# ESTIMATION OF HEAT SOURCES IN PLANETARY CRUSTS FROM ISOTHERM DEPTH, SURFACE HEAT FLOW, AND CRUSTAL THICKNESS

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**Abstract.** The depth to an isotherm provides clues on the intensity of heat sources within a planetary crust. In this work, we show that the depth to an isotherm and crustal thickness can be jointly used to give an approximate estimation of the fraction of the surface heat flow that is being originated from the crust of a terrestrial planet. Relationships between crustal heat generation rate and crustal thickness, and surface and mantle heat flow variations on a planet were also explored. The proposed methodology may serve to improve present descriptions of the crustal temperature-depth profiles of terrestrial planets, and may also provide information on chemical and thermal evolution.

**Keywords:** Crustal heat sources, crustal thickness, isotherm depth, surface heat flow, terrestrial planets

## 1. Introduction

A fraction of the heat lost from the surface of a terrestrial-type planet is originates within the crust, while the rest arises from the underlying mantle. Thermal models of the Earth describing the distribution of crustal and lithospheric heat sources have reached a high level of sophistication (for reviews see for example Beardsmore and Cull, 2001; Turcotte and Schubert, 2002). Besides radioactive heating, these models could also take into account lithospheric cooling, or even viscous friction heating at the crust-mantle boundary (Burov and Diament, 1995).

In addition, several indirect markers of temperature have been defined, and these might prove useful in constraining the Earth's temperature-depth profile (e.g., Beardsmore and Cull, 2001), and, therefore, in constraining the crustal heat sources distribution. For example, in certain cases, rock electrical resistivity soundings may be used to roughly estimate the depth of an isotherm (e.g., Majorowicz et al., 1993). A more promising possibility, is to determine the depth of the Curie temperature, which is mineralogy dependent and indicates the temperature above which the rocks could not retain their magnetism (e.g., Dunlop and Özdemir, 1997; Beardsmore and Cull, 2001). It has also been suggested that isotherms can define

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the base of the elastic lithosphere (e.g., Watts, 1978) or the base of the sismogenetic layer (Chen and Molnar, 1983; Wiens and Stein, 1983).

Works that focus on other planets lack suitable data on the distribution of crustal heat sources. Thus, for other terrestrial planets, geophysical and tectonic research requiring descriptions of crustal and lithospheric thermal structures, generally uses linear thermal gradients (e.g., Banerdt et al., 1992; Phillips et al., 1997). However, in several recent studies on Mars, parabolic thermal gradients were used (Parmentier and Zuber, 2001; Nimmo and Stevenson, 2001; Nimmo and Gilmore, 2001); in these works, the intensity of crustal heat sources, assumed to be homogenous, is a poorly constrained parameter, which depends on different theoretical considerations.

In this paper we show how the depth to an isotherm and crustal thickness can be jointly used to calculate the approximate fraction of the total surface heat flow of a terrestrial planet (or a planetary region) generated in their crust, assuming that heat sources are homogeneously distributed within the crust. In this sense, several indications (although rough) on both crustal thickness and ancient crustal isotherm depths are available for planets other than Earth.

Global maps of crustal thickness based on gravity and topography data have been proposed for the Moon and Mars (for reviews see Hood and Zuber, 2000; Zuber, 2001, respectively); in the case of Venus, these data are unsuitable for global mapping of crustal thickness, but it has been possible to make estimates for some regions (for a review see Grimm and Hess, 1997). On the other hand, the discovery of magnetic anomalies on Mars (Acuña et al., 1999, 2001) has become the basis for approximate calculations of the total thickness of the magnetic crust (Connerney et al., 1999; Nimmo, 2000; Arkani-Hamed, 2001), although it is not clear that the base of the magnetised layer corresponds to the depth of an isotherm over the time in which the anomalies were originated. Moreover, recent gravity and topography data have also served to improve estimates of elastic thickness (in the time when the topography was formed) for some regions of Venus (e.g., Barnett et al., 2002) and Mars (e.g., Zuber et al., 2000).

Here we first perform a general analysis for a region for which surface heat flow is known. This is followed by an application of our basic analysis to other terrestrial planets, in which past surface heat flow must be estimated from theoretical considerations. The assumptions made in the analyses are discussed in the final section.

## 2. Calculation of Crustal Heat Sources from the Depth to an Isotherm, Surface Heat Flow, and Crustal Thickness

In a layer in thermal conductive equilibrium heated from below, and also heated from within by homogeneously distributed heat sources, the temperature at a depth $z$ is given by

$$T_z = T_s + \frac{Fz}{k} - \frac{Az^2}{2k} \tag{1}$$

(Roy et al., 1968), where $T_s$ and $F$ are the temperature and heat flow at the surface, $k$ is the thermal conductivity, and A is the volumetric rate of heat dissipation ($A$ is usually associated with radioactive heating, but may also include a cooling component). On Earth, $A$ can be directly measured (at least in surface rocks), but up to the present time this has not been possible for other planetary bodies this parameter must either be assumed or calculated from planetary evolution models (e.g., Nimmo and Stevenson, 2001). If $A$ is taken as a constant for a crust of thickness $b$,

$$A = F_c/b, \tag{2}$$

where $F_c$ is the component of $F$ that is generated within the crust. The fraction of surface heat flow of crustal origin can be defined as $f \equiv F_c/F$, and so Equation (2) can be rewritten again as

$$A = fF/b; \tag{3}$$

substituting (3) in Equation (1), and taking $k$ as constant for the whole crust, we obtain

$$T_z = T_s + \frac{Fz}{k} - \frac{fFz^2}{2kb}. \tag{4}$$

Thus, if the temperature at a depth $z_{\text{iso}}$ is known, the fraction of the total heat flow derived from within the crust is given by

$$f = \frac{2b}{z_{\text{iso}}}\left[1 - \frac{k(T_{\text{iso}} - T_s)}{z_{\text{iso}}F}\right]. \tag{5}$$

Mantle heat flow (heat flow from below the crust) is

$$F_m = F(1 - f). \tag{6}$$

The analysis presented in this section requires measurements (or at least estimates) of surface heat flow in the region where an indicator of isotherm depth is available. Although unequally distributed, for Earth there is an abundance of current heat flow data (e.g., Pollack et al., 1993), but this is not the case for other planets. In fact, the only direct heat flow measurements performed on a planetary body other than the Earth are two Apollo determinations made on the Moon (Langseth et al., 1976). Moreover, the surface heat flow is required for the time for which the inferred isotherm depth is representative.

## 3. Application to Terrestrial Planets

A reasonable estimation of the average surface heat flow of a planet can be used to apply the methodology described in previous section. In this section, two possibilities are suggested in order to make that application to terrestrial planets. The necessary estimation of the mean surface heat flow could be made (although cautiously) from theoretical considerations.

A commonly used procedure for planets other than the Earth involves the use of the mean surface heat flow value, $\bar{F}$, for any region of the planet (e.g., Nimmo and Stevenson, 2001). In this case, a local value of $f$ is obtained using $F = \bar{F}$ in Equation (5) for the region in which the depth to an isotherm is inferred, and the local temperature-depth profile can be obtained using this $f$ value in Equation (4). If it is supposed (as was assumed for $F$) that $f$ takes a constant value throughout the planet's regions, the value of $A$ should vary locally with the local crust thickness according to

$$A = f\bar{F}/b, \tag{7}$$

in order to satisfy the condition $Ab =$ constant.

A more realistic possibility than that examined previously would be that surface heat flow varies from one region of the planet to another. If both constant mantle heat flow throughout the planet and homogeneously distributed heat sources within the crust are assumed, differences in surface heat flow among regions will be related to differences in crustal thickness according to

$$\Delta F = A\Delta b, \tag{8}$$

where $A$ satisfies the relation

$$A = fF/b = \bar{f}\bar{F}/\bar{b}, \tag{9}$$

Thus, the surface heat flow in any zone is given by

$$F = \bar{F} + A(b - \bar{b}) = \bar{F}\left[1 + \bar{f}\left(\frac{b}{\bar{b}} - 1\right)\right]. \tag{10}$$

Substituting (9) and (10) in Equation (1), the temperature at a depth $z$ is obtained for an area of crustal thickness $b$,

$$T_z = T_s + \frac{\bar{F}z}{k}\left[1 + \bar{f}\left(\frac{b}{\bar{b}} - 1\right)\right] - \frac{\bar{f}\bar{F}z^2}{2k\bar{b}}. \tag{11}$$

Taking $T_z = T_{\mathrm{iso}}$ and $z = z_{\mathrm{iso}}$ in Equation (11), we can calculate $\bar{f}$ as,

$$\bar{f} = \frac{1 - k(T_{\mathrm{iso}} - T_s)/\bar{F}z_{\mathrm{iso}}}{1 - (b - z_{\mathrm{iso}}/2)/\bar{b}}. \tag{12}$$

Once $\bar{f}$ has been estimated, the temperature-depth profile of any region (included those for which there is no available data on the depth to an isotherm) can be calculated using Equation (11).

## 4. Discussion and conclusions

The validity of the analysis presented here mainly depends on the correctness of assuming a homogeneous distribution of crustal heat generation. When the Earth is thermally modeled, another option considers an exponential decay of heat production with depth (Lachenbruch, 1968, 1970). Both linear and exponential models provide an explanation for the linear relationship observed between measured radiogenic production in surface rocks and surface heat flow in many continental areas of the Earth of different petrological characteristics (Birch et al., 1968; Lachenbruch, 1968; Roy et al., 1968).

Models based on exponential decay have been widely applied to Earth (e.g., Cermak and Rybach, 1989; Turcotte and Schubert, 2002), but the accuracy of their use for other terrestrial planets is uncertain. For example, Turcotte (1995) pointed out that, despite an upward concentration of radiogenic isotopes is possible within Venus' crust, at present no distribution estimations can be made, so a homogeneous distribution was assumed by this author. Moreover, it has been suggested that vertical differentiation on Mars is not as significant as on Earth (e.g., McLennan, 2001). Hence, the assumption of a homogeneous distribution of crustal heat sources as a starting point for terrestrial planets would appear to be the most reasonable.

Using an average surface heat flow implies the assumption of constant surface heat flow or constant mantle heat flow as a necessary simplification. Our preferred analysis in Section 3 assumes constant mantle heat flow and that increased crustal thickness leads to an increase in surface heat flow. This contradicts the inverse relationship between surface heat flow and crustal thickness observed in some of the Earth's continental crust regions (e.g., Cermak, 1993). However, it has also been argued that younger and thinner crust exhibits higher surface heat flow (Cermak, 1993). Hence, for areas of similar age, the approach of constant mantle heat flow may be accurate if $\bar{F}$ and $\bar{b}$ are substituted by the appropriate average values for these regions.

Alternatively, the surface heat flow can be calculated from depth to an isotherm in terms of $f$, taking in account that $f$ must be between 0 and 1. Even if approximate, any estimation of crustal heat sources or surface heat flow of a terrestrial planet (past or present) should improve description of the crustal temperature-depth profiles (and therefore improve current tectonic and geophysical models) and increase our knowledge about global thermal or chemical evolution.

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