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Conductive Heat Flow Anomalies Over a Hot Spot in a Moving Medium

FRANCIS S. BIRCH

Department of Earth Sciences, University of New Hampshire, Durham, New Hampshire 03824

A simple mathematical model of conductive heat flow from a hot spot in a moving medium shows that as the speed increases, the surface heat flow anomalies become weaker, narrower transverse to the motion, steeper upstream, and flatter downstream. The peak of the anomaly shifts downstream. Detectable heat flow anomalies, in this model, extensively melt the lower lithosphere.

INTRODUCTION

Hot spots hold a central place in many discussions of plate tectonics. They are held responsible for volcanism, uplift, plate breakup, and even plate motion [*Wilson and Burke,* 1973]. On the other hand, little is written about their physical characteristics. Are they a consequence of upwelling plumes [*Morgan,* 1971], of asthenosphere 'bumps' [*Menard,* 1973], or of thermal expansion of the lithosphere? How hot is a hot spot? Where does the heat come from?

It has been suggested that high plate speed relative to a hot spot suppresses surface manifestations of the hot spot [*Wilson and Burke,* 1973; *Birch,* 1975]. To test this idea and to investigate asymmetrical thermal effects due to plate motion, the surface heat flow and underground temperatures from a simple model of a hot spot are calculated.

After the model is described, the results will be presented and discussed.

MODEL

In the model the hot spot is represented by a point source of heat in an infinite half space moving uniformly in the x direction with velocity U (z is positive downward; y is horizontal and normal to motion). Only steady state conductive heat transfer is considered. The upper boundary condition, zero surface temperature, is satisfied by addition of a negative image source at an equal height above the upper surface. More complicated sources can be modeled by superposition of the results for a point source. It is useful to realize that the source may be replaced by any temperature distribution at depth that is itself a solution to the original problem; temperatures above this surface are unaffected. The solution for temperature in the medium is [*Carslaw and Jaeger,* 1959]

$$T(x, y, z) = (q/4\pi K) \cdot \left(\frac{\exp\,[-(R_1 - x)\,U/2k]}{R_1} - \frac{\exp\,[-(R_2 - x)\,U/2k]}{R_2} \right)$$

where q is the strength of the source, K is the thermal conductivity, k is the thermal diffusivity, and R_1 and R_2 are the distances to the source and the image source.

The surface heat flow $Q(x, y, 0)$ is equal to the conductivity times the vertical component of the temperature gradient:

$$Q(x, y, 0) = (-qz_0/2\pi R_1^2)(1/R_1 + U/2k) \cdot \{\exp\,[-(R_1 - x)U/2k]\}$$

where z_0 is the depth of the source.

Numerical values in all the calculations are $z_0 = 100$ km, $K = 0.005$ cal/cm s °C, and $k = 0.01$ cm^2/s.

RESULTS

Surface heat flow maps (Figure 1) show that as plate speed increases, the anomalies become smaller in amplitude, the peak heat flow shifts downstream, the width of the anomaly decreases, the upstream side becomes steeper, and the downstream side becomes flatter. These effects are quite pronounced for speeds of 1 cm/yr or more. Thus this model confirms the intuitive idea that rapid plate motion suppresses thermal effects at the surface. (Numerical integration of the heat flow equation for the time-dependent case indicates that the heat flow pattern reaches half the steady state value in about 60 m.y. The anomaly shape is essentially independent of time. This information is from F. S. Birch (unpublished calculations, 1975).)

Vertical temperature sections (Figure 2) show very similar features. At low speeds the isotherms are barely distorted. At high speeds they trail behind the source; ahead of the source the temperature is essentially unaltered by the presence of the source.

The depth to the 1300°C isotherm under a standard 75-km oceanic lithosphere [*Sclater and Francheteau,* 1970] (Figure 3) for a source of 10^9 cal/s shows a large almost symmetrical bulge over the source at low speeds; at high speeds the isotherm is almost flat, its peak being shifted far downstream. This isotherm can be interpreted as the lithosphere/asthenosphere boundary.

DISCUSSION

How strong a source is needed to produce detectable heat flow anomalies at the surface? The estimated accuracy of heat flow measurements is about 0.1 HFU (1 HFU = μcal/cm^2 s), although measurements are usually reported to the nearest 0.01 HFU. Thus an anomaly of a 0.5-HFU peak amplitude and an areal extent of 10^4 km^2 might be detectable by closely spaced measurements. A weaker, or smaller, anomaly might be attributed to local conditions or be inadequately delineated. For low speeds, such an anomaly corresponds to a source of about 10^9 cal/s. What are some of the consequences of such a source?

One consideration is that such a source is about 10^{-4} of total world heat flow [*Williams and Von Herzen,* 1974]. Thus if the total hot spot population is about 100–200 [*Kidd et al.,* 1973], the plate-driving hot spot machine uses about 1–2% of the total heat flow.

Such a source under a standard ocean lithosphere would

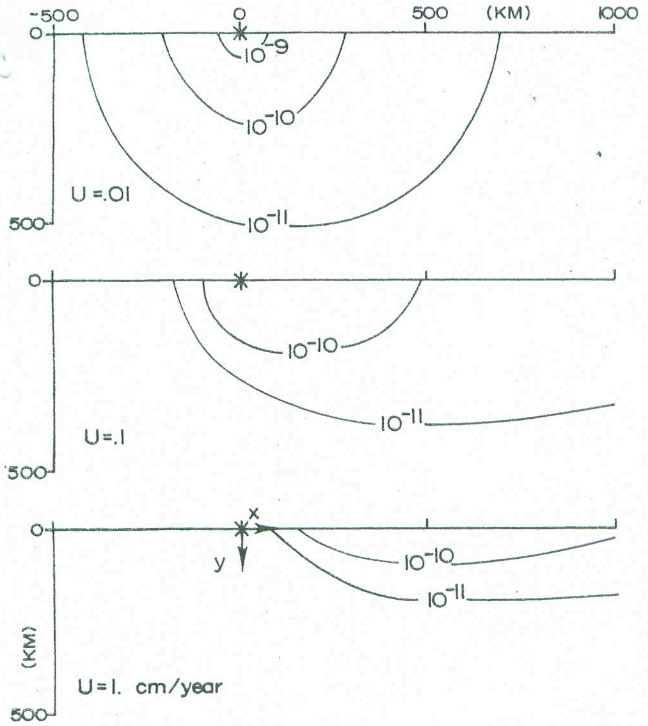

Fig. 1. Surface heat flow for unit source (1 cal/s). Contours are in heat flow units (1 HFU = μcal/cm^2 s). At 10 cm/yr the highest contour (10^{-11} HFU) falls beyond x = 1000 km. Stars mark projection of the source at the surface. The flow of the medium is to the right ($+x$ direction). Contours are derived from values calculated on 100 × 100 km grid.

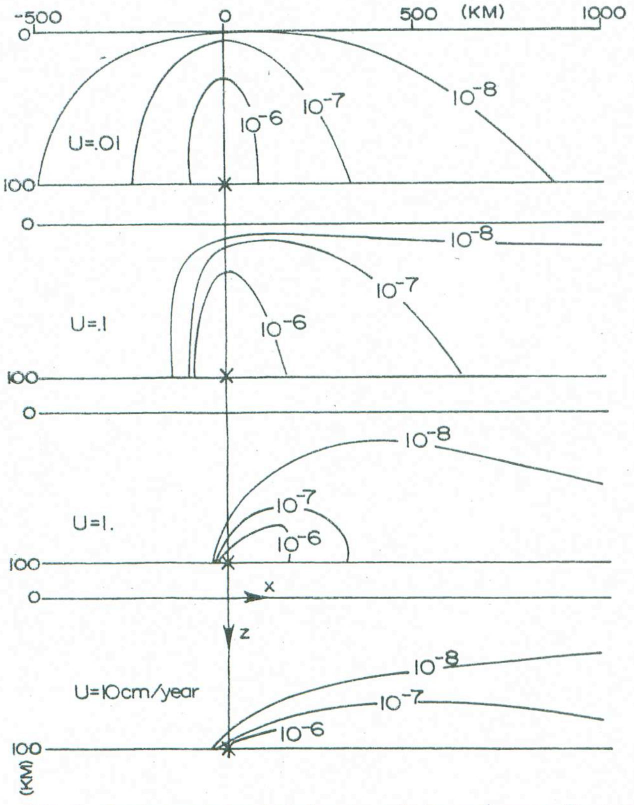

Fig. 2. Isotherms in vertical plane (y = 0) for unit source (1 cal/s). Contours are in degrees Celsius. Stars mark the source. The flow of the medium is to the right ($+x$ direction). Contours are derived from values calculated on 100-km (in x) by 25-km (in z) grid.

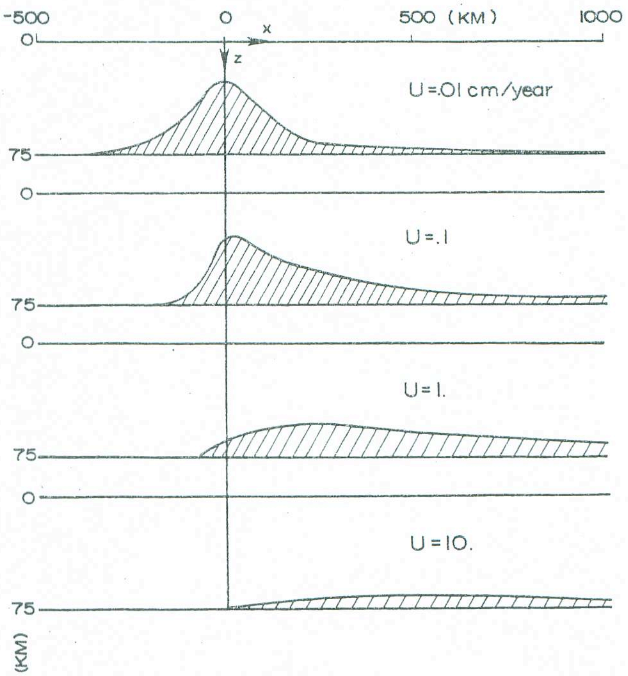

Fig. 3. Depth to 1300°C isotherm is vertical plane (y = 0) for source of 10^9 cal/s added to steady state temperatures in standard oceanic lithosphere. Flow of medium is to the right ($+x$ direction). Contours are derived from values calculated on 100-km (in x) by 25-km (in z) grid. Shaded areas are hotter than 1300°C.

lead to extensive melting. This follows directly from Figure 3 if the 1300°C isotherm is interpreted as a lower boundary condition and also as the lithosphere/asthenosphere boundary. Mathematically, the temperature field above this isotherm is unaltered by the state of the underlying material; physically, the presence of a molten asthenosphere would have many consequences. The amount of melting, or lithospheric thinning, ranges from 45 to 5 km for speeds of 0.01–10 cm/yr. Such thinning should be detectable by seismic observations. The topographic uplift from thermal expansion ranges from 0.4 to 0.1 km for these speeds (if a coefficient of thermal expansion of 3.5 × 10^{-5}/°C is assumed). Present world heat flow data appear inadequate for detection of such asymmetrical patterns. The measurements are too few and are too strongly influenced by local conditions such as shallow heat sources or ground-water convection.

CONCLUSIONS

Surface heat flow anomalies over a point source become weaker and more asymmetrical as speed increases. Sources strong enough to produce detectable anomalies produce large zones of lower lithospheric melting.

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