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Discussion

Comments on "Earth's heat flux revised and linked to chemistry" by A.M. Hofmeister and R.E. Criss ☆

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We were very interested in the recent review and analysis by Hofmeister and Criss (2005) (hereinafter designated H and C), as it has been twelve years since the last published heat flow data compilation and review of the Earth's thermal budget (i.e., Pollack et al., 1993). Although there is still considerable uncertainty in estimates of the many parameters affecting the dynamics of the interior, an improved understanding of the thermal budget at the Earth's surface may provide us with an important boundary condition to constrain them. The conclusions of H and C most relevant to the discussion that follows are:

1) The mean surface heat fluxes of both continental and oceanic regions are similar, ~65 mW m^{-2}.
2) The total surface heat flow is ~30 TW, at least 10 TW less than previously estimated (Pollack et al., 1993), as a result of an overestimated oceanic hydrothermal component.

H and C's review of continental heat flow seems quite similar to that of Pollack et al. (1993), and it is not clear to us how much additional data, if any, is included in their analysis (their referenced web site of Gosnold and Panda is not presently available; the current version of the database, now residing at www.heatflow.und.edu, may be different from Gosnold and Panda). H and C have also considered other sub-topics of geophysics and geochemistry to argue that heat generated in the Earth's deep interior may be transported relatively rapidly to the surface. Although we do not consider these arguments further here, it appears to us that significant uncertainties remain in the processes and parameter values relevant to estimating heat transport in the Earth's interior, uncertainties that leave considerable latitude in estimated rates of heat transfer to the surface. From another perspective, the range of opinion in the scientific community regarding the depths to which subduction extends (e.g., AGU Fall Meeting, 2004a), or from which plumes originate (e.g., AGU Fall Meeting, 2004b), must also translate to significant uncertainty in the estimated time required for heat generated in the Earth's interior to be transported to the surface.

However, it is mainly the analysis of oceanic heat flow by H and C to which we take exception. We believe it represents a biased and misleading view of the present understanding of heat flow through the seafloor, and hence of the total heat flow for the entire Earth. We discuss below the various sub-topics relevant

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to this problem as considered by H and C; our overall conclusions are that the mean heat flux through the seafloor is substantially higher than that through continents, and that the total heat flow through the Earth's surface is closer to (and probably exceeds) 40 TW, as previously estimated, rather than the ~30 TW argued by H and C. Although this difference may seem at first glance to be relatively small, it is a result of significantly different conclusions about the temperature structure and heat transfer mechanisms in the crust and upper mantle beneath the seafloor.

1) *The half-space (plate) boundary condition at spreading ridges*. H and C state (p. 167) that "Prediction of infinite flux at $t = 0$ ... indicates that the half-space cooling (HSC) model is unrealistic." This issue has been extensively discussed previously in papers not referenced by H and C (e.g., Davis and Lister, 1974; Lister, 1977). Both of these papers point out that a heat balance at the spreading boundary (between conductive loss through the seafloor and advected heat associated with plate creation) provides a more realistic condition, but that the integrated heat flux is hardly different from the simpler HSC model. H and C appear to argue that the mathematical condition of infinite heat flux at $t = 0$ invalidates any estimates of total heat flow based on the $t^{-1/2}$ (inverse root time) model of HSC, even though the mathematically infinite heat flux exists only for an infinitesimal time. In fact, they show (correctly, p. 167) that the mean heat flux up to time t for the half-space (or plate) cooling model is finite and exactly twice the heat flux at time t, as originally pointed out by Lister (1977). Because the ridge singularity is integrable, Stein and Stein (1994) found less than 0.4% difference in average heat flux of young lithosphere from that obtained by including the modified ridge boundary condition. Thus, neglecting the effects of hydrothermal circulation (see below), there is little or no problem with using the simple HSC model for young (<80 My) seafloor.

Fig. 2 of H and C is both incorrect and misleading. The HSC model of Stein and Stein (1992, 1994) for the relation between heat flux (q, mW m^{-2}) and age (t, My), known as GDH1, is $q = 510\ t^{-1/2}$ (not $501\ t^{-1/2}$). It is derived from northwest Atlantic and north Pacific measurements and applies only to seafloor younger than ~55 My (for reasons given below); an exponential fit is used for older seafloor. The other suggested fits by H and C to the selected data averages using different functions are arbitrary (i.e., without physical or conceptual bases). The GDH1 model was slightly modified with the use of data from other ocean basins to GDH2 by DeLaughter et al. (1999), but the relationships with age are virtually the same. The uncertainties (standard deviations) in the age-binned means, presented in Stein and Stein (1992, Fig. 1) but not shown by H and C, are large, such that the description in the caption by H and C – "Experimental uncertainties in the measured heat flux averaged over these short intervals of time are considerably smaller than the symbols." – is clearly incorrect.

It is well understood that the GDH1 (and GDH2) models do not fit the heat flow data for seafloor ages <~60 My because of unmeasured hydrothermal heat loss. Instead, the curves for this age range are derived from an HSC model constrained primarily by seafloor depths, not heat flux. The effects of hydrothermal circulation on depth anomalies at these ages are small because only the uppermost part (few km) of the plate is involved. There is no inconsistency here: heat flow is strongly affected by fluid flow at shallow sub-seafloor depths, whereas seafloor depth is not.

2) *Temperature dependence of thermal conductivity and other parameters*. This potential problem has also been considered in the aforementioned references. Insofar as the parameters are only weakly pressure (depth) dependent, as affirmed by H and C (p. 166), the inverse root t relationships for both seafloor elevation and heat flux are valid (again, without the complication of hydrothermal circulation). Only the constant factors multiplying the inverse root t relationships for elevation and heat flux would be affected by the temperature dependence of these parameters, not the relationships themselves. The values of these constants determined from the data (e.g., Lister, 1977; Parsons and Sclater, 1977; Stein and Stein, 1992; Harris and Chapman, 2004) include the effective temperature sensitivity.

3) *Seafloor depths at older (>100 My) ages do not match boundary-layer cooling predictions*. Although mean seafloor depths at great age show little systematic variability with age, depth fluctuations of different wavelengths are present, perhaps even more so than in young areas (e.g., Stein and Stein, 1992, Fig. 1). Potential causes for these depth fluctuations include the thermal effects of hotspots (e.g., Heestand and Crough, 1981) and other manifestations of mantle convection, and the volcanic additions to crustal structure. The first two add to the heat associated with simple lithospheric boundary-layer cooling in a way that is to this day poorly understood, but it is generally accepted that the simplest form of boundary-layer cooling (1-D half-space cooling, referred to by H and C on pp. 163–166) can be applied only to a limited age range.

The evolution of oceanic depth and heat flux over the full seafloor age range is much better fit with a 1-D plate model (e.g., McKenzie, 1967). A plate model with uniform temperature or heat flux at depth matches the age dependence of seafloor depth and heat flux much better than a HSC model, which requires both to change much faster than observed at seafloor ages >100 My. The early portion (<80 My) of plate model cooling is identical to HSC; significant differences begin at younger ages for seafloor depth than for heat flux, which explains why different cutoff ages are used to express depth and heat flux (H and C, pp. 164–5). Thus the different age ranges used to estimate depth and heat flow based on a plate model are not arbitrary, but have a physical basis. The various fits of seafloor depth and heat flux for younger seafloor in different oceans basins depend largely on the differences in physical parameters that control hydrothermal circulation (see below).

4) *Comparison of continental and oceanic heat flux histograms (H and C, Fig. 1)*. H and C apparently believe that this figure shows the similarity of continental and oceanic heat flux means. Because of the non-uniform spatial distributions of both continental and oceanic data that is primarily the result of an emphasis on geothermally active and other anomalous areas, histograms of individual values are not appropriate for comparisons. The continental histogram is much more peaked than the oceanic, and the fact that the preponderance of the data <20 and >135 mW m^{-2} is oceanic, despite the greater total number of continental data, reinforces this difference. This characteristic of the oceanic data is expected in the presence of vigorous hydrothermal circulation in the seafloor. It is largely coincidental that the most frequent values and apparent means are close to each other. The coincidence disappears when the quantitative effects of hydrothermal circulation in the ocean crust are included (see below). Histogram comparisons might be more useful if the individual values were carefully edited to eliminate unusual environments, and binned (by region, age, or other appropriate parameters) to minimize the uneven spatial distributions of the measurements.

5) *Estimating mean heat flux via spherical harmonic analysis*. H and C are apparently confused about the use of spherical harmonic analysis (SHA) in a geothermal context. SHA has long been applied effectively to estimate magnetic and gravitational field strength throughout the Earth's volume and in space beyond Earth's surface, because the physics of these fields is controlled by potential functions. However, for heat flow, where variations are caused by processes such as mantle convection and fluid flow that are not generally represented by potentials, SHA cannot be used to estimate heat flow field strength either across the surface or in the interior of the Earth. The quantitative representation of the surface heat flow as a series expansion in terms of surface harmonic functions (Associated Legendre Functions) is simply a description of the spatial variability. It does yield an estimate of the global mean heat flow from the leading term of the series, but it does not easily yield estimates of mean values of continental and oceanic heat flow, nor has it been used to estimate heat flux in regions without measurements. Such estimates (e.g. in Pollack et al., 1993) are derived for oceanic regions from tectonic (plate) models that are well constrained by observations of seafloor depth and age, and for continents from empirical estimators based on observations of heat flux in crustal units of various ages.

6) *Estimating the effects of hydrothermal circulation on oceanic heat flux*. The many statements throughout H and C that attempt to minimize the effects of hydrothermal circulation on ocean heat flux ignore a large body of evidence accumulated over more than 30 years that document its importance and relevance in the marine environment. Beginning with carefully controlled measurements on the Juan de Fuca ridge (Lister, 1972), then extending to regional surveys that clearly included one or more lateral wavelengths of the hydrothermal circulation patterns (e.g., Davis and Lister, 1974; Williams et al., 1974; Sclater et al., 1974; Becker and Von Herzen, 1983; Fisher and Becker, 1991; Langseth et al., 1988), the dramatic effects of hydrothermal circulation on surface heat flux have been documented by many surveys on young (<20 My) seafloor. Many of these investigations were implemented on seafloor with reasonably complete sediment cover that inhibits local heat loss by advection through the seafloor. Even so, the mean conductive heat loss in such regions is frequently ~20–50% of that expected from plate cooling, almost certainly the result of convective heat loss through occasional basement outcrops as documented in recent detailed surveys (e.g., Fisher et al., 2003a; Wheat et al., 2004). The fraction of heat loss by conduction is even less in large regions of the eastern Pacific (e.g., Von Herzen and Uyeda, 1963; Von Herzen and Anderson, 1972) where very low values of heat flux in sediment ponds initially ascribed to sediment slumping are now recognized as almost certainly caused by ventilated hydrothermal circulation. Other evidence for the ubiquitous and significant effects of hydrothermal ventilation through the seafloor include pore water chemistry (e.g., Baker et al., 1991), dating of crustal water (Elderfield et al., 1999), and the chemical and mineralogical alteration of seafloor rocks (e.g., Alt,

2004). Many of these and other topics, including an appraisal of the age range over which thermally significant hydrothermal circulation persists (Von Herzen, 2004), have been summarized and updated in a recent textbook (Cambridge University Press, 2004).

H and C (pp. 168–9) invoke evidence of the pore water circulation around cooling plutons in continental crust as analogous to that of hydrothermal circulation in ocean crust. The geometries and geological settings of continental plutons and ocean crust are obviously very different, and inferences from the former cannot be confidently applied to the latter. The greatest weakness of the analogy is almost certainly rooted with the large differences in the important parameters of permeability (k), and the associated Rayleigh (Ra) and Nusselt (Nu) numbers. Values that H and C believe apply to seafloor hydrothermal circulation are grossly underestimated. Estimates for Ra and Nu values in the oceanic crust made in the 1970s and early 1980s (the most recent literature on this topic cited by H and C) are now known to be wrong. Numerous studies have shown supercritical Ra values and Nu values well in excess of 25, perhaps >1000 in some cases on ridge flanks (Davis et al., 1997, 2004; Spinelli and Fisher, 2004; Wang et al., 1997). Also, a caveat is that these dimensionless numbers apply strictly to idealized systems, not including sloping boundaries, variable fluid properties, and other characteristics. It has also been shown that the permeability of young upper oceanic basement rocks can be well in excess of 10^{-12} m^2 at scales of kilometers or more (e.g., Becker and Davis, 2003; Becker and Fisher, 2000; Davis and Becker, 2002; Davis et al., 2000, 1997, 2001; Fisher, 1998; Fisher et al., 2003a; Spinelli and Fisher, 2004; Stein and Fisher, 2001, 2003). Although appropriate measurements are difficult to obtain, these parameters may have even higher values on the young crust without sediment cover that characterizes most spreading ocean ridges, and perhaps in somewhat older crust that has not reached the relatively high temperatures of the thickly sedimented sites most commonly studied.

H and C (p. 168, par 4) are incorrect to assert that hydrothermal circulation cannot account for the difference between standard plate cooling model predictions and observations. Numerous studies have shown that ridge-crest hydrothermal fluxes can be readily accounted for on the basis of the heat available from cooling and latent heat release from the upper crust close to the ridge (e.g., Baker et al., 1996; Humphris and Cann, 2000; Wilson et al., 1988). Ocean ridge hydrothermal circulation is, of course, most active in neovolcanic zones and adjacent areas, and its lateral extent varies with location and time. The accounting for ridge flank fluxes *starting* at 1 My is a conservative use of the data, neglecting anything closer to the ridge that might have been cooled already. The statement by H and C that, "Of course, much of the heat is removed conductively..." [at the ridge], is contradicted by many peer-reviewed studies in numerous settings. The studies cited above (and many others) show that the measured heat flux at ridges (as determined by measurements of thermal and geochemical plumes) matches well the heat budget for cooling of the uppermost 2–4 km of crust. In addition, these fluxes have virtually nothing do to with heat flow anomalies on ridge flanks, with which H and C seem to be primarily concerned, which are caused by advective heat extraction at relatively low temperatures far from the axis. The assertion of H and C (p. 168, par 6) that "huge volumes and short timescales" cited for hydrothermal fluxes on flanks are "not credible" is a qualitative view unsupported by data or analyses. In fact, the global hydrothermal fluid flux is thought to be about the same magnitude as the global riverine flux to the ocean (e.g., Wheat and Mottl, 2004) and is entirely credible.

Finally, the discussion by H and C (p. 169, par 4, Fig. 8) of total heat fluxes quantified from gradients measured in sediments with shallow heat flow probes shows a complete misunderstanding of how geothermal heat is advected from the oceanic crust, and is highly misleading. The boundary layer theory will apply only if fluids pass upward *through* the boundary layer. As shown in numerous studies of ridge flank sediments and fluid pressures measured in basement rock over the last twenty years, the sediment permeabilities and driving forces are too small (by many orders of magnitude) for significant advective heat fluxes through sediments (e.g., Bryant et al., 1974; Davis and Becker, 2002; Davis et al., 1996, 1997; Davis and Fisher, 1994; Fisher et al., 1997, 1994; Giambalvo, 2001; Giambalvo et al., 2000; Mottl, 2003, 1989; Mottl and Holland, 1975; Mottl and Wheat, 1994; Spinelli et al., 2004; Stein and Fisher, 2001; Wheat and Mottl, 1994). Large quantities of lithospheric heat are extracted from ridge flank crust not by passing warm fluid through sediments but by *bypassing sediments entirely* (e.g., Fisher et al., 2003a,b; Villinger et al., 2002).

7) *Alternative methods to determine mean oceanic heat flux*. H and C (pp. 170–1) suggest alternative ways to obtain ocean heat flux by different averaging schemes: mid-plate (or, in their view, mid-convection cell) averages, averaging of seafloor age strips, or numerical integration of binned (by age) data. Because seafloor heat flux is non-linear with age, the latter two

methods are preferable to the first. However, all are substantially biased unless the unmeasured advected flux carried by ventilated hydrothermal circulation is accounted for, as discussed above. We do not understand how spherical harmonic analysis can remove the effects of "weak" hydrothermal circulation.

In summary, by failing to account for the full integrated effects of ocean hydrothermal circulation, H and C arrive at a total Earth heat flow of ~31 TW. This value is at least 25% less than that estimated from the magnitude and distribution of values corrected for unmeasured advective heat loss through the seafloor (e.g., Stein et al., 1995, Fig. 5). The previous deduction by others (Williams and Von Herzen, 1974; Pollack et al., 1993) that the mean oceanic flux including the unmeasured hydrothermal flux (~101 mW m^{-2}) is about 50% larger than the mean continental heat flux (~65 mW m^{-2}) is consistent with the contrasting tectonic regimes and mean age differences of oceans and continents. We believe 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. In doing so, far better constraints are placed on the largely unmeasured and unknown (and therefore more speculative) processes that operate in Earth's deep interior.

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