

Heat Flow in Iceland

Árni Hjartarson (ÍSOR)

Iceland GeoSurvey-, Grensasvegur 9, 108 Reykjavik, Iceland

ah@isor.is

Keywords: Heat flow, geothermal gradient, thermal conductivity, Iceland

ABSTRACT

A heat flow map of Iceland has newly been created. It is based on measurements in over 1000 wells and in several places on estimates and calculations where convection flow and hydrothermal circulation disturbs the regional convective heat flow. The heat flow map of Iceland indicates generally high values with rather large variations ranging from less than 40 to over 300 mW/m². The highest values generally border or are located inside the volcanic zones. In Borgarfjörður and Breiðafjörður regions in western Iceland is a prominent area with high heat flow that is probably related to the volcanic flank zone of Snæfellsnes. The lowest heat flow is found in the areas farthest away from the volcanic belts in east and west Iceland. The average heat flow for all of Iceland, according to the map, is approximately 175 mW/m².

1. INTRODUCTION

Heat flow from the interior of the Earth derives in uncertain proportions from the decay of radio-active elements (primarily uranium, thorium, and potassium) and primordial energy of planetary accretion and solidification of the Earth's core (Pollack et al., 1993).

The main modes of heat transfer in the crust to the surface are convection and conduction. In mapping regional heat flow, an important goal is to separate out near surface processes, such as groundwater flow and hydrothermal circulation, from the deeper heat flow from the Earth's interior.

Knowledge on the spatial variation in geothermal gradient and heat flow is of direct importance for the growing geothermal investigation and harnessing worldwide. It is also important for oil and gas exploration because temperature controls in large part the transformation of organic matter to oil and gas in a sedimentary basin. Additionally, temperature measurements and heat flow calculations are important calibration data for basin modelling of the burial, maturation and hydrocarbon generation history of source rocks in sedimentary basins.

Heat loss by conduction through the lithosphere is larger over the oceans than over the continents because the oceanic lithosphere is much thinner and younger than continental lithosphere. Average global surface heat flow ranges between 87-91 mW/m² where the mean heat flow over the continents is 65-71 mW/m² and the mean heat flow over the oceans is 100-105 mW/m² (Pollack et al., 1993; Davies and Davies, 2010), (Table 1). Heat flow is expected to be high in areas where thermal energy is transported toward the crust by mantle convection such as along mid-ocean ridges and mantle plumes.

The quality of the heat flow data varies depending on the method of calculation or measurement. In many cases worldwide the heat flow calculation is based on a single bottom hole temperature measurement. In other cases it is based on an exclusive temperature log along with many measurements of the thermal conductivity. The latter is always the case in Iceland (Fig. 1).

Heat flow data is often corrected for paleoclimatic changes. The effects of Pleistocene ice ages, which lasted for several hundred thousand years, can in some cases extend to depths of several kilometres and last for thousands of years after the end of the glaciation (Slagstad et al. 2009; Majorowicz and Wybraniec 2010). Here no such corrections have been made. The high heat flow in Iceland is suggested to have wiped out most of the paleoclimatic signature.

Table 1: The global heat flow and the heat flow in Iceland.

Domain	Heat flow mW/m ²	Ref.
Average global surface heat flow	87-91	Pollack et al. 1993; Davies and Davies, 2010
The continental crust	65 -71	Davies and Davies, 2010
The oceanic crust is	100-105	Davies and Davies, 2010
Continental Europe	63	Majorowicz and Wybraniec 2010
Iceland	175	This work

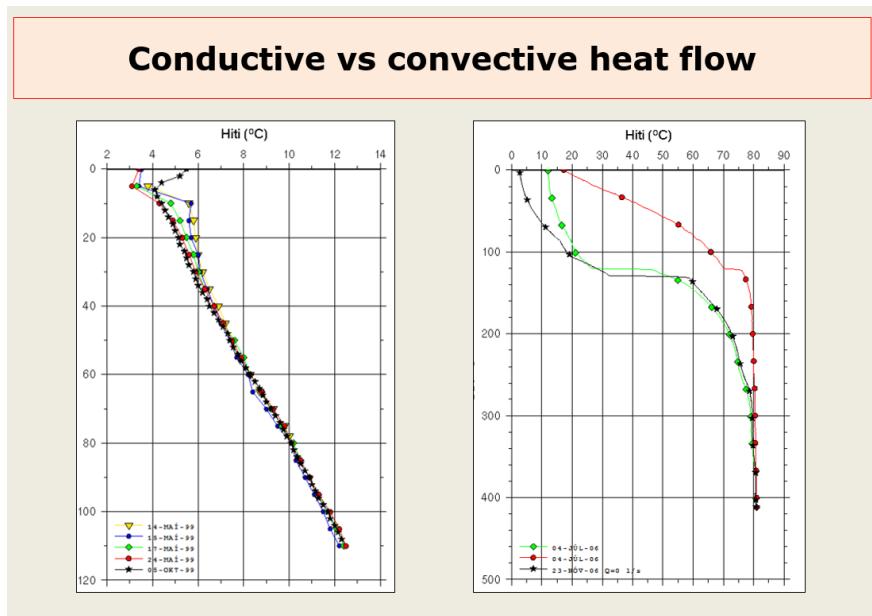


Figure 1: Conductive and convective geothermal gradient in two boreholes in Iceland. Regular geothermal gradient in the well SEY-12 Seyðisfjörður, E-Iceland, indicates conductive heat flow (to the left). Irregular gradient in the well HO-42, NW-Iceland, indicates a convective heat flow and a geothermal groundwater circulation below 100 m depth.

2. HEAT FLOW IN ICELAND

A heat flow map of Iceland has newly been created (Hjartarson et al. 2014). It is based on measurements in wells and in several places inside the volcanic zones on estimates about the thermal output of the high temperature areas. (Fig. 2 and 3). Thousands of wells have been drilled where the majority of wells are in the range of 50-1000 m but the deepest ones over 3000 m. Most are located inside and around the various geothermal areas where convective groundwater flow influence the thermal measurements. However, many wells have been drilled outside these areas in order to map the regional temperature gradient for drinking water utilisation and for other purposes. Rather few boreholes are located in the Central Highlands. Around 1000 wells have been used to construct the heat flow map of Iceland. In most occurrences the temperature gradient obtained from the shallow wells is supposed to continue with depth with minor deviations. In many cases, however, groundwater circulation and geothermal convection disturb the regular gradient. In these cases some corrections and estimates have been made while deriving the geothermal gradient.

The data indicate large variations in heat flow ranging from less than 40 to over 300 mW/m² and sometimes even up to 500 mW/m². The extreme values could sometimes be attributed to convective groundwater flow near the surface. High heat flow and regular gradient in the uppermost several hundred meters is sometimes explained by a convective geothermal system deeper down than shallow wells in the area can reveal. The distribution of the heat flow is therefore skewed towards higher values because in many cases the data points cluster around geothermal sites.

3. HEAT FLOW IN THE VOLCANIC ZONES AND THE HIGH TEMPERATURE AREAS

The volcanic rift zones are characterized by highly porous and unaltered lava and hyaloclastite formations in the uppermost 0.5-1.0 km and are cut by numerous faults and open fractures. Therefore the geothermal gradient within the active rift zones is wiped out by intense groundwater convection. Often, no gradients or only very low temperature gradients can be detected in the uppermost 0.5-1.0 km, but below these depths high gradients are observed. Exceptions exist inside the high temperature areas where boiling hot springs and geysers are located. These are only found inside the volcanic rift zones. There, the temperature is typically more than 200°C at 1 km depth. This is at least partly due to magmatic activity at high levels in the upper crust. In most cases, deep wells (1-3 km) only indicate extensive geothermal convection flow inside the high temperature areas. Where direct measurements are lacking inside the volcanic zones of central Iceland, indirect estimates have been used to define the heat flow. The total natural thermal output from the high temperature areas has been estimated to be around 9000 MW (Pálmarson, 2005). If this is assumed to be the only output for the whole volcanic rift zone, which covers an area of 32000 km², the average heat flow is 280 mW/m². This is a minimum and in reality the heat flow is likely to be higher, or over 300 mW/m².

4. THERMAL CONDUCTIVITY

Very little thermal conductivity data are available for Icelandic rocks. That might sound strange in a country that relies so much on thermal energy. The fact is that in geothermal utilisation the geothermal gradient is more interesting than the exact heat flow and information about the convective flow of the heat is much more valuable than about the conductive flow. Oxburgh and Agrell, (1982) have reported a few direct measurements from E-Iceland. In addition there exist around 150 single laboratory measurements of the thermal conductivity of air-dry Icelandic basalt, giving the average value of 1.7 W/m°C (Pálmarson et al. 1979). Florenz and Sæmundsson (1991) studied the effect of the porosity on the near surface thermal conductivity in different regions of Iceland in order to calculate heat flow and found conductivity variations between 1.6-1.9 W/m°C. Their method has been used here for defining the thermal conductivity for the diverse regions of the country. The thermal conductivity for the young and porous volcanic rocks is 1.6 W/m°C, for the intermediate aged rocks 1.7-1.8 W/m°C and 1.9 W/m°C for the oldest and densest volcanic rocks.

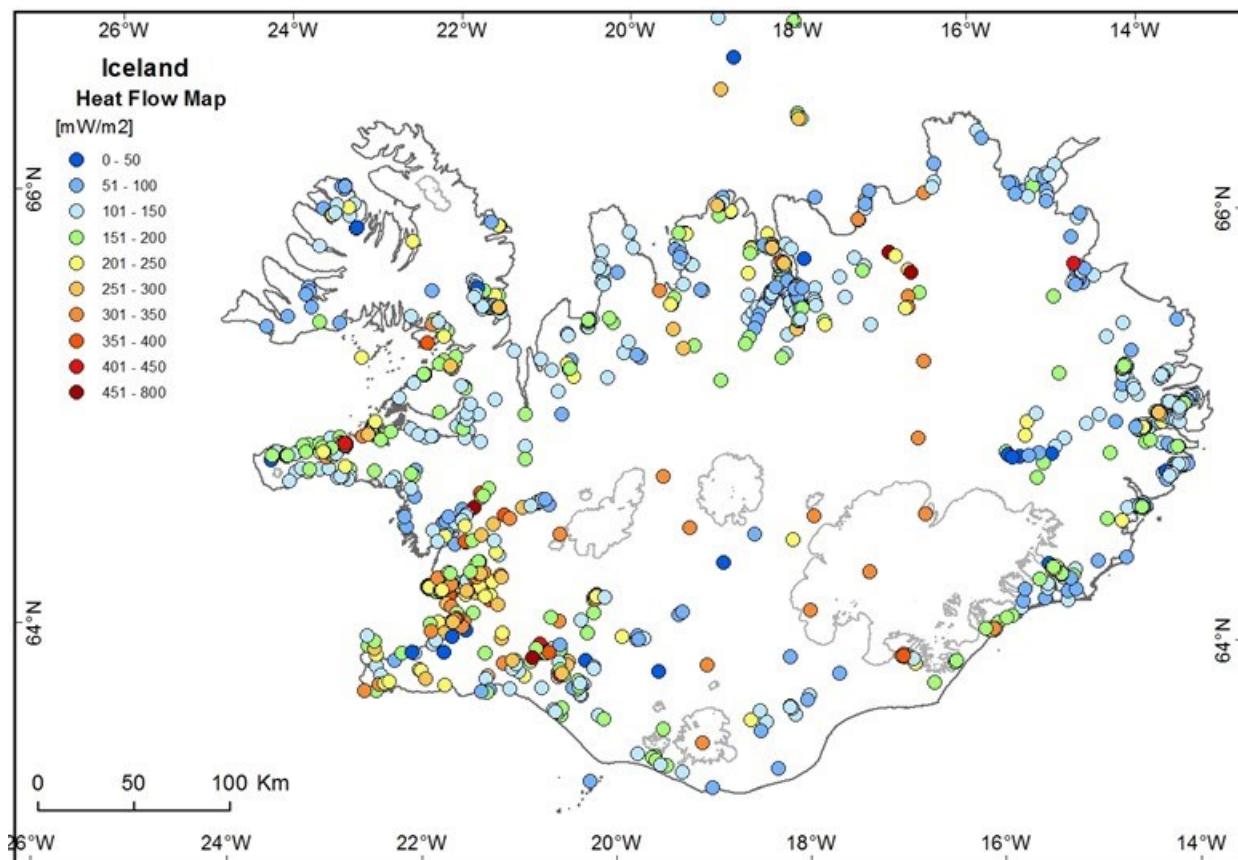


Figure 2: Distribution of heat flow data points in Iceland. The colors indicate the heat flow value.

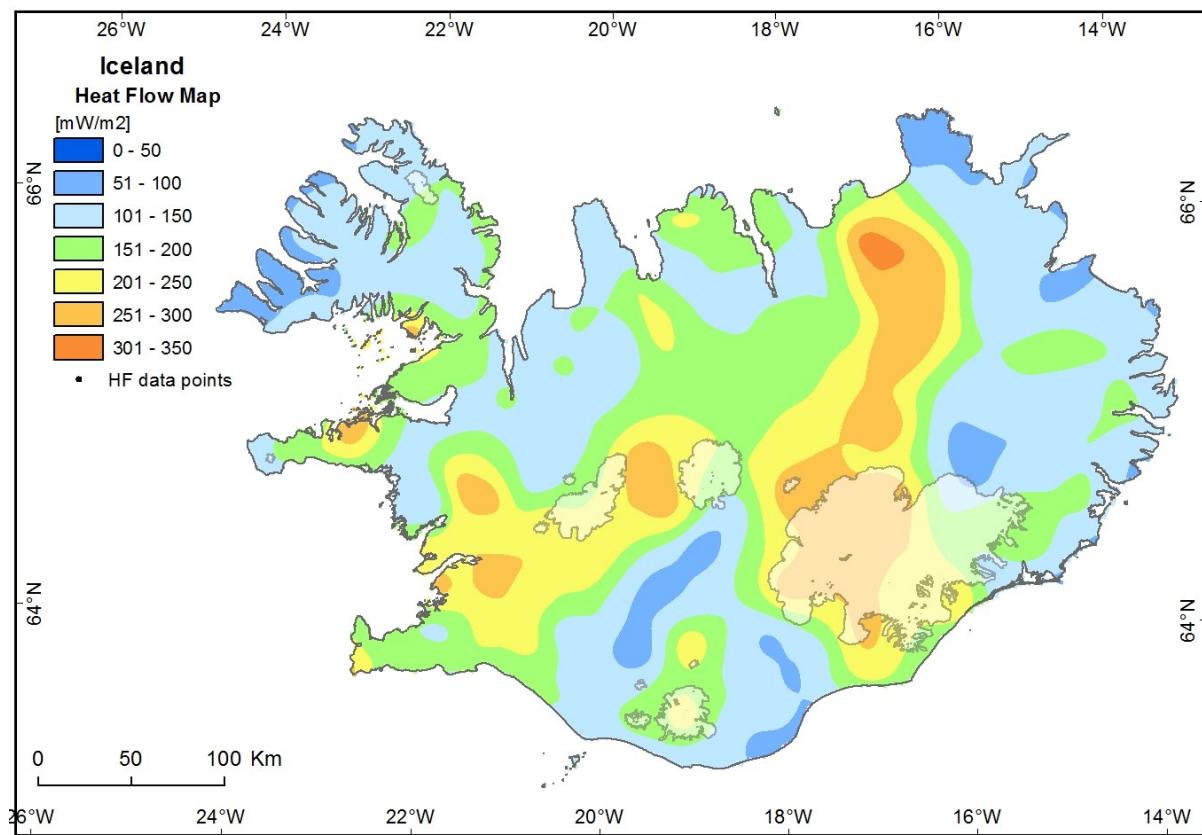


Figure 3: Data driven heat flow map of Iceland. The high heat flow (> 200 mW/m²) reflects roughly the volcanic zones.

5. CONCLUSION

The heat flow map of Iceland generally indicates high values with rather large variations ranging from less than 40 to over 300 mW/m² (Fig. 3). The highest values generally border or are located inside the volcanic zones. In Borgarfjörður and Breiðafjörður regions in western Iceland is a prominent area with high heat flow that is probably related to the volcanic flank zone of Snæfellsnes. The lowest heat flow is found in the areas farthest away from the volcanic belts. The average heat flow for all of Iceland, according to the map, is approximately 175 mW/m².

REFERENCES

Davies, J. H., & Davies, D. R.: Earth's surface heat flux. *Solid Earth*, **1**, (2010), 5-24..

Flóvenz, Ó.G. and Sæmundsson, K. 1991.: *Iceland*. In: Hurtig et al. (ed.), *Geothermal Atlas of Europe*, pp. 48-51.

Flóvenz, Ó.G. and Sæmundsson, K.: Heat flow and geothermal processes in Iceland. *Tectonophysics* **225**, (1993), 123-138

Hjartarson, Á., Verweij H., Fattah, R.A. and Boxem, T.: Heat flow. In: Hopper, J.R., Funck, T., Stoker, M., Árting, U., Peron-Pinvidic, G., Doornenbal, H. and Gaina, C. (ed.). *Tectonostratigraphic Atlas of the North-East Atlantic Region*, 215-222

Majorowicz, J. and Wybraniec, S.: New terrestrial heat flow map of Europe after regional paleoclimatic correction application. *International Journal of Earth Sciences*, (2010) DOI: 10.1007/s00531-010-0526-1.

Oxburgh, E.R. and Agrell, S.O. Thermal Conductivity and Temperature Structure of the Reyðarfjörður Borehole. *JGR* **87**, (1982), 6423-6428.

Pálmarson, G.: Jarðhitabók. Eðli og nýting auðlindar. Hið íslenska bókmenntafélag, Reykjavík, (2005), 298 pp.

Pálmarson, G., Arnórsson, S., Friðleifsson, I.B., Kristmannsdóttir, H., Saemundsson, K., Stefánsson, V., Steingrímsson, B., Tómasson, J. and Kristjánsson, L.: The Iceland Crust: Evidence from Drillhole Data on Structure and Processes. In: Deep Drilling Results in the Atlantic Ocean: Continental Margins and Paleoenvironment. AGU, Maurice Ewing Ser. vol. **3**, (1979), 43-65.

Pollack, H. N., Hurter, S.J. and Johnson, J.R.: Heat flow from the Earth's interior: Analysis of the global data set, *Rev. Geophys.*, **31**, (1993), 267–280, doi:10.1029/93RG01249.

Slagstad, T., Balling, B., Elvebøll, H., Midttømme, K., Olesen, O., Olsen, L. and Pascal, C.: Heat-flow measurements in Late Palaeoproterozoic to Permian geological provinces in south and central Norway and new heat-flow map of Fennoscandia and the Norwegian-Greenland Sea. *Tectonophysics* **473**, (2009), 341-361.