# A Reappraisal of Global Heat Flow Data

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## Abstract

A reappraisal of world heat flow data has been carried out in an attempt to understand the characteristic features of global thermal field. The initial effort was directed at verifying the overall structure, quality and internal consistency of the database. Thus the present system of intercalating tables and references was transformed into a coherent and organized database that is amenable for scientific analysis. Subsequently, the format employed for geographic coordinates has been replaced by a consistent decimal degree system that allows implementation of automatic computer based processing facilities. At present, a detailed verification of the entire data set is being carried out to minimize problems arising from typographic errors.

The restructured database has been used in calculating mean values of heat flow for a regular grid system composed of $5^0 \times 5^0$ surface area elements. Spherical harmonic analysis of this system of regular grid values have allowed calculation of a new set of fully normalized Legendre coefficients (169 coefficients for a 12 degree expansion). Maps based on the new set of coefficients have lead to identification of several new features in the conductive component of global heat flow. Comparison with results of previous studies indicates discrepancies in several regions. There are indications that some of the major high heat flow anomalies identified in previous studies are artifacts of interpolation procedures. The reason appears to be widespread use of synthetic values instead of experimental data.

## Introduction

The heat flow database employed in the present work refers to the one compiled by the International Heat Flow Commission – IHFC and is available for download at the web site of the National Geophysical Data Center (NGDC). It includes 21453 records of heat flow measurements over the globe. Of these 12,105 are on land, 9,053 in oceanic regions and the remaining 295 in transition regions, such as continental platform areas and shallow water bodies. The database in its present form may be considered as having two parts: continental and oceanic. The heat flow data pertaining to the different countries has been grouped together and forms the continental data base. For oceanic regions several sets of data ensembles have been put together, following roughly the chronological order of heat flow measurements. As a result the data sets for the different sectors and tectonic units of oceanic regions are not grouped together properly.

The overall distribution of heat flow data over the globe is illustrated in Figure (1). It is obvious that the distribution is highly heterogeneous. The availability of data is poor in several of the major regional sectors and geotectonic units of the Earth. A closer examination reveals that there are also considerable differences not only in data density but also in the quality of primary data A direct consequence of such difficulties is that our understanding of global thermal field remains poor. Mapping heat flow fields on a regional scale is one form of minimizing problems arising from non-homogeneous distribution. However features revealed in such maps are to a large extent dependent on the density and distribution of the primary data used in the analysis.

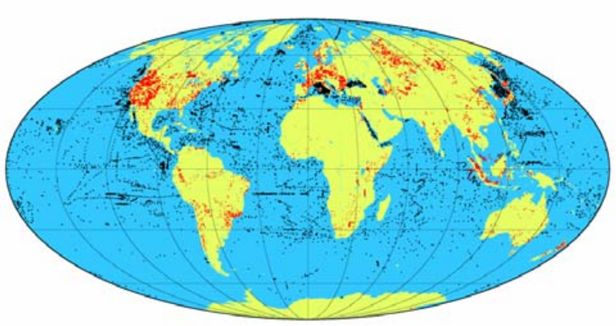

Figure (1) Distribution of global heat flow data.

The database in its present form may be considered as an outgrowth of earlier compilations by Birch (1954), Lee (1963), Lee and Uyeda (1965) and Jessop et al (1976). It is structured essentially as an intercalating system of tables and references. Consequently, the contents are not easily amenable for scientific analysis. The format adopted for the individual fields of information has been discussed in detail by Balling et al (1981). However, lack of a uniform and consistent format for the geographic coordinates of the sites of heat flow measurements has lead to widespread confusion in analysis and interpretation of data. It is in this context that the present work has been proposed, where the main objectives include a reappraisal of the database and also analysis of heat flow on a global scale.

## Restructuring the IHFC Database

Few attempts have so far been made for examining heat flow variations on a global scale, an indication of the difficulties in analysis of the database. Clearly there is a need for restructuring and reformatting the database. In the present case a restructuring the heat flow database was carried out in four distinct stages, described below.

***1- Migration to a spreadsheet based system:*** The current database make use of ASCII text files in collating both data and references. Obviously a change from the current system, to a spreadsheet based system was necessary to gain flexibility in automatic processing of the information contained in the separate data fields. For this purpose the database was divided into two parts. The first one contains digital information on location, coordinates, temperature gradient and thermal conductivity and heat flow values. The second one contains the list of references. The immediate advantage of this separation has been the ease with which automatic processing of information pertaining to any particular field of information or sets of data could be implemented.

***2- Reformatting the geographic coordinates:*** As mentioned earlier the format used in the database for the geographic coordinates is neither uniform nor consistent. This has lead to problems in analysis of data. In an attempt to overcome such problems the decimal degree system was adopted for the coordinates. The conversion from the current system to the decimal degree system was implemented using a set of conversion scripts. In spite of the facilities available for automatic conversion in spreadsheet calculations the operation for coordinate conversion in the present case turned out to be a tedious task. Line by line verification of the entire database was found necessary, in view of the frequent changes in the number and position of significant digits in the values of the coordinates.

***3- Verification of the locations of data points and identification of offshore and inland sea data sets:*** The results obtained in the previous stage of coordinate conversions brought to light additional problems in the database. These are:

- Widespread occurrence of typographic errors in the coordinates;
- Classification of data from offshore areas as part of data from adjacent continental regions; and
- Lack of a specific group for data from inland seas and shallow water bodies.

Corrections of problems arising from typographic errors in coordinates require detailed examination of relevant information in the original references. However, large scale errors of locations in continental areas can easily be identified through the use of outline maps for the countries. As an illustrative example consider the locations of heat flow measurements in Morocco, illustrated in Figure (2). It is obvious that one of the data point has a possible typographic error in its latitude, leading to its incorrect location in the neighboring Mali Republic. It must be pointed out that this procedure does not allow identification of small scale errors in coordinates. The procedure is also not very effective for the oceanic regions as the outlines of the sectors and provinces in oceanic areas are not well defined.

The practice of classifying data from offshore areas as part of adjacent continental data is another source of confusion. Generally the crustal structure in offshore areas undergoes rapid changes with distance from the coast line and this often has profound influence on its thermal field. Hence such data are better classified as belonging to the respective continent – ocean transition zones. As an illustrative example, consider the map of heat flow sites for Spain, presented in Figure (3). It indicates that a number of offshore measurements have been retained as part of continental data.

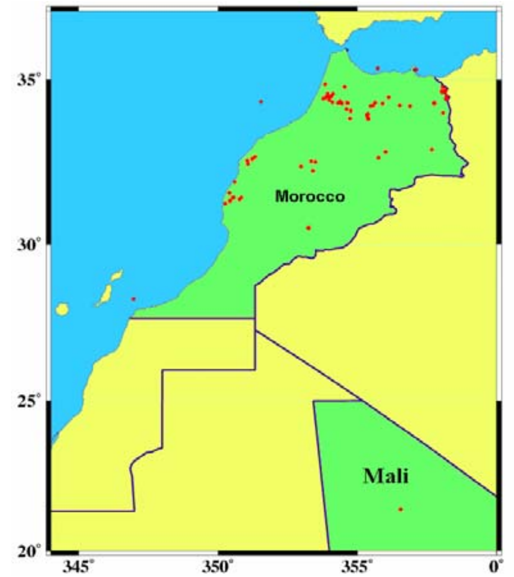

Figure (2) Sites of heat flow measurements in Morocco. Note the data point located in the Mali Republic.

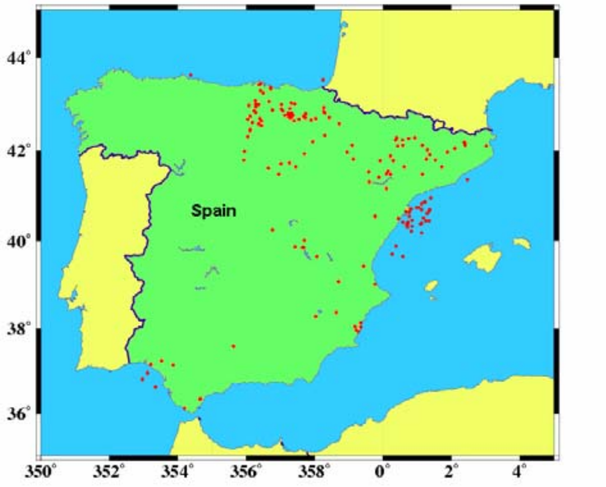

Figure (3) Distribution of heat flow measurements in Spain. Note the data from offshore areas.

Classification of data from inland seas and areas of shallow water bodies in the interior of continents is another problem that has not been addressed properly in the IHFC database. For example, in earlier compilations, parts of data from the Mediterranean were listed as continental data belonging to the now extinct USSR. This problem was also pointed out in the work of Pollack et al (1993). However most of the data from inland water bodies are still classified as continental data. Some of the inland water bodies (as for example Lake Baikal in Russia) are situated in regions where the underlying crustal structure is different from that of the adjacent continental areas. Hence a better practice would be to classify data from such areas as belonging to a separate group. The location map of Figure (4) illustrates the distribution of continental data for Europe and western parts of the now extinct USSR. Note that it includes also data for Black Sea, Caspian Sea and several small inland water bodies.

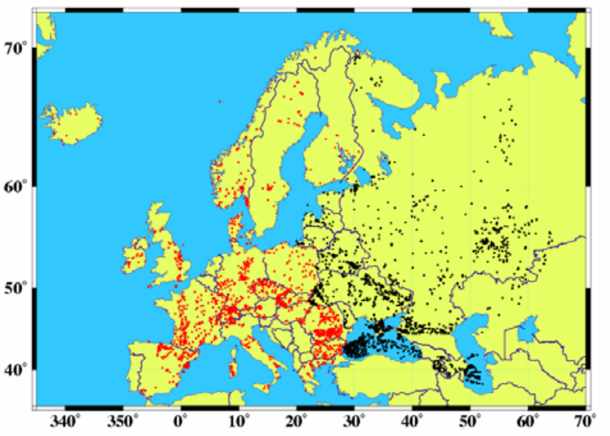

Figure (4) Distribution of heat flow measurements in Europe and the western parts of the now extinct USSR.

4- ***Updating the database for the South American continent:*** A large part of heat flow data compiled in the work of Hamza and Muñoz (1996) have not been included in the IHFC database. Since 1996 the Geothermal Laboratory of the National Observatory (Rio de Janeiro) maintains an updated list of heat flow measurements for the South America. This data has been included in the present work as part of an attempt to improve the distribution and data density for the South American continent.

Table (1) provides a summary of corrections introduced in the IHFC database. Most of the corrections are for continental areas of Asia, Europe and North America. A number of incorrect locations were also found for data from oceanic regions. Some of the incorrect data for Africa may be traced back to original publications on heat flow measurements. No corrections were needed for data from the South America and the Antarctic. The total number of large scale errors in coordinates is 847, out of a total of 22,106 data points.

Table (1) Summary list of corrections for the IHFC database.

| Region | Locations of Data Points | | Total |
|---|---|---|---|
| | Correct | Incorrect | |
| **Africa** | **526** | **21** | **547** |
| **Central America** | **83** | **1** | **84** |
| **South America** | **822** | **0** | **822** |
| **Antarctic** | **9** | **0** | **9** |
| **Asia** | **3967** | **365** | **4332** |
| **Europe** | **1943** | **112** | **2055** |
| **North America** | **4466** | **156** | **4622** |
| **Australia and Pacific** | **264** | **23** | **287** |
| **Seas and Oceans** | **9179** | **169** | **9348** |
| **Total:** | **21259** | **847** | **22106** |

### Analysis of the Corrected Database

An examination of the regional distribution of the corrected database is necessary before further attempts can be made for analysis of the global heat flow pattern. In the earlier attempts (see for example, Lee and MacDonald, 1963, Lee and Uyeda, 1965; Horai and Simmons, 1969) the procedure adopted has been based on methods that create an over determined set of equations based on experimental data, which in turn is solved for the unknown coefficients. This approach has the inherent weakness that the coefficients are sensitive to changes in data density. In the work by Chapman and Pollack (1975) problems arising from uneven data distribution were minimized by dividing the surface of the globe into a grid system of $5^0$ x $5^0$ and calculating mean values of heat flow for this system of surface elements. In addition, they employed estimated values of heat flow for those area elements for which experimental data were not available. Empirical predictors, based on the well-known heat flow-age relation (Polyak and Smirnov, 1968; Hamza and Verma, 1969), were employed in obtaining estimated values. This approach was also adopted in the present work, where mean heat flow values were calculated for 5°x5° area elements. The results obtained indicate that the present database covers only 49% of the surface area of the Earth. The grid system for which experimental data are available is illustrated in Figure (5). In this figure the red dots indicate grid elements for which experimental data are available. Similarly the white dots indicate grid elements for which estimated values based on empirical predictors were calculated.

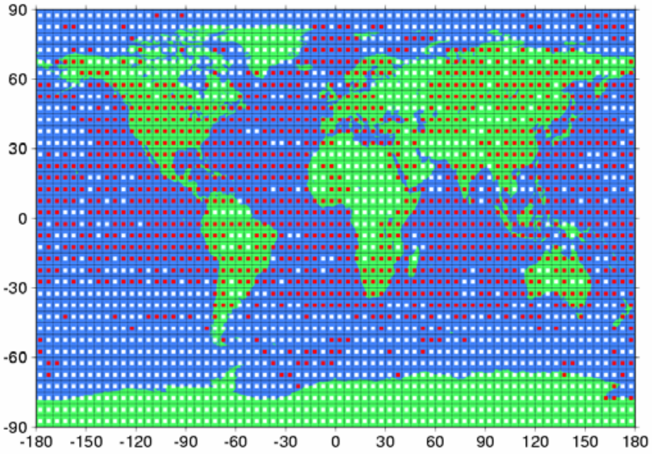

Figure (5) Grid system of 5°x5° surface area elements used for calculating mean heat flow over the globe. The red dots indicate grids for which experimental data are available. See text for details.

In the later work of Pollack et al (1993) the use of empirical predictors was extended to mid-ocean ridge areas. However, unlike the previous works, results of experimental measurements were discarded in favor of theoretical heat flow values calculated on the basis of plate cooling models. The practice of using theoretical estimates in place of experimental data is open to criticism as it is based on assumptions as to the nature of thermal processes at deeper levels in the crust, which is what we are trying to determine in the first place. Another problem with this procedure is that it requires extensive pre-processing of related geological and geophysical data. In many cases such information is not readily available, since detailed geologic mapping of ridge areas in oceanic regions have not so far been carried out. Also, the current level of knowledge about the tectonic and structural features in oceanic areas (which are water loaded and sediment covered) is far inferior to that in continental areas. Obviously such procedures are cumbersome and prone to errors, especially when large data sets are involved. Pollack et al (1993) selected ‘suitable’ values of tectonic age for the different sectors of ocean ridge areas and ignored the possibilities of alternative interpretations. In particular, the possibility that different sectors of ocean ridges could have distinctly different evolutionary history and geotectonic characteristics was not considered. In the present work the use of empirical predictors has been restricted exclusively to areas for which experimental data are currently not available.

## Spherical Harmonic Representation

Spherical harmonic analysis is one of the convenient forms of examining characteristics of potential fields of the Earth. The harmonic representation of heat flow (q) is usually expressed as:

$$q(\theta,\phi)=\sum_{n=0}^{N}\sum_{m=0}^{n}\left[A_{nm}\cos(m\phi)+B_{nm}\sin(m\phi)\right]P'_{nm}(\cos\theta) \quad (1)$$

where $\phi$ is the longitude $\theta = 90 - \psi$, is the colatitude, $P'nm(\cos\theta)$ is the associated Legendre function that is fully normalized and $A_{nm}$ and $B_{nm}$ the coefficients of the harmonic expansion. The expression for evaluation of $P'_{nm}$ is:

$$P'_{nm}=\frac{P_{nm}}{\sqrt{K_n^m}} \quad (2)$$

where $P_{nm}$ is the associated Legendre function given by:

$$P_{nm}(\cos\theta)=\frac{\sin^m\theta}{2^n}\sum_{t=0}^{Int\left(\frac{n-m}{2}\right)}\frac{(-1)^t(2n-2t)!}{t!(n-t)!(n-m-2t)!}\cos^{(n-m-2t)}\theta \quad (3)$$

and

$$K_n^m=\frac{1}{H(2n+1)}\frac{(n+m)!}{(n-m)!}\ ,\ \begin{cases} if\ \ m=0\Rightarrow H=0 \\ if\ \ m\neq 0\Rightarrow H=2\end{cases} \quad (4)$$

In equation (3) *Int[(n-m)/2]* refers to the largest integer that is lower than *(n-m)/2*.

Full normalization of associated Legendre functions ($P_{nm}$) requires that the following equations be satisfied:

$$\int_0^{2\pi}\int_0^{\pi}\left[P'_{nm}(\cos\theta)\sin(m\phi)\right]^2\sin\theta\ \ d\theta\ \ d\phi=4\pi \quad (5a)$$

$$\int_0^{2\pi}\int_0^{\pi}\left[P'_{nm}(\cos\theta)\cos(m\phi)\right]^2\sin\theta\ \ d\theta\ \ d\phi=4\pi \quad (5b)$$

## Evaluation of the harmonic coefficients by the method of Least Squares

Ponte Neto and Hamza (2004) presented a least square method for obtaining estimates of the spherical harmonic coefficients. Here we reproduce only a brief summary of the main steps involved. The coefficients are obtained by fitting the harmonic expansion to the set of experimental data, which are the heat flow values (*q*) and their respective geographic coordinates ($\phi$ and $\theta$). The relation for *q* may be written as:

$$\begin{aligned} q=&A_{00}\cos(0.\phi)P'_{00}+A_{10}\cos(0.\phi)P'_{10}+A_{11}\cos(1.\phi)P'_{11}+ \\ &B_{11}\sin(1.\phi)P'_{11}+A_{20}\cos(0.\phi)P'_{20}+A_{21}\cos(1.\phi)P'_{21}+ \\ &B_{21}\sin(1\phi)\,P'_{21}+B_{1212}\sin(12\phi)P'_{q1212}\end{aligned} \quad (6)$$

where the expression for $P'_{nm}(\cos\theta)$ is abbreviated as $P'_{nm}$.

As has been pointed out by Ponte-Neto and Hamza (2004) equation (6) may be rewritten in a compact form for each of the data $q_i$, forming thus a system of equations for the whole set of *w* data points:

$$\begin{cases} y_1=a1+a2.x1_1+a3.x2_1+a4.x3_1+\dots\dots\dots a168.x167_1 \\ y_2=a1+a2.x1_2+a3.x2_2+a4.x3_2+\dots\dots a168.x167_2 \\ \\ .\quad .\quad .\quad .\quad .\quad .\quad .\ . \\ y_w=a1+a2.x1_w+a3.x2_w+a4.x3_w+\dots\dots a168.x167_w\end{cases} \quad (7)$$

For large values of *w* this becomes an over determined system of equations amenable to analysis using least square methods. For this purpose it is convenient to reformulate it in matrix form with summation running over the range of w data points. This allows reformulation of (7) in compact form (Ponte Neto and Hamza, 2004):

$$D = M\ .\ a \quad (8)$$

where *M* is a square matrix of 168x168. Hence the coefficient matrix is given by the inverse of the summation matrix *M* and the column matrix *D*:

$$a = M^{-1}\ .\ D \quad (9)$$

Computational programs written in FORTRAN and Visual Basic were used in calculating the new set of harmonic coefficients.

## Patterns in Global Heat Flow

The new set of harmonic coefficients calculated by the method least squares were used in mapping heat flow on a global scale. In the present work maps were generated using the GMT computational package (Wessel and Smith, 1990). A number of numerical simulations were carried out using the built-in routines available in the GMT, the purpose being to assess the influence of gridding and interpolation procedures in map representations.

As an example of the results obtained we present in figure (6) the global heat flow map based on the new set of harmonic coefficients. A remarkable feature that is easily discernible in this map is the high degree of variability in the conductive component of regional heat flow. The Nazca ridge in the Pacific, off shore areas of western US, Japan Sea and the Red Sea stands out as oceanic regions of relatively high heat flow (>100 mW/m$^2$). Mid-ocean ridges in the Atlantic, Pacific and Indian Oceans also appear as zones of higher than normal heat flow (generally in the range of 80 to 100mW/m$^2$). The ocean basins and areas of low angle subduction appear to be characterized by normal heat flow (in the range of 60 to 80mW/m$^2$). On the other hand, the central parts of the continental areas of Africa, Asia, North America, South America, Antarctic and Australia seem to be characterized by relatively low heat flow values (<60 mW/m$^2$).

At this point a comparative analysis of the global heat flow patterns of the present work with those of earlier ones is in order. Since the works prior to 1990 are based on limited data sets meaningful comparison is possible only against the results of Pollack et al (1993). The differences in global heat flow field between the present work and that reported by Pollack et al (1993) are illustrated in the map of figure (7). In spite of the fact essentially the same database has been employed in both studies the differences are significant, ranging from -60 to >100mW/m$^2$. The regions of major discrepancies are located in the southern hemisphere along the Nazca, South Atlantic and South Indian ridges. Even though heat flow is relatively high in certain segments of these ridges no direct evidences (geological or geochemical) have been found for the possible existence of large contiguous areas anomalous high regional heat flow. Characteristics of regionally averaged Pn velocities and geoid anomalies also preclude this possibility. The features are certainly not related to values reported in the database itself. Hence we conclude that these are artifacts arising from the widespread use of synthetic heat flow values in substitution of experimental data. Supporting evidence comes from a close examination of heat flow patterns for the continental areas, where the use of synthetic data was limited. In this case the differences are much less, mainly restricted to areas of Cenozoic tectonic activity.

## Conclusions

Modifications introduced in the current heat flow database have contributed to considerable flexibility in automatic processing of its contents. The error prone system used for geographic coordinates has been transformed into the decimal degree system. The reformatted database has been used in calculating mean heat flow values for a regular grid system of $5^0 \times 5^0$ area elements. These values were subsequently employed in calculating a new set of harmonic coefficients.

Global heat flow maps generated using the revised set of spherical harmonic coefficients has allowed identification of several new features in the overall heat flow pattern. Regional heat flow is found to be higher than 100mW/m$^2$ along the Nazca ridge, western USA, Red Sea and the Japan Sea. On the other hand, the central parts of the continental areas of Africa, Asia, North America, South America, Antarctic and Australia seem to be characterized by relatively low heat flow values (<60 mW/m$^2$).

Comparison with global heat flow patterns reported in earlier works indicate that there are substantial differences. The regions of major discrepancies are located in the southern hemisphere along the Nazca, South Atlantic and South Indian ridges. There are at present no independent evidences concerning the occurrence of anomalous thermal regimes on regional scales in such areas. Hence such differences are considered as numerical artifacts of data manipulation in earlier works, where widespread use has been made of synthetic heat flow in substitution of experimental values.

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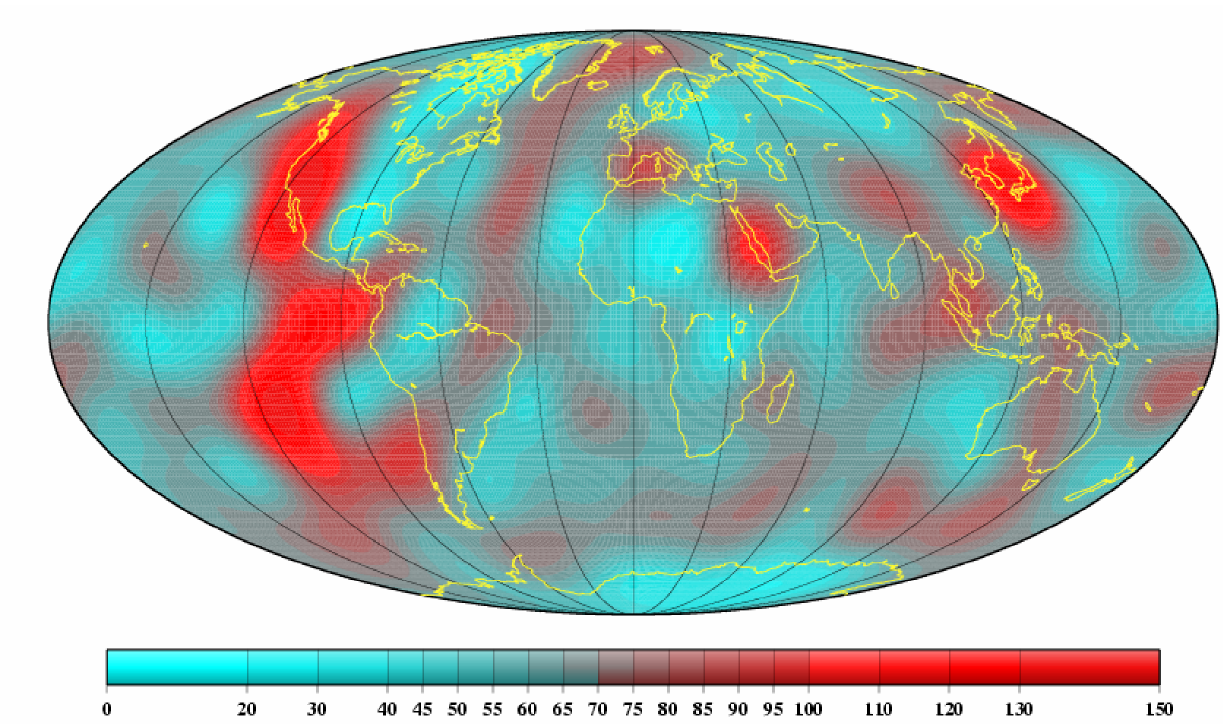

Figure (6) Spherical harmonic representation of the conductive component of global heat flow, calculated on the basis of the corrected database. Note that heat flow is <100 mW/m$^2$ in several segments of the global mid-ocean ridge system.

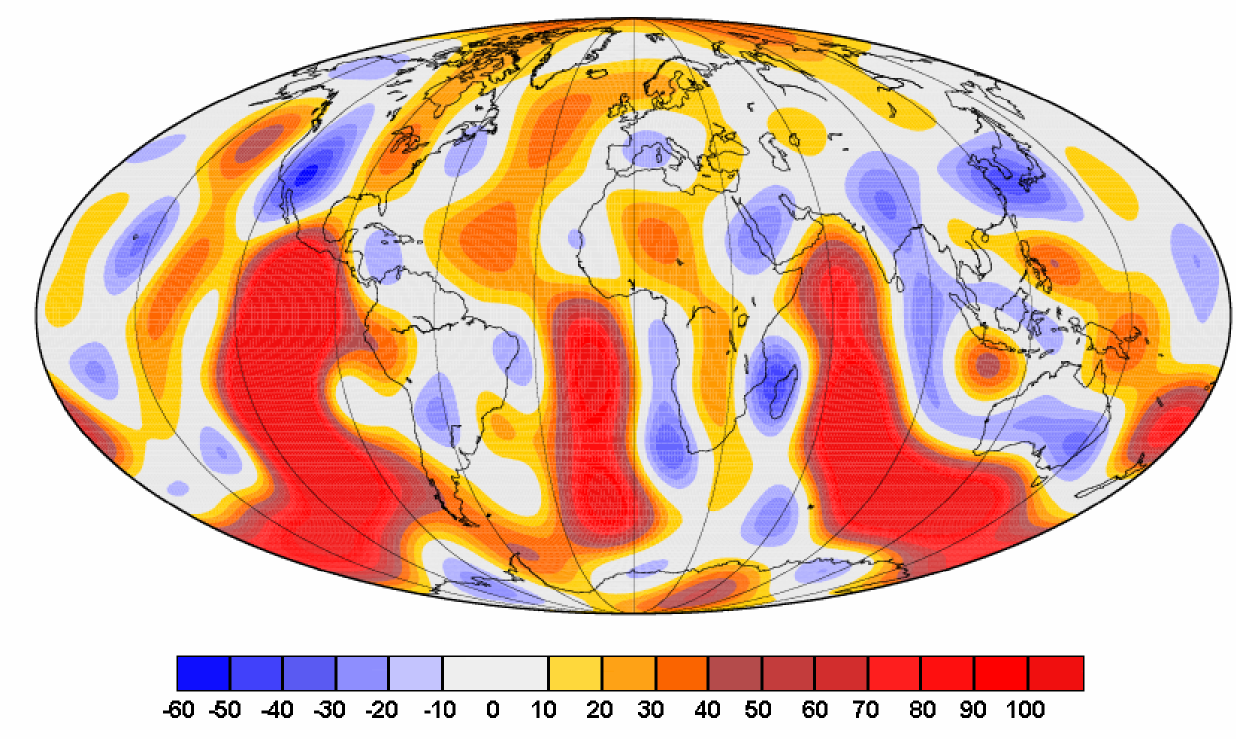

Figure (7) Differences in global heat flow patterns determined in the present work and those of the earlier work of Pollack et al (1993). Note that the major zones of discrepancies are located in the mid-ocean ridge areas. See text for details.