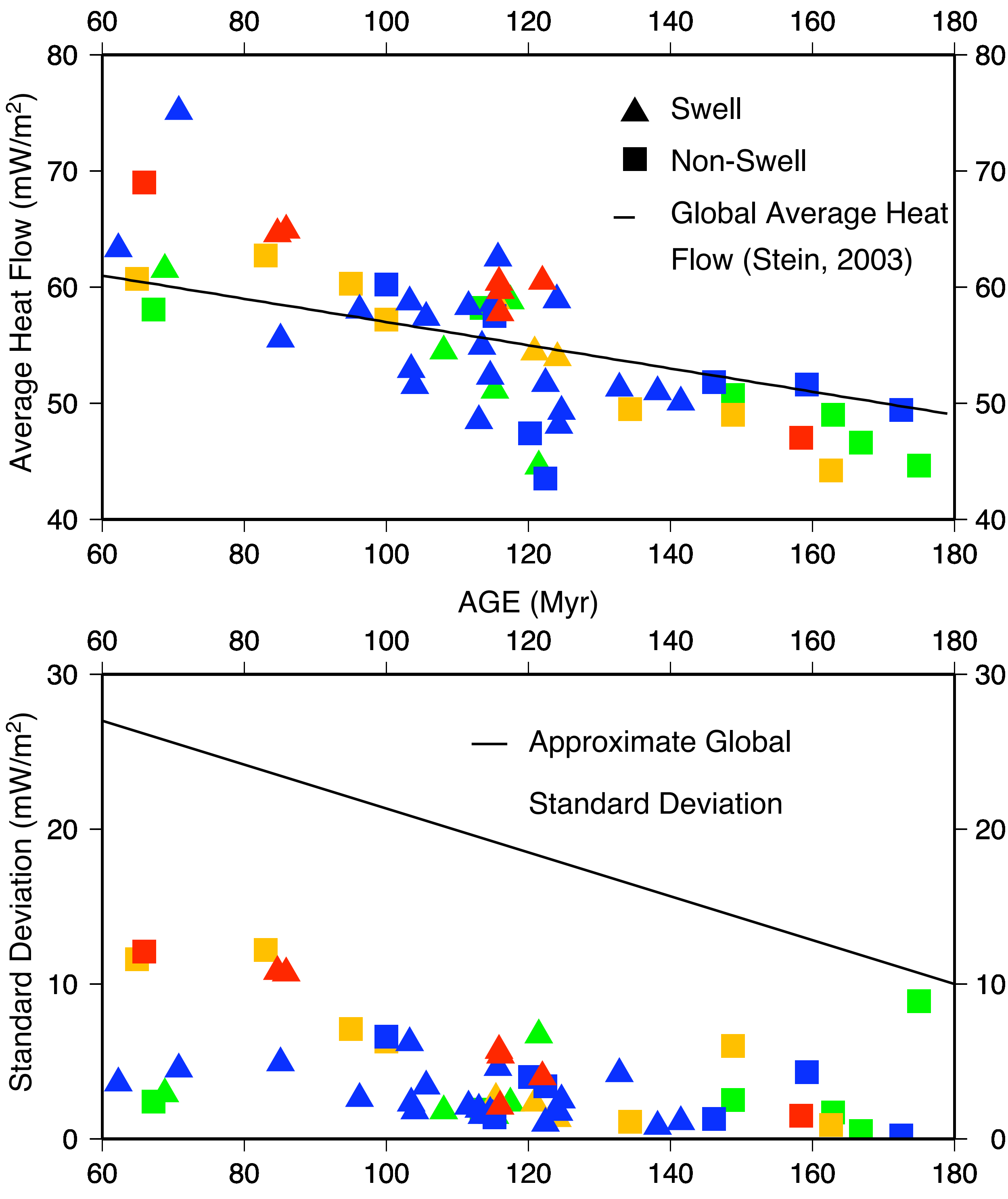


Figure 7

Stein & Von Herzen