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Discussion

Reply to comments by R. Von Herzen, E.E. Davis, A.T. Fisher, C.A. Stein and H.N. Pollack on "Earth's heat flux revised and linked to chemistry"

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Abstract

The lengthy comment by Von Herzen et al. does not address the most important conclusions of the paper by Hofmeister and Criss [Hofmeister, A.M., Criss, R.E., 2005, Earth's heat flux revisited and linked to chemistry. Tectonophys. 395, 159–177.]. These are 1) that actual measurements better describe the Earth than do simplistic models with demonstrably unrealistic boundary conditions that diverge markedly from the data; and 2) that the models are unconstrained, resulting in a series of papers proposing values for the global flux that have become increasingly disparate from the growing data base over time (Fig. 3 in our paper). We disagree strongly with penultimate concluding statement of Von Herzen et al., "that it is preferable to base surface heat flow analysis not only on the extensive measurements but also on well understood processes that are known to bias the values and statistics of the measurements," as our Fig. 3 demonstrates that no consistent magnitude has been assigned to the alleged advective flux, so that neither the processes nor the correction are "well understood". We do not deny the existence of submarine hydrothermal systems, but we disagree strongly with the scales over which they are alleged to operate, and with the large Rayleigh and Nusselt numbers Von Herzen et al. assign to them.

Keywords: Heat flux; Hydrothermal circulation

1. Introduction

Von Herzen et al. stridently defend the use of the half space cooling (HSC) model to determine the global heat flux (e.g., Pollack et al., 1993). Although related models (e.g., GDH, see Stein and Stein, 1992) exist, for brevity, we focus on the HSC model, as its variants are based on similar assumptions, provide similar output, and require the same ad hoc argument of hydrothermal circulation carrying vast amounts of heat in one direction only to reconcile huge differences between model values and actual heat flux measurements of the ocean floor. Hydrothermal circulation cannot be used to justify the 13 TW discrepancy between global power obtained using the HSC model and that obtained directly from the measurements for reasons discussed in our paper.

The key issues are covered in the next three sections of this reply. First, we discuss the effect of hydrothermal circulation on the heat flux profile with distance, and how this contraindicates the HSC model. Second, we present evidence that the HSC model has hallmarks

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of a failing paradigm; moreover, this same model was once used to evaluate cooling of the Earth, and subsequently and conclusively disproved. Third, we discuss mathematical problems with the HSC model, which include being underconstrained and having a singularity that controls the calculated value for the global heat flux. A final section addresses minor issues.

2. Effect of the coupled flow of heat and water during hydrothermal circulation on heat flux

Most of the comment of Von Herzen et al. is based on the misconception that hydrothermal circulation makes up the huge difference between the HSC model and numerous heat flux measurements. Our paper pointed out a large number of inconsistencies with this hypothesis, none of which are addressed by Von Herzen et al. One important issue is that hydrothermal flow is predominantly lateral and therefore the key assumption underlying the HSC model of 1-D (vertical) heat flow is violated. The alleged hydrothermal component of global heat flux is huge, 13 TW, inferred by comparing the 31 TW obtained from heat flux measurements (Hofmeister and Criss, 2005) to the 44 TW obtained by using the HSC model (Pollack et al., 1993). If hydrothermal circulation is as important to heat flow in the ocean plates as argued by Von Herzen et al., then all 1-D models, including HSC, are inapplicable (Fig. 4 in our paper).

Because the effect of hydrothermal circulation in the ocean floor on heat flow has been misunderstood on an elementary level, we describe this physical process in some detail. The key effect of hydrothermal systems is that the physical flow of the fluid causes gross redistribution of heat (Fig. 1), simply because the flows of water and heat are coupled. Water recharging the system is cold, or it would not sink, just as water leaving the system is hot, or it would not rise. The upward flux occurs near the ridges because this is where the subjacent rocks and percolating fluids are hottest. The ocean provides the recharge and absorbs the discharge and thus completes the circulation cell. For the temperature of the percolating water to increase during its lateral traverse towards the ridge requires heat to be transferred from the rocks to the fluid (Fig. 1a). Heat flows from the rocks to the water where the water is relatively cold, i.e., near the recharge region and in the ensuing lateral flow. Therefore, the heat flux at the surface near the recharge area is lower for a hydrothermal system than for the corresponding "dry" system. This behavior persists until the temperatures of the rocks and the water flowing through them are the same. Fig. 1 depicts this point near the center of the convection cell for simplicity: in real systems, the equilibrium point is most likely reached in the upwelling limb. For this region in the slab, the heat flux in the hydrothermal system is the same as it would be in a dry system (Fig. 1). In contrast, within the discharge region, rising hot water encounters progressively cooler rocks. One end-member possibility is that all the heat carried by the water is directly released to the cold ocean. Another end-member is that all the heat carried by the water is absorbed by the rocks at shallow depths. These cases set limits on the heat flux (Fig. 1b). The lowest possible heat flux measured in the rocks near the ridge equals that of the dry system, but more likely values should be larger.

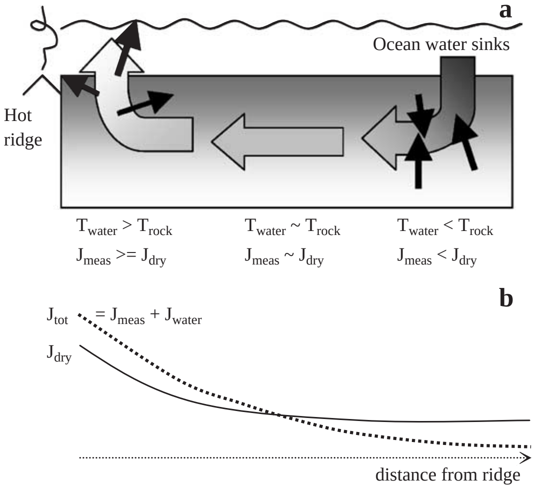

Fig. 1. Schematic depicting the flow of water and heat in a hydrothermal system. (a) Physical processes. Large rectangle depicts the slab, with darker colors representing cooler temperatures near the surface. Distant from the ridge, cold, dense ocean water (block arrow) sinks and is warmed by absorbing heat from the rocks, indicated by solid black arrows. The gradually warming water flows toward the heat source (mid-ocean ridge) to replace the buoyant hot water rising near the ridge. The rising hot water (light block arrow) releases its heat both to the ocean and to the cold rocks near the surface (solid black arrows). Relative temperatures of water and rock govern the flow of heat, as indicated below the panel, where J_{dry} is the conductive heat gradient in the absence of hydrothermal circulation and J_{meas} is the actual heat flux measured in the rocks. (b) Comparison of the heat flux in a dry slab to that in a hydrothermal system. Energy is conserved during the lateral transfer of water and heat. Note that if all the heat from the rising water is released to the oceans, then $J_{meas}=J_{dry}$ near the ridge. The other endmember case is that all the heat from the rising water warms the cold rocks near the surface, and then $J_{meas}=J_{tot}$ near the ridge. In no case would J_{dry} exceed the measured flux near the ridge. The half-space cooling model, which supposedly represents J_{dry}, is instead larger than the measured flux near the ridges, showing that hydrothermal circulation is not the cause of the discrepancy.

The HSC model is a conductive cooling model, and if valid, should represent J_{dry} for the ocean floor. If hydrothermal circulation were the cause of the disparity between the measurements and the HSC model, then the heat flux measurements would be equal to or larger than the HSC model values near the ridge, whereas away from the ridge, the model flux should be larger than the measurements. The opposite is true, as shown in Fig. 2b of our paper and in several figures from Stein and Stein (1992). Hydrothermal circulation cannot be the reason that the HSC model fails to fit the heat flux measurements.

The importance of *lateral* heat transfer cannot be overemphasized. Over the hydrothermal system as a whole, the fluid does not add heat or take away heat, but rather alters the spatial distribution (Fig. 1). Some heat is released into the oceans, but the source of this heat is the rocks along the flow path, which includes large contributions of heat from the recharge area. In contrast, Pollack et al. (1993) estimated the global heat flux by assuming a one-way advection of heat. They used measured heat flux for rock ages more than ~66 Ma, and the HSC model at younger ages, which given larger heat flux than the measurements, thereby providing excessively large global power.

The immense lateral extent (~1000 km either side of the ridge, spanning ~1/2 of the ocean floor; Johnson and Pruis, 2003), excessive heat flux (13 TW, which is ~1/3 the global heat budget), and absurdly huge Nusselt number (25 to perhaps 1000, according to Von Herzen et al.) inferred for hydrothermal circulation all point to the HSC model being unrealistic.

3. Historical perspectives

Paradigms fail when measurements in conflict with the model are sufficient in quantity or quality that the physical evidence cannot be ignored. Up to that point, justification is sought to deal with the disagreement. Often, rationalizations are modified as condradicting data accumulate. The classic example is the use of epicycles, and later epicycles within epicycles, to describe planetary motions in order to uphold the geocentric model of the universe. Employing the HSC model to infer global heat flux has the hallmarks of a failing paradigm, as suggested by the following examples:

1. It has long been known that the inferred large hydrothermal heat flux necessitates huge Rayleigh and Nusselt numbers which require permeabilites far greater than those expected, based on available measurements of rocks similar to those on the ocean floor. To provide flow in the right places, Sleep and Wolery (1978) envisioned tunnels at young age, which closed at old ages. Newer, in situ measurements of the permeability failed to provide the high values needed to justify the model, leading Davis et al. (1997) to conclude that bulk formation permeability is not representatively sampled by drilling.
2. Magmatic activity at the ridges has historically been considered as the source driving hydrothermal circulation. However, recent studies show that magmatic activity at the ridges contributes <4 TW (Elderfield and Schultz, 1996). Much of this heat is released through conductive cooling, and only part would power hydrothermal circulation, so that the actual hydrothermal power near the ridges is grossly lower than the 13 TW required by the HSC model. Because this justification is refuted, hydrothermal circulation is now considered to occur off axis (e.g., Von Herzen et al., 2005), despite the fact that the largest discrepancy between model and measurements occurs near the ridge. Moreover, these hypothetical submarine convective systems are alleged to have flows that equal the total flow of all rivers on Earth's surface (Wheat and Mottl, 2004). Existence of immense submarine flow requires that the weak process of internal radioactive decay, supplying to the ocean floor nearly 6000 times less energy than that delivered by the Sun to Earth's surface, drives fluid flow in volumes on par with the most conspicuous product of Earth's hydrologic cycle. Physical evidence is lacking for such monstrous systems, rather we expect the actual flow to roughly scale with the energy available to the respective systems.
3. Von Herzen et al. assert that studies of continental hydrothermal systems around plutons are irrelevant to submarine hydrothermal processes. The parallelism is obvious, and the two systems are governed by the same equations with similar boundary conditions.
4. In arguing for the accuracy of the model, Von Herzen et al. compare results from the HSC model used by Stein and Stein (1992) to a similar model in that study (probably GHD1) and conclude that the uncertainty in their model is only 0.4%. Cross comparison of models in no way validates their correctness, particularly because neither explains the data.
5. Von Herzen et al. claim that the process of hydrothermal circulation is well-understood, yet parameters extracted in various ways for the flow are in disagreement. For example, recent

estimates of submarine flow volume vary by a factor of 5 (cf. Johnson and Pruis, 2003; Wheat and Mottl, 2004).

The above examples document repeated assertions that quantitative measurements are irrelevant compared to the predictions of a favored model. Cavalier dismissal of data should be a clear indication that rationalization, not evaluation, of the HSC model prevails.

It is revealing to compare the HSC to the historic failure of a closely related model. The mathematical equation providing the basis for the HSC model (the 6th equation in Stein and Stein, 1992) is identical to that used by Kelvin in 1864 to "prove" that the Earth is only 100 million years old (see Eq. (1) on p. 85 of Carslaw and Jaeger, 1959). Geologic evidence was dismissed in favor of model results. Adherence to the 1-D equation for heat flux being a valid description for the cooling of the 3-D Earth impeded progress in quantifying Earth's evolution for decades. Not until the discovery of radioactivity in the early 1900's was Kelvin's model overturned. For over 50 years, the consensus was that Kelvin's model was correct. The claim of Von Herzen et al. that consensus currently supports the HSC model does not prove that it is valid. Acceptance of this simplistic model over copious, conflicting geologic observations is the same principle that now guides proponents of the HSC model. History repeats itself, sometimes over surprisingly short intervals.

4. Mathematical problems

The HSC model predicts infinite heat flux exactly at the ridge, which is obviously unrealistic. Von Herzen et al. dismiss this singularity at the ridges by stating that it is "integratable." Rather, the *integrable* nature of the singularity is highly relevant because it is through integration that the singularity strongly impacts the mean heat flux derived from the HSC model. Moreover, the particular form of the singularity controls the mean heat flux from the model. To show this, we generalize Eq. (4) in our paper to account for slightly different types of singularities: Let the heat flux $=J=C/t^n$, where C is a constant, t is time and n is between 0 and 1 ($n=1/2$ in the HSC model). The average heat flux over the interval $t=0$ to τ is then

$$\mathrm{Avg} = \frac{\int_0^\tau J(t)\mathrm{d}t}{\int_0^\tau \mathrm{d}t} = \left.\frac{Ct^{-n}}{(1-n)}\right|_0^\tau = \frac{1}{1-n}J(\tau) \qquad (1)$$

The average flux calculated in this manner increases with the strength of the singularity, and thus the particular form of the heat flux used in the half-space cooling model controls the corresponding mean. The control exerted over the average heat flux by the singularity at the ridges is an intrinsic flaw in the half-space cooling model that cannot be overlooked.

It is the 1-D nature of the HSC model which mandates that $n=1/2$. Therefore, the excessive heat flux calculated using the model results from the assumed 1-D vertical heat flow. It should come as no surprise that unrealistic boundary conditions lead to an untenable result.

Von Herzen et al. state that the constant factor (C) is affected by the temperature dependence of thermal conductivity (k). We agree: C is proportional to k, so J is proportional to k. As stated in our paper, k is not fixed and tradeoffs with other parameters exist, so global power from the HSC model depends strongly on the value chosen for k. The tradeoffs with k, plate thickness and basal temperature were explored in detail by Honda and Yuen (2004a,b).

More importantly, the available data provide 2–3 constraints (heat flux, depth, and, in Honda and Yuen's (2004a) effort, also the geoid slope) whereas the HSC model has 5 free parameters (thermal diffusivity, thermal conductivity, thermal expansivity, temperature at the base of the slab, and slab thickness). Since thermal conductivity is the product of heat capacity, density, and thermal diffusivity, it must be counted separately from thermal diffusivity. Density is more or less constrained by thermal expansivity and is not counted separately. Physical properties of real rocks are not used. A surfeit of free parameters (2–3), allows one to arbitrarily mold a dataset to a model (M. Disney, quoted by H. Ratcliffe, 2005). That the fit to heat flux is poor, especially near the ridge, means that even with the favorable situation of being under-constrained, the half-space cooling model fails to describe the data, and a 6th free parameter is invoked (hydrothermal circulation). According to the criterion of Disney, the HSC model lacks statistical significance, and is not even empirically viable.

5. Minor issues

Regarding Fig. 2 in our paper, von Herzen et al. are correct to point out a typographic error (0.501 rather than 0.510) in the factor "*C*" in Fig. 2. The correct value was stated in our text and used in the graphs and tables, and its unconstrained nature was discussed above. Even had this erroneous value been used in our paper, it would have introduced only a 2% error in the calculated global flux, i.e. a disparity of <1 TW. Their concern is misplaced, given the 570% disparity of HSC model values from extensive heat flux measurements in Quaternary rocks.

Von Herzen et al. charge that we under-represent uncertainties. To the contrary, Fig. 2 depicts the data of Pollack et al. (1993), which were stated to have uncertainties of 1 to 10 mW/m^2. The symbols on this figure are clearly larger than 10 mW/m^2.

Von Herzen et al. express concern as to exactly what data set we used to determine the mean heat flux. With ~10 000 measurements on the ocean floor now available, one would not expect utilization of different published data sets (i.e. Pollack et al., 1993; or Gosnold and Panda, 2002; or most recently www.heatflow.und.edu.) to yield different averages of the heat flux. In fact, our paper showed that the analysis of Lee (1970) utilizing 2000 measurements closely compared with each of three different averages (Table 4) based on ~10 000 measurements described by Pollack et al. (1993). The global dataset has become so large that even substantial differences in the size of the oceanic dataset have negligible impact on the mean heat flux, and furthermore, various methods of manipulating the data have scant effect on the average. In contrast, using the HSC model, provides a 42% increase in the inferred global power over that indicated by the measurements. Given that the authors of the comment place so little stock in the voluminous database, why do they criticize us for not providing more data?

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