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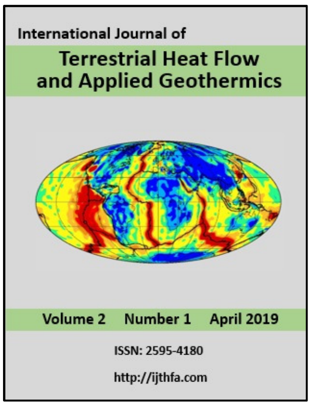

Terrestrial heat flow versus crustal thickness and topography – European continental study

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Abstract

The relation between heat flow, topography and Moho depth for recent maps of Europe is presented. Newest heat flow map of Europe is based on updated database of uncorrected heat flow values to which paleoclimatic correction is applied across the continental Europe (Majorowicz and Wybraniec 2010). Correction is depth dependent due to a diffusive thermal transfer of the surface temperature forcing, of which glacial–interglacial history has the largest impact. This explains some very low uncorrected heat flow values of 20–30 mW/m^2 in shallow boreholes in the shields, shallow basin areas of the cratons, and in other areas including orogenic belts where heat flow was likely underestimated due to small depth of the temperature logs. New integrated map of the European Moho depth (Grad et al 2009) is the first high resolution digital map for European plate, which is understood as an area from Ural Mountains in the east to mid-Atlantic ridge in the west, and Mediterranean Sea in the south to Spitsbergen and Barents Sea in Arctic, in the north. For correlation we used the following: onshore heat flow density data with palaeoclimatic correction (5318 locations), topography map (30x30 arc seconds, by Danielson and Gesch 2011) and Moho map by Grad et al (2009), providing longitude, latitude and Moho depth (with resolution of 0.1 degree). Analysis was limited to locations for which datasets were available. The area of continental Europe has been divided into two large domains: Precambrian East European craton and Palaeozoic Platform of the West Europe. In addition, two smaller areas were considered, corresponding to Scandinavian Caledonides and Anatolia. The results obtained reveal significantly different correlations between Moho depth, elevation and heat flow for these regions. For each region detailed analysis of these relations in different elevation ranges are presented. In general, it is observed that Moho depth is more significant for heat flow than elevation. Depending on the region and elevation range, heat flow value is up to two times larger than Moho depth, while relation of heat flow to elevation has much more variability.

1. Introduction

Statistical relationships between heat flow and Moho depth has been reported in the past for regional cases (Cermak 1993, Majorowicz 1978). It was questioned recently by Jaupart et al (2016) who presented a scatter plot of heat flux and crustal thickness for the global data set comparing heat flux (averaged over 1°×1° cells) versus crustal thickness (derived from CRUST1.0 model). The best linear fit to the cloud of points showed very low correlation coefficient (r) of –0.24. On the other hand, such relationship was theoretically predicted to exist by Bodri and Bodri (1985) for the general case and by Hyndman and Lewis (1999), who included elevation into the equation. It was confirmed in a study of the Canadian Cordilleran region by Majorowicz and Osadetz (2008; their Fig. 6). Also, results of a study of the Polish Lowland, illustrated in Figure 1, agree with the general theoretical relationships of Bodri and Bodri (1985) and Hyndman and Lewis (1999).

This figure illustrates the relation between heat flow, crustal thickness and elevation (Bodri and Bodri 1985; Hyndman and Lewis 1999) for thermal isostasy. Simple model confirms equilibrium between heat flow (Majorowicz and Wybraniec 2010) and crustal thickness on several deep seismic sounding profiles of the POLONAISE'97 and CELEBRATION 2000 (Grad et al 2009) experiments (low heat flow—thick crust of the Polish part of the Precambrian craton and high-heat flow—thin crust of the adjacent accreted terranes of western Poland).

Such agreement between theoretical and observational data was also shown for the Polish Lowland by Majorowicz et al (2008). The relation between heat flow, crustal thickness and elevation for thermal isostasy case of equilibrium between low heat flow—thick crust and high-heat flow—thin crust of the areas was observed in the Polish Lowland (Majorowicz et al 2008). Later studies based on new crustal thickness map of Europe (Grad et al. 2009, 2016) and new heat flow map (with correction for paleo climate effects) of Europe (Majorowicz and Wybraniec 2010), in combination with the topographic map of the continent, allowed study of the statistical strength of the correlation between these parameters. In the present work, we examine the relation between heat flow, topography and Moho depth for updated maps of Europe for the recent European data base.

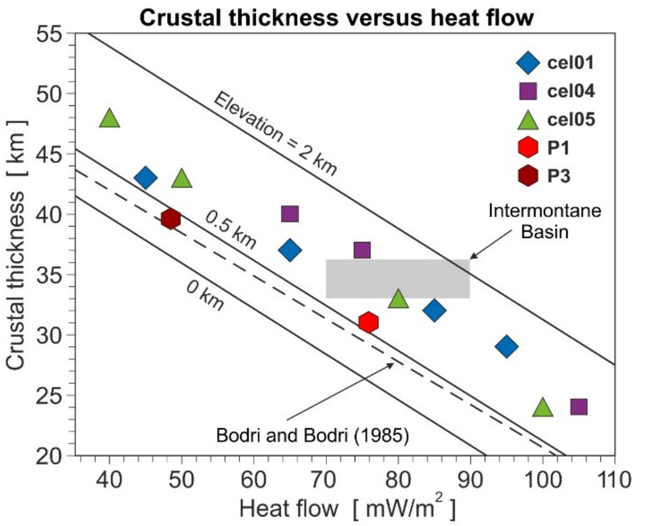

Figure 1 - The relation between heat flow, crustal thickness and elevation (Bodri and Bodri 1985; Hyndman and Lewis 1999) for thermal isostasy. Simple model confirms equilibrium between heat flow (Majorowicz and Wybraniec 2010) and crustal thickness on several deep seismic sounding profiles of the POLONAISE'97 and CELEBRATION 2000 (Grad et al 2009) experiments (low heat flow—thick crust of the Polish part of the Precambrian craton and high-heat flow—thin crust of the adjacent accreted terranes of western Poland).

2. Tectonic setting of the study area

The complex tectonic history of Europe reflects the break-up of Neoproterozoic supercontinent Rodinia/Pannotia (Dalziel 1997) to form the fragment of Baltica and the subsequent growth of continental Europe, beginning with the Caledonian orogeny. Caledonian and younger Variscan orogenesis involved accretion of Laurentian and Gondwanan terranes to the rifted margin of Baltica during the Paleozoic (Pharaoh 1999). The suite of sutures and terranes that formed the so called Trans-European suture zone (TESZ), adjacent to the rifted SW margin of Baltica. The TESZ is far more complex than a single suture, but in a broad sense, it is the boundary between the accreted Phanerozoic terranes and Proterozoic Baltica. Understanding its structure and evolution is one of the key tectonic challenges in Europe and is certainly of global importance to studies in terrane tectonics and continental evolution. The younger Alps, Carpathian Mountains arc and Pannonian back-arc basin in the south form interrelated components of the Mediterranean arc-basin complex and are the result of intricate Mesozoic/Cenozoic plate interactions in the Mediterranean region as the Tethys Ocean closed during convergence of crustal segments of Europe and Afro-Arabia. All tectonic processes and geological structures mentioned above have left their imprint in the Moho map. It is also evident in the oldest Archean and Proterozoic crust of thickness 40-60 km, continental Variscan and Alpine crust of thickness 25-35 km, and the youngest oceanic crust of Atlantic of thickness 10-20 km (Grad et al 2009).

3. Data sets and maps of heat flow, Moho and topography

We are looking into three data sets: a) paleoclimate corrected heat flow, b) Moho depth for the newest European data base and c) topography. We have mapped these using scaled colour circles. The circles in the maps are 50 km in diameter. In case of overlapping cirles values are averaged.

a) *Corrected heat flow*

New heat flow map of Europe (Figure 2) is based on updated database of uncorrected heat flow values to which paleoclimatic correction has been applied across the continental Europe (Majorowicz and Wybraniec 2010). Correction is depth dependent due to a diffusive thermal transfer of the surface temperature forcing, of which glacial–interglacial history has the largest impact. This explains some very low uncorrected heat flow values 20–30 mW/m^2 in the shields, in shallow basin areas of the cratons, and in other areas including orogenic belts, where heat flow was likely underestimated.

The most recent high amplitude surface temperature change from Pleistocene glacial period to Holocene is the largest influence upon observed variations of heat flow with depth, arising from the diffusive nature of the process. Surface temperature changes of similar amplitude that occurred during earlier glacial interglacial periods are of lesser influence (Majorowicz et al 2008). The northern and central area of Europe was covered by ice sheet during the last glacial maximum (LGM), 25–15 ka ago. Thus, cold climate was present there and in surrounding areas to the south.

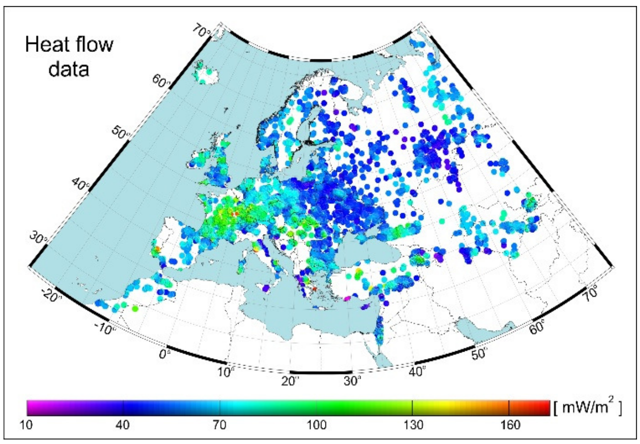

Figure 2 - The heat flow corrected for paleoclimate using Majorowicz and Wybraniec (2010) approach map. Circles on all maps are 50 km in diameter. In case of overlapping cirlesaverage values were employed.

Synthetic heat flow transient profiles were calculated in accounting for response to glacial cycles with glacial–interglacial surface temperature amplitude 7ºC–14ºC range, for a homogeneous model with diffusivity $10^{-6}m^2s^{-1}$. The paleoclimatic correction for the above amplitude of change, as proposed by Demezhko et al (2006), has been calculated for the above forcing. The results range as a depth dependent heat flow correction (Majorowicz and Wybraniec 2010). This correction has been applied to thousands of reported uncorrected heat flow values in the IHFC (International Heat Flow Commission) data base and also to additional new data reported in recent years for Poland, Germany and Spain. Such corrections are high for shallow wells and low for deep wells (with depths >2km). This procedure has allowed to bring all data to the same reference level. The correction method resulted in relatively higher heat flow values for the East European Craton. The previous heat flow values were underestimated due to many cases, based on measurements in shallow wells of few hundred meters deep. As can be seen in Fgure 2 the correction is significant, with values >10mW/m^2.

The statistical distribution is slightly skewed towards high heat flow (see Figure 3). The average heat flow (HF) value for the continental Europe is 70.6 mW/m^2 and has a rather large standard deviation (SD) of 32.7 mW/m^2. This characterises large variability of HF values, with low values (in the range of 30-50mW/m^2) in the shields where transfer of heat is conductive, to high values (usually >100mW/m^2) in volcanic areas where component of convective transport of heat can be very significant. Water movement in sedimentary basins and mountaneous terraines, where aquifers with varying hydraulic head and faults can also disturb entirely conductive heat transport.

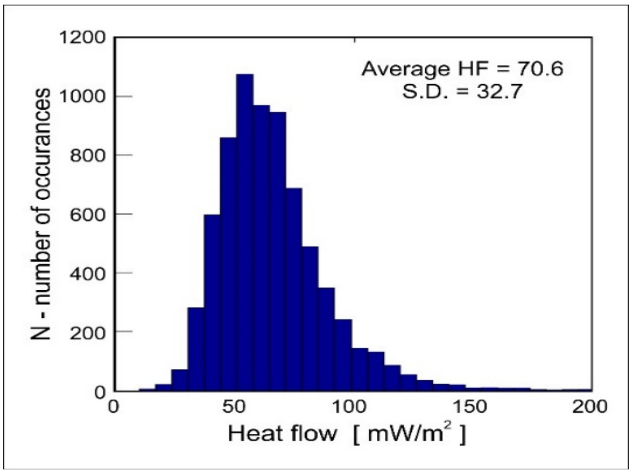

Figure 3 - The histogram of heat flow values (N - nummber of measurements vs HF - heat flow value), employed in deriving map of Figure 2.

b) ***Moho depth***

New integrated data of the European Moho depth for the map constructed by Grad et al (2009) allowed high resolution map for European plate area, extending from Ural Mountains in the east to mid-Atlantic ridge in the west, and Mediterranean Sea in the south to Spitsbergen and Barents Sea in Arctic in the north. The new digital Moho depth map was compiled from more than 250 data sets of individual seismic profiles, 3D models obtained by body and surface waves, receiver function results, and maps of seismic and/or gravity data compilations (Grad et al. 2009). Maps derived from these data sets point to three large domains within European plate crust, as can be seen in the map of Figure 4. The oldest Archean and Proterozoic crust has thickness 40-60 km, continental Variscan and Alpine crust has thickness 20-40 km, and the youngest oceanic Atlantic crust has thickness 10-20 km..

c) ***Elevation***

Digital model of elevation above sea level gives additional information about total thickness of continental crust. High resolution Digital Elevation Model topography map derived for a network of cells with 30 x 30 arc seconds (Danielson and Gesch, 2011) was used to calculate elevation at localities where heat flow was measured. The results are illustrated in Figure 5.

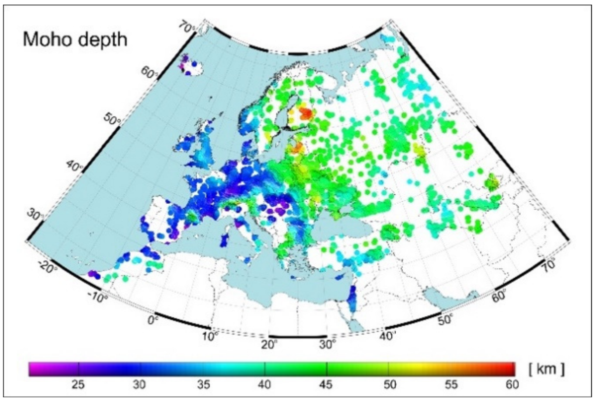

Figure 4 - TheMoho depth map (in km) of the European plate at areas where all three datasets have data.

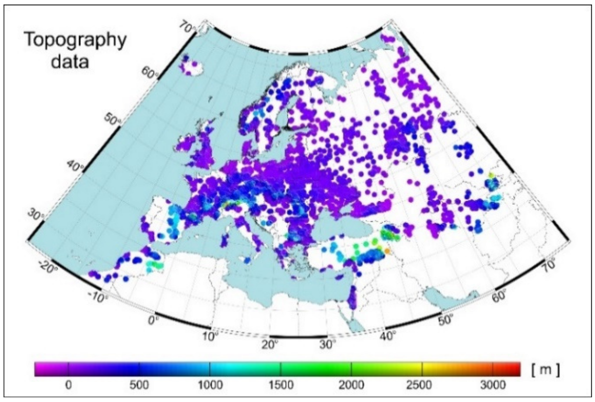

Figure 5 - Map illustrating values of elevation in meters [m] above (or below) sea level, for areas with observational data. Values of elevation were obtained by SRTM setelitte.

4. Calculations and Results

For analysis of relations between heat flow, Moho depth and topography we calculated the factor (M+H)/HF, where M is Moho depth in km, H elevation in km and HF heat flow in mW/m^2. As the topography H is small compared with Moho depth M, practically the resulting value is close to ratio M/HF. We decided not to search for correlations where HF is > 160 mW/m^2, as such values are representative only of volcanic areas. Maps derived from analysis of results of the calculated ratio (M+H)/HF (Figure 6) reveals that crustal structure of European continental plate is composed of at least four distinct domains.

In searching for functional relations between heat flow, Moho depth and topography we examined several sets of values for coefficients 'a' and 'b' that minimize the sum of squares of difference (SSD) in the relation:

$$(a * M + b * H) - HF \quad (1)$$

Note that ideal correlation occurs when the difference has null value. Analysis of maps of calculated coefficients show that European continental plate is composed of at least four domains, with distinctly different values. These are areas related to Precambrian East European craton (A), Paleozoic Platform (B), Scandinavian Caledonides (C), and Anatolia (D). Approximate boundaries of such domains are indicated by black lines in Figure 7.

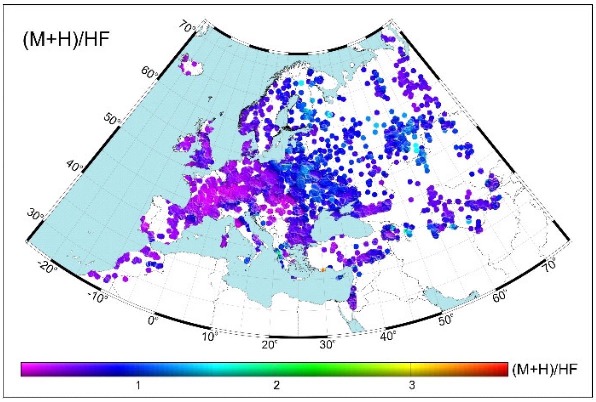

Figure 6 – Map derived from results of the calculated ratio (M+H)/HF, pointing to the possibility that crustal structure of Europe is composed of four domains.

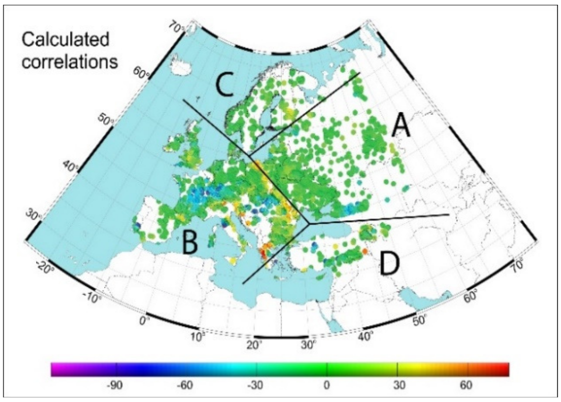

Figure 7 - Map illustrating distribution of calculated correlations for the relation a·M+b·H-HF. It highlights four age groups of the continental crust. These are:A - thickest and oldest crust of Archean and Proterozoic Baltica; B - the continental crust of Variscan and Alpine Europe; C - Scandinavian Caledonides; D - Anatolia.

For each of these areas, the nature of correlation of heat flow in relation to Moho depth and elevation above sea level was examined. The purpose has been to map the domain of minimum values of the relation between the coefficients '*a*' and '*b*' in relation (1). The results are illustrated in Figure 8 for each of the areas A, B, C and D. Minimum values of calculated coefficients of '*a'* and '*b'* are respectively 1.35 and -28.23 for area A, 2.28 and -3.00 for area B, 1.64 and -11.01 for area C and 1.18 and 21.02 for area D (Polkowski et al 2013).

5. Discussion

Quality of correlation was checked for all four analyzed areas. Consider for example the case of Precambrian Platform (A). Figure 9 shows histogram of values for correlation quality check for this area, the extension of which is illustrated in Figure 7. Extension of this analysis reveals that expected correlation exists for many regions and especially for areas A and C with values quasi symmetrical around 0. Significantly negative values are found in the area of Massif Central, southern Molasse basin and southern Rhine Graben in Germany, in and around Pannonian Basin and also in the southern part of area A. These are areas with high to elevated heat flow and with normal to low depths to Moho.

Positive values much greater than zero were observed along the border and just west of it and partly aligned with Teisseyre–Tornquist zone (see Grad et al 2016) in Poland and Western Ukraine. It is a region with low heat flow and large crustal thickness.

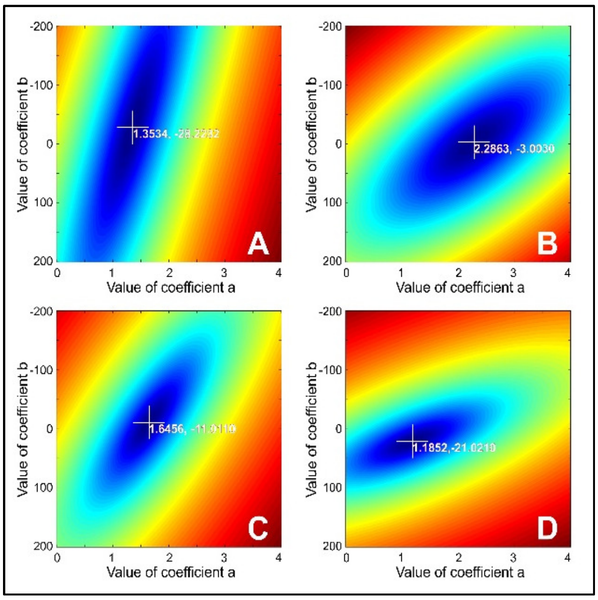

Figure 8 – The domains of minimum values in the relation between the coefficients 'a' and 'b', for the areas A, B, C and D.

It is obvious that the correlation is far from ideal but in general it is symmetrical around 0 (ideal correlation) in many areas. Correlating values of heat flow and Moho depth from several geological areas like in Figure 1 (here high heat flow with low Moho depth in the Paleozoic platform and low heat flow with high Moho depth) shows significant statistical relationship. However, it may be biased by differences in radiogenic crustal heat production in both areas of different geological history. It seems that thicker crust of the cratons is characterized by low upper crustal heat production than the younger and thinner crust of the Paleozoic platform (Majorowicz et al 2019). Therefore, thinner crust – higher heat flow, thicker crust lower heat flow leads to negative HF *vs* Moho depth correlation seen in Figure 1.

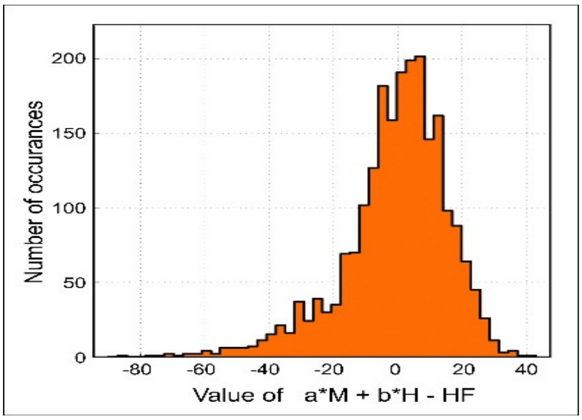

Figure 9 – Histogram of values of minimized for the relation a·M+b·H-HF, where 0 is for ideal correlation for all measurements in given area.

6. Acknowledgment

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