GLOBAL HEAT FLOW: COMPARATIVE ANALYSIS BASED ON EXPERIMENTAL DATA AND THEORETICAL VALUES.

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Abstract

Understanding the nature of large scale variations in the internal thermal field of Earth often require integrated use of both experimental and estimated values of terrestrial heat flow. In the present work we report progress obtained in blending such data sets for obtaining statistically meaningful representation of the geothermal field on regional and global scales. An experimental geothermal data set consisting of over 40000 heat flow values was employed for this purpose. The estimated values were derived on the basis of the well-known empirical relations between geologic age and heat flow. The age values were determined from tectonic maps of continental and oceanic regions, a task which required manipulation of geologic information on local and regional scales using GIS techniques. The results obtained have allowed comparative analysis of global maps of terrestrial heat flow derived from experimental data and theoretical values on a global scale.

Introduction

Problems arising from low data density and its inhomogeneous distribution are common in many areas of geophysics. The current knowledge of thermal state of the Earth depends to a large extent on results of measurement of heat flow in boreholes penetrating the near surface layers of the Earth. The problem however is that experimental data are available only for specific regions, there being large areas without any data at all. One of the ways of getting around this problem is to make use of empirical relations between heat flow and geological characteristics of the surface layers. Hamza (1967) proposed the existence of a possible correlation between heat flow and geologic age. Following this pioneering work Polyak and Smirnov (1968) and Hamza and Verma (1969) have pointed out the possibility of developing empirical relations between heat flow and tectonic age. In later works of Chapman and Pollack (1975) and Pollack et al (1993) this empirical relation was used in estimating heat flow values for areas for which experimental data were not available.

In the procedure adopted by Chapman and Pollack (1975) the heat flow estimates are derived on the basis of geological features identifiable in $5^0 \times 5^0$ cells. In the work of Pollack et al (1993) the procedure for referencing geology was based on a system of $1^0 \times 1^0$ equal longitude cells. Selection of dominant geology in each cell and estimation of number of cells was carried out manually and hence prone to perturbing effects of potential errors. Also, in cells with more than one geologic unit this procedure is also prone to errors in association of heat flow values with the corresponding geology unit.

In the present work we point out that such difficulties can easily be overcome with the use of modern techniques in handling geospatial data sets. Techniques developed in Geographic Information Science (GIS) are particularly suitable for derivation of digital geological and geophysical maps and in handling irregularly spaced data sets. Other major advantages of GIS techniques include matching heat flow measurements with geology polygons and estimating errors with appropriate weighting by area. In the following items we outline the methodology employed and present the results obtained in comparative analysis of maps on global scales.

Method

The method adopted in the present work is based on analysis of global geothermal data sets and estimated heat flow values derived from information available in tectonic maps. Brief descriptions of the procedures adopted are given in the following sections.

Observational Heat Flow Data

In the present case we have used an updated data set (designated HCV10) of surface heat flow. The revised data set subsumes information available in the original IHFC data base (corrected for obvious errors in coordinate locations), additional data sets reported in the recent study of Davies and Davies (2010) as well as updated heat flow values for the South American continent. The total number of updated data is over 40000. The geographic distribution of the updated data set is illustrated in the map of Figure (1).

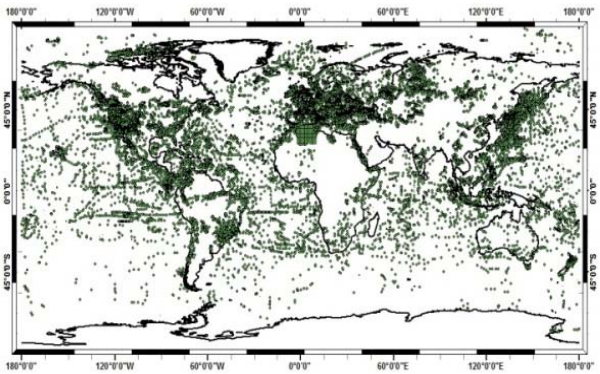

Figure (1) - Geographic distribution of updated heat flow data set.

A comparison of heat flow data of the recent compilations (see Table -1) points to significant improvements in both continental and oceanic heat flow measurements. However, significant parts of this data are not yet formally incorporated into the IHFC data base.

Table (1) List of heat flow data sets reported since 1990.

Description	N^0	Reference
1993 Data Set	20201	Pollack et al, 1993
1993 Data Set Corrected for errors	24141	Cardoso, 2006; Hamza et al, 2008
2010 Data Set	38374	Davies and Davies (2010)
2011 Data Set	43049	Vieira and Hamza (2010)

Estimates of heat flow for continental & oceanic areas

In the present work we follow essentially the same procedure as that employed by Chapman and Pollack (1975) and Pollack et al (1993) in deriving estimated heat flow values. However, unlike the practice of Pollack et al (1993) we have restricted the use of estimated heat flow values only for regions for which experimental data are not available. The estimated heat flow values are derived from the relations between heat flow and tectonic age in continental and oceanic regions. In the following item we outline the methodology employed and present the results obtained.

Use of GIS Techniques

Availability of digital thematic maps have opened up the possibility of assigning theoretical heat flow values, with appropriate weighting for the tectonic context, for regions for which observational data are not currently available. This however is not an easy task and demanded the use of modern techniques in handling geospatial data sets. Techniques developed in Geographic Information Science (GIS) are particularly suitable for elaboration of digital geological and geophysical maps and in handling irregularly spaced data sets. Other major advantages of GIS techniques include matching heat flow measurements with selected polygons and estimating errors with appropriate weighting by area.
The digital map chosen in the present work are reproduced in Figure (2) for the continental regions. The procedure adopted consists of imposing in these maps a system of 1^0 x 1^0 degree equal longitude grid, which consists of 64800 cells. Six categories of tectonic age were used in outlining the polygons. A set of 137 polygons was found sufficient in delimiting the tectonic age pattern. The area extent of these polygons is determined using GIS techniques and values of mean heat flow calculated for the corresponding area segments. A brief summary of the system of polygons and age categories used in outlining tectonic age patterns for continental areas is provided in Table (2).

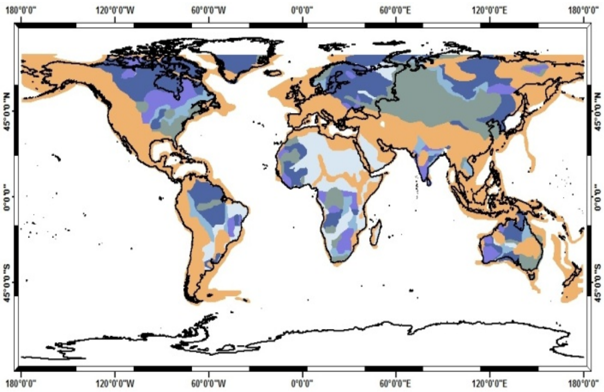

Figure -2. Digital map of tectonic age for continental areas.

Table (2) List of tectonic age polygons for continental areas.

Location	Num. of Polygonos toTectonic Age	
Africa	6	Archean
	4	Early Proterozoic
	3	Middle Proterozoic
	6	Late Proterozoic
	7	Paleozoic
	5	Meso and Cenozoic
Asia	7	Archean
	6	Early Proterozoic
	6	Middle Proterozoic
	3	Late Proterozoic
	5	Paleozoic
	6	Meso and Cenozoic
Europe	3	Archean
	2	Early Proterozoic
	1	Middle Proterozoic
	0	Late Proterozoic
	1	Paleozoic
	3	Meso and Cenozoic
Greenland	0	Archean
	2	Early Proterozoic
	0	Middle Proterozoic
	0	Late Proterozoic
	1	Paleozoic
	3	Meso and Cenozoic
North America	2	Archean
	4	Early Proterozoic
	3	Middle Proterozoic
	0	Late Proterozoic
	5	Paleozoic
	7	Meso and Cenozoic
South America	2	Archean
	4	Early Proterozoic
	2	Middle Proterozoic
	5	Late Proterozoic
	1	Paleozoic
	3	Meso and Cenozoic
Oceania	3	Archean
	3	Early Proterozoic
	2	Middle Proterozoic
	2	Late Proterozoic
	2	Paleozoic
	7	Meso and Cenozoic
TOTAL OF POLYGONS	137	

A similar procedure was used for assigning age values for oceanic regions. We chose for this purpose the map of digital isochrones of the ocean floor, reproduced in Figure (3). In this case however 15 categories of tectonic age were used in outlining the polygons. A set of 13 polygons was found sufficient in delimiting the tectonic age pattern. The area extent of these polygons is determined using GIS techniques and values of mean heat flow calculated for the corresponding area segments.

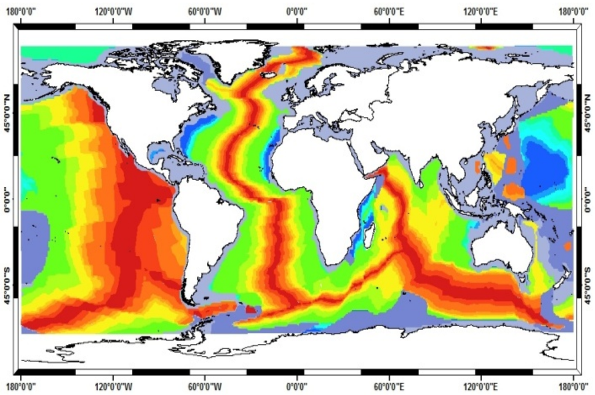

Figure -3. Digital map of isochrones for oceanic regions.

Characteristics of Empirical Relations

The data sets for continental and oceanic regions were fit to empirical relations, assuming inverse square root dependence between heat flow and age. An example of the results obtained under this procedure is illustrated in figure (4) for the continental area of Europe.

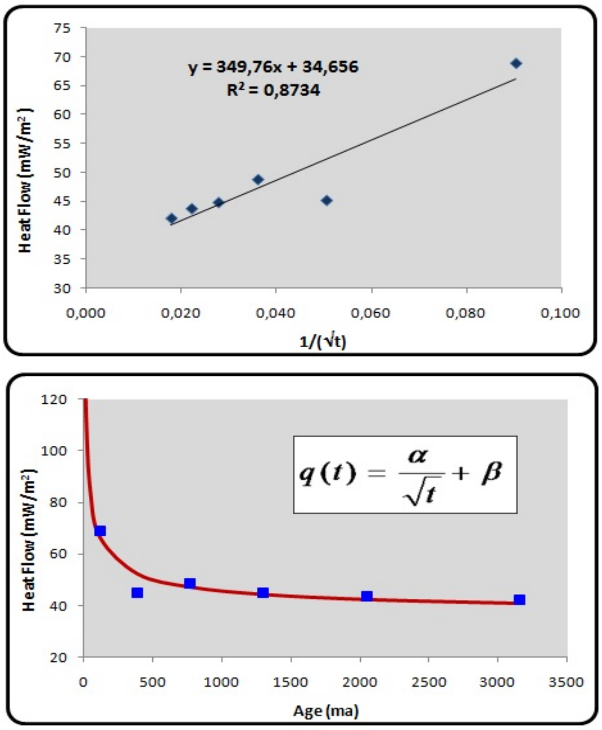

Figure 4 - Relation for estimating heat flow for Continent Europe

In the case of oceanic regions the estimated heat flow values were calculated on the basis of recent thermal models proposed by Hamza et al (2010) and Cardoso and Hamza (2011). These models assume that hydrothermal circulation take place only on local scales in young ocean crust. The stable oceanic crust is free of the effects convective heat transport in its sedimentary cover. An example of the results obtained under this procedure is illustrated in figure (5) for the oceanic regions. In the lower panel of this figure the blue curve indicates the variation of heat flow with age according to the VBA model of Hamza et al (2010) and FHS model of Cardoso and Hamza (2011). The dotted curve refers to the variation of heat flow according to the Half-Space Cooling model of Stein and Stein (1993).

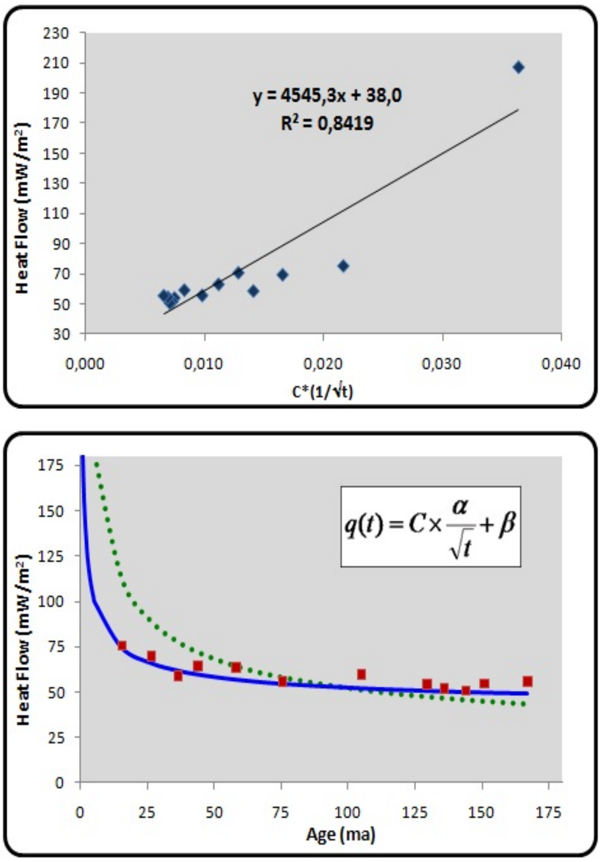

Figure 5 - Relation used in determining heat flow in oceanic regions.

The set of heat flow values derived from the tectonic age polygons provides the basis for setting up a mosaic of estimated heat flow pattern and a corresponding data base for the estimated heat flow values. In the present work we use the term "theoretical heat flow" to refer to such estimated values derived from empirical relations between heat flow and age. The GIS techniques were then used in calculating weighted mean values for a regular grid system with cell sizes varying from 1^0 to 5^0.

Theoretical Heat Flow Map

The availability of estimated values for the grid systems covering the entire continental and oceanic regions opened up the possibility of deriving global theoretical heat flow maps. As an illustrative example we present in Figure (6) the global theoretical heat flow map averaged over a grid system of 5^o x 5^o. The outstanding features discernible in this map are areas with heat flow in excess of 100mW/m^2 in the southern oceans (Southeast Pacific, South Atlantic and South Indian Ocean). Most of the ocean ridge systems and back-arc regions also stand out as areas with heat flow in excess of 80mW/m^2. On the other hand the central parts of the continental areas are characterized by heat flow lower than 50mW/m^2. The remaining sectors of continental areas and ocean basins are characterized by normal heat flow values in the range of 50 to 80mW/m^2.
Another important result is the relatively low values of heat flow for young ocean crust, when compared with the data base used by Pollack et al (1993). Thus the upper limit for grid averaged mean heat flow in ocean ridge areas is less than 150mW/m^2, a consequence of the use of VBA model of heat flow for the conductive cooling of the oceanic lithosphere (Hamza et al, 2010).

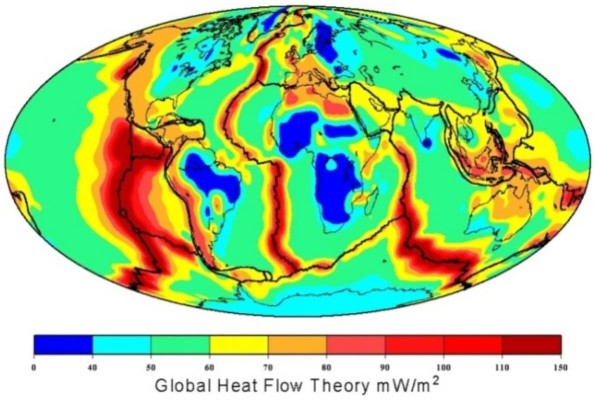

Figure (6) -Theoretical Heat Flow Map derived from digital geophysical maps and empirical heat flow – age relations.

Global Map Based on Integrated Data Base

The observational data set may be appended with the set of estimated heat flow values calculated for the continental and oceanic regions. At present 10031 grid elements have one or more observational data. The changes relative to the data set reported by Davies and Davies (2010) is restricted mainly to the improved data sets in the South American continent. In particular, there has been a significant improvement in the number of heat flow values in Colombia. Estimated heat flow values have been employed for the remaining 54769 grid elements.

The geographic distribution of this integrated data set (observational data and theoretical values) is illustrated in Figure (7). Here we have used a 5^0 x 5^0 grid system for representation of the data sets. In this figure the red color dots indicate grid cells with experimental data and the white color dots grid cells with theoretical heat flow values.

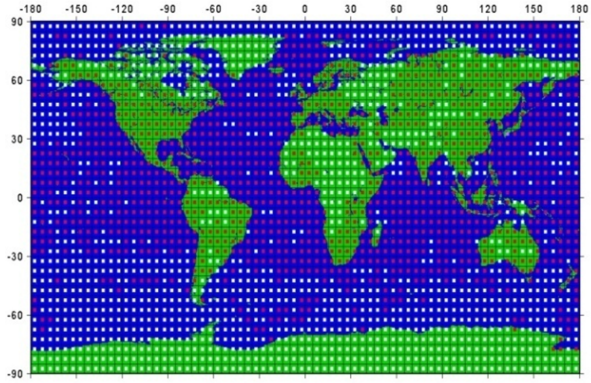

Figure (7) Map illustrating distribution of observational data and theoretical values forming the integrated data base for heat flow.

The global heat flow map based on the integrated data base is presented in Figure (8). The features discernible in this map bear considerable resemblances with those of the theoretical heat flow map of Figure (6), for oceanic regions. Prominent examples are areas with heat flow in excess of 100mW/m^2 in the southern oceans (Southeast Pacific, South Atlantic and South Indian Ocean). Most of the ocean ridge systems and back-arc regions also stand out as areas with heat flow in excess of 80mW/m^2. In continental areas however there are significant differences. Prominent examples are high heat flow areas in West Central Europe, Northwestern USA and Southeast Asia.
As in the case of Figure (6) the upper limit for heat flow in ocean ridge areas is less than 150mW/m^2, a consequence of the use of VBA model of heat flow for the conductive cooling of the oceanic lithosphere (Hamza et al, 2010).

Conclusions

New global heat flow maps have been derived on the basis of updated observational and theoretical data sets. Recent improvements in continental and oceanic data sets have contributed significant reductions in the number of grids without data. Use of GIS techniques has allowed considerable advances in assigning appropriate weighting factors and in calculating representative theoretical heat flow values in areas of complex geology. The results obtained have allowed comparative analysis of global maps of terrestrial heat flow derived from experimental data and theoretical values on global scales. Comparisons with results of previous works reveal that estimates of heat flow in young ocean crust need to be downsized by at least 30%. This observation also has similar implications for estimates of global heat loss.

Acknowledgments

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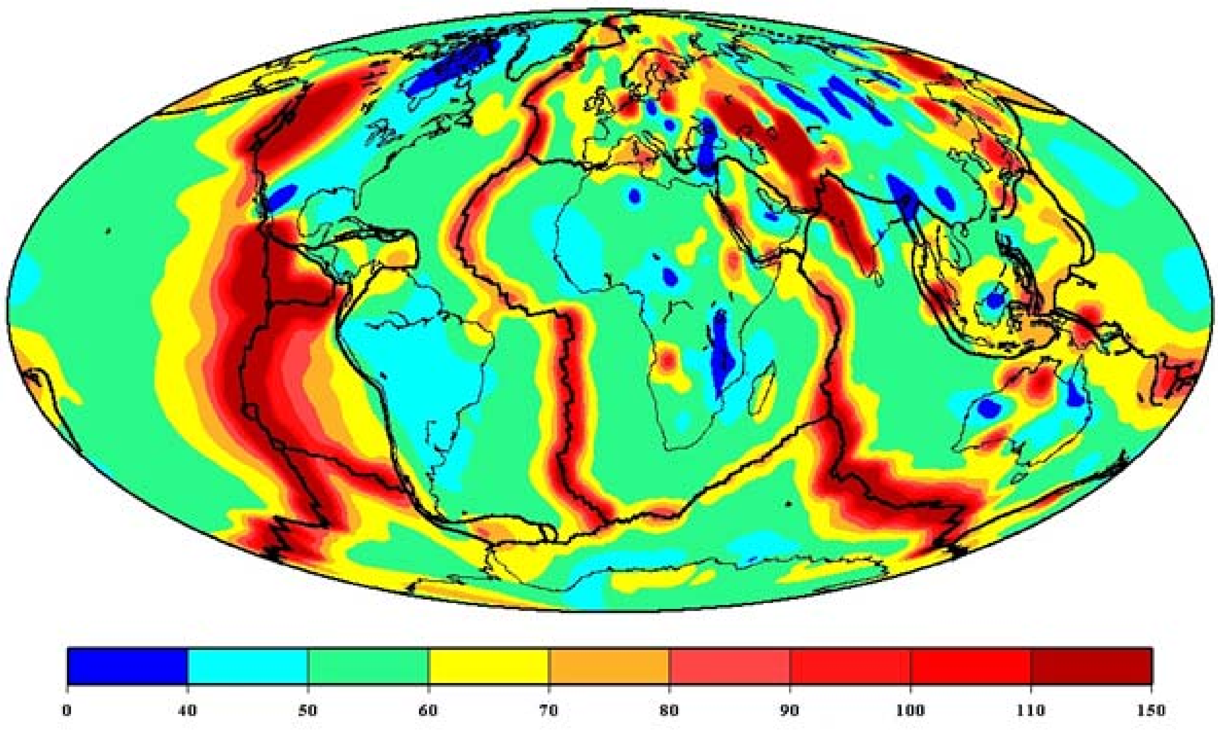

Figure 8 - Global Map of Heat Flow derived from experimental and theoretical data sets. The color bar indicates values of heat flow in units of mW/m^2.