Available online at www.sciencedirect.com
ScienceDirect
Tectonophysics 428 (2006) 101 – 103
TECTONOPHYSICS
www.elsevier.com/locate/tecto

Correspondence

# Reply to comment on: "Estimates of heat flow from Cenozoic seafloor using global depth and age data"

The original purpose of our paper (Wei and Sandwell, 2006) was to provide an estimate of the global Cenozoic heat flow that was largely independent of the sometimes-biased conductive heat flow measurements (Hofmeister and Criss, 2005). The increasing seafloor depth with increasing age is one of the most obvious signals of global plate tectonics. Global mantle convection with thin surface plates provides an efficient mechanism for transferring heat out of the mantle. The objective of our study was to use this obvious depth signal to place bounds on global heat flow from the Earth. We developed a new method of estimating heat flow using depth and age grids and applied it to a Cenozoic seafloor. However, the fundamental equation relating depth and heat flow was derived at least three times previously (Parsons and McKenzie, 1978; O'Connell and Hager, 1980; Doin and Fleitout, 1996). Our contribution was basically to use the new global estimates of depth and heat flow to estimate the Earth's heat output.

*Hofmeister and Criss* [comment] claim that there are errors in our derivation and also that some of our assumptions may not be valid. We believe that the derivation and final equation are correct but rather than spend time addressing each of their objections, we will re-derive the fundamental result from first principles and highlight the assumptions and approximations. The basic equation in question relates the subsidence rate to the surface heat flow

$$\frac{\partial d}{\partial t} = \frac{-\alpha}{\rho C_p} q_s \quad (1)$$

where $d$ is depth (positive up), $t$ is time, $\rho$ is density, $\alpha$ is the volumetric coefficient of thermal expansion, $C_p$ is the heat capacity, and $q_s$ is the surface heat flow (positive up). We have simplified the model a bit by removing the density effect of the ocean and also did not consider heat flow into the bottom of the plate although this is a trivial modification.

Consider the following schematic model of the cooling oceanic lithosphere (Fig. 1).

The lithosphere of mass $m$ is enclosed in a rigid bucket having insulating walls. The top opening of the bucket has a constant area of $A$. There is no mass flowing into or out of the bucket so it floats at a constant depth of $L$.

**Assumption 1**. The material in the bucket has no horizontal variations in temperature. Note the vertical variations in temperature are not constrained and do not necessarily obey the rules of heat diffusion. The vertical heat transport mechanism is irrelevant so the thermal conductivity or diffusivity do not enter the calculation.

**Assumption 2**. The bucket floats in a liquid mantle having properties that do not change with time. Note

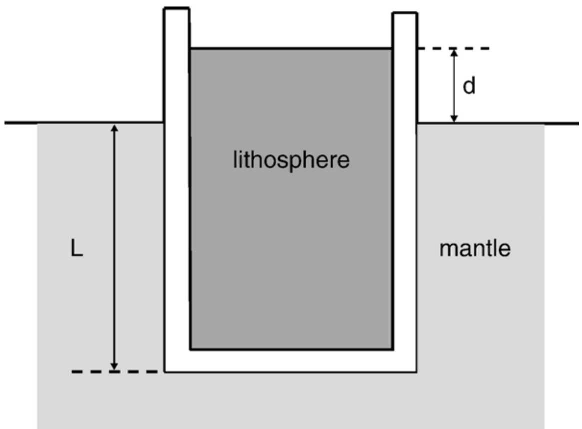


Fig. 1.


doi:10.1016/j.tecto.2006.08.007

that since the mass in the bucket does not change and the area does not change, the depth to the bottom of the bucket $L$ remains constant.

**Assumption 3**. The volume of the material in the bucket $V$ is a function of the total heat content in the bucket $Q$.

**Assumption 4**. In their comment, *Hofmeister and Criss*, make an important point that we use a volumetric coefficient of thermal expansion instead of a linear coefficient. The implication is that we are treating the shrinkage of the lithosphere as being uniform in all three dimensions. This is the same assumption used in all depth versus age models (c.f. (Parsons and Sclater, 1977)). If the plate could somehow be pinned at its margins to prevent horizontal shrinkage then it would be more appropriate to use a linear coefficient of thermal expansion which is approximately 1/3 the value of the volumetric expansion coefficient. *Hofmeister and Criss* [this comment] correctly pointed out that if we were to use a linear expansion coefficient our Cenozoic heat flow estimate would increase by a factor of 3. In our schematic model, horizontal shrinkage will pull the edges of the lithosphere away from the container leaving voids. We will assume for mathematically simplicity that the lithosphere has no strength so it flows to fill the voids. In the special case of top-down lithospheric cooling, large thermal stresses will develop and most studies propose that the plate deforms in response to these stresses (Parmentier and Haxby, 1986; Sandwell, 1986; Turcotte, 1974).

Now we ask the question, how does the elevation of the lithosphere, $d$, vary with time? Assuming volume depends on total heat content, one uses the chain rule to obtain the following formula.

$$\frac{\partial d}{\partial t}=\frac{1}{A}\frac{\partial V}{\partial t}=\frac{\partial V}{\partial Q}\frac{1}{A}\frac{\partial Q}{\partial t} \quad (2)$$

Since heat can only escape from the surface of the volume, the surface heat flow is related to the time derivative of the total heat content by $q_s=\frac{-1}{A}\frac{\partial Q}{\partial t}$ so the equation can be rewritten as

$$\frac{\partial d}{\partial t}=-\frac{\partial V}{\partial Q}q_s \quad (3)$$

The final issue is how does the volume of the lithosphere vary with heat content. We'll expand this derivative to arrive at more physically meaningful parameters.

$$\frac{\partial V}{\partial Q}=\frac{\partial V}{\partial T}\frac{\partial T}{\partial Q}=\frac{\alpha}{\rho C_p} \quad (4)$$

where $\alpha\equiv\frac{1}{V}\frac{\partial V}{\partial T}$ and $\rho C_p\equiv\frac{1}{V}\frac{\partial Q}{\partial T}$. Note the expansion of these more familiar parameters is unnecessary and one could simply use $\partial V/\partial Q$ to relate surface heat flow to depth (Eq. (3)). *Hofmeister and Criss* [this comment] correctly pointed out that, in general, the volume will be a nonlinear function of heat content. In our global calculation we assumed that the depth-integrated value is nearly constant as proposed by Doin and Fleitout (1996) . Nevertheless the largest uncertainty is related to this combination of parameters as discussed in our paper.

We believe we have addressed all the issues summarized in Table 1 of the *Hofmeister and Criss* [comment]. Items 1, 2, and 5 are related to the parameter $\frac{\alpha}{\rho C_p}$ that, we agree, could be a non-linear function of temperature. We explicitly conserve mass to which addresses item 3. We no longer perform an integration which addresses item 4. We agree with item 6 that neglect of lateral heat conduction will lead to an error in our estimate of heat loss. As discussed in our paper this will be most important near the ridge axis so we cannot estimate heat loss over young seafloor. The local isostasy assumption is also invalid near the ridge axis as discussed in our paper. Indeed our inability to estimate the heat flow near the ridge axes is the main weakness of our approach.

Finally, *Hofmeister and Criss* [comment] pointed out that the half-space (HS) cooling model obeys Eq. (1) and therefore our formulation is somehow linked to the process of thermal diffusion. It is clear from the derivation above that the mode of heat transport from the volume to the surface was not specified except that we implicitly assumed vertical heat transport. Eq. (1) must be true for all types of vertical heat transport including the special case of the half-space cooling model with constant thermal conductivity. Therefore the HS cooling model is one of the infinite number of heat transport models that must satisfy Eq. (1) under the assumptions.

## References

Doin, M.P., Fleitout, L., 1996. Thermal evolution of the oceanic lithosphere: an alternate view, Earth planet. Sci. Lett. 142, 121–136.

Hofmeister, A.M., Criss, R.E., 2005. Earth's heat flux revised and linked to chemistry, Earth planet. Sci. Lett. 395, 159–177.

O'Connell, R.J., Hager, B.H., 1980. On the Thermal State of the Earth. In: Dziewonski, A., Boschi, E. (Eds.), Physics of the Earth's Interior. Elsevier, New York, pp. 270–317.

Parmentier, E.M., Haxby, W.F., 1986. Thermal stress in the oceanic lithosphere: evidence from geoid anomalies at fracture zones. J. Geophys. Res. 91, 7193–7204.

Parsons, B., McKenzie, D., 1978. Mantle convection and the thermal structure of the plates. J. Geophys. Res. 83, 4485–4496.

Parsons, B., Sclater, J.G., 1977. An analysis of the variation of the ocean floor bathymetry and heat flow with age. J. Geophys. Res. 82, 803–827.
Sandwell, D.T., 1986. Thermal stress and the spacings of transform faults. J. Geophys. Res. 91, 6405–6417.
Turcotte, D.L., 1974. Are transform faults thermal contraction cracks? J. Geophys. Res. 79, 2573–2577.
Wei, M., Sandwell, D., 2006. Estimates of heat flow from Cenozoic seafloor using global depth and age data. Tectonophysics 417, 325–335.

Meng Wei*
David Sandwell
*Scripps Institution of Oceanography, United States*
*E-mail address:* mwei@ucsd.edu.
*Corresponding author.

10 August 2006