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Highly varying radiogenic heat production in Finland, Fennoscandian Shield

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Keywords: heat production; radiometric; uranium; thorium; heat flow; Precambrian

Highlights:

- Radiogenic heat production was mapped using Finnish lithogeochemical data
- Data were available from 6465 rock outcrops, mostly from the Fennoscandian Shield
- Data were averaged spatially using regular grid and actual geological units
- Heat production appeared to be highly variable and largest in granitoid areas
- Heat production and heat flow have weak positive correlation

Abstract

Radiogenic heat production in Finland has been previously studied using airborne gamma-ray surveys and glacial till measurements alike. For the first time, this paper presents a detailed survey on the spatial variation in radiogenic heat production determined using outcrop samples obtained from all

important lithologies of the country. The dataset of 6465 samples represents mostly Mesoarchean (about 2.7 Ga), Paleoproterozoic (ca. 2.2-1.8 Ga) and Mesoproterozoic (ca. 1.6-1.3 Ga) rocks. Nearly all data are from Precambrian Fennoscandian shield area, but heat production appears to be highly variable, and above global Archean and Proterozoic averages. Spot readings show an arithmetic average of $1.34 \pm 1.19 \mu\text{Wm}^{-3}$, and a range from 0.02 to $19.4 \mu\text{Wm}^{-3}$. The interpolated areal average of the whole area is $1.42 \pm 1.41 \mu\text{Wm}^{-3}$. The high standard deviation of data is related to the geochemical characteristics of uranium (U), thorium (Th) and potassium (K) resulting in a skewed distribution of heat production. Mesoproterozoic anorogenic rapakivi granites, and late Paleoproterozoic Svecofennian granitoids show the highest heat production values in the range of 3-5 μWm^{-3} . The results show no distinct dependencies of heat production with geological age, metamorphic grade nor seismic P-wave velocity, but an increasing trend of heat production with SiO_2 content and decreasing trends of heat production with Fe_2O_3 content and with rock density are evident. Surface heat flow (44 borehole data values) correlates weakly with heat production ($r = 0.35$). The general heterogeneity of heat production calls for supporting information from other geophysical methods for better understanding of the thermal state of the lithosphere in Finland and beyond.

1. Introduction

Radiogenic heat production from the decay series of long-lived radioactive isotopes is one of the major heat sources of the planet. Surface heat flow values determined in deep boreholes are essentially affected by the radiogenic heat generated in the crust as well as heat transported from deeper levels of the Earth. Today, heat production is mostly due to the decay series of the isotopes ^{238}U , ^{235}U and ^{232}Th and the single-step decay of ^{40}K , while other long-lived isotopes (e.g. ^{87}Rb and ^{147}Sm) are irrelevant in terms of heat production and can be ignored (Rybach, 1973).

The observation of the relationship between the surface heat flow and near-surface heat production in the late 1960s led to the concept of heat flow provinces (Birch et al., 1968; Roy et al., 1968; Lachenbruch, 1970). They were thereafter reported in various regions of the world, the Fennoscandian shield included (e.g., Buntebarth, 1984; Morgan and Sass, 1984; Pinet and Jaupart, 1987; Kukkonen, 1989a,b). Each heat flow province was characterized by a linear relationship between surface heat flow and heat production. The slope of the line was considered to represent the thickness of the heat producing layer, whereas the intercept on the heat flow axis was considered to represent the heat flow from below the layer. Despite being a correct interpretation in a 1-dimensional earth, the concept of heat flow provinces was considered inadequate in a crust with 3-dimensional spatially varying distributions of heat production and thermal conductivity already in the 1980s (Jaupart, 1983; Fountain et al., 1987; Furlong and Chapman, 1987; Nielsen, 1987). Forward modeling of heat transfer in a crust with 3-dimensional heterogeneous heat production and conductivity structures suggests a positive correlation with heat flow and heat production (Furlong and Chapman, 1987; Nielsen, 1987), but the parameters of the linear relationship do not provide useful data on the crustal thermal or geological structure. Therefore, the empirically documented linear-like relationships are mostly expressions of conductive redistribution of heat in complex crustal structures, and often results from too few data points. It is evident that much more detailed information than simple regression lines is needed on the crustal composition, structures and thermal properties to be able to solve the thermal regime of the crust and lithosphere. Interest towards comprehensive studies of this kind has been also driven by needs of Finnish energy industry, as geothermal heat extracted from Fennoscandian basement has been planned to replace fossil fuels as a source of district heating in Espoo, Helsinki metropolitan area (Leary et al. 2017).

The concentrations of U, Th and K are results of the geochemical behavior of the elements during the geological evolution of the respective unit. U and Th are incompatible trace elements with strongly skewed, typically log-normal, concentration histograms. Therefore, their abundances are not strongly related to the content of major rock constituents that are generally used in the discrimination between geologic units (Jaupart and Mareschal, 2003). U and Th have large ionic radii, and do not easily fit in the crystal frameworks of typical silicate minerals. They are typically present in accessory minerals (e.g. zircon, monazite, apatite, sphene). U and Th concentrate in melts, and the upward transport and emplacement of melts results in a vertical differentiation of heat production in the crust. The differentiation is one of the main factors contributing to the thermal stability of the continental lithosphere. Under oxidizing conditions, U is relatively easily mobilized, whereas Th is more conservative. The geochemical characteristics of K are somewhat different, and its concentration histogram is not log-normal. In crustal rocks it is typically a major component and present in most of the major rock-forming minerals (Sandiford et al. 2002; McLaren and Powell, 2014).

Due to the differentiation of U, Th and K in partial melting processes, heat production increases in plutonic rocks with the trend ultramafic-mafic-intermediate-felsic, and the contrast between ultramafic rocks in the mantle and upper crustal granitoids can be 2-3 orders of magnitude. In sedimentary rocks heat production is variable and typically reflects the sediment provenance as well as various sorting and lithification processes. In metamorphic rocks an increasing trend with increasing metamorphic grade from greenschist to granulite facies (Rybach, 1988) has been recently questioned (Hasterok et al., 2017). These trends are, however, generalizations and in specific cases considerable variation is observed, reflecting the origin and geochemical evolution of the rocks. For instance, the variation between heat production values in different types of granitoids can be about 10-fold (Kukkonen and Lahtinen, 2001; Kukkonen et al., 2008; Kukkonen and Lauri, 2009), and granulite facies rocks may show variations by a factor of about five (Jöeleht and Kukkonen, 1998).

Thus, a lithological type or metamorphic grade alone is not a generally reliable estimator of heat production despite locally observed local contrasts between heat production of cratons and adjacent metamorphic rocks (McLaren et al. 1999; Kumar et al. 2007). In particular, advective heat transfer has been used explain unusual thermal conditions in low-pressure granulite terrains (Kühn et al. 2004; Guidotti, 2000) although the absence of abundant granitoids in the proximity of these areas has been used to defend the hypothesis of conductive heat transfer (Sandiford and Hand, 1998).

In Finland, nearly entirely a part of the Precambrian Fennoscandian Shield, a long tradition exists in studying heat flow and radiogenic heat production (Puranen et al., 1968; Järvimäki, 1968; Järvimäki and Puranen, 1979; Kukkonen, 1993; Kukkonen and Lahtinen, 2001; Kukkonen et al., 2011). The first comprehensive survey of heat production in Finland was based on geochemistry of glacial basal till samples (Kukkonen, 1989a). In a previously glaciated area with very few bedrock outcrops, basal till, which is a mechanical disintegration product of the glacier eroding the bedrock surface, provides a practical sampling medium because till is present practically everywhere. The glacial processes have mixed the till material, and the till sample represents also its surroundings. Till is also often recycled material from several glacial periods. The glacial and postglacial history, transport distance, direction, applied grain size fraction, and subsequent hydrogeochemical evolution affect the representativeness of the sample (Koljonen, 1992; Lintinen, 1995). Nevertheless, glacial till is widely applied as a sampling medium in mineral deposit exploration in Finland (Koljonen, 1992; Salminen and Tarvainen, 1995; Taivalkoski et al., 2015).

The glacial till data applied in Kukkonen (1989a) comprised U-Th-K analyses of 1054 composite till samples (Koljonen, 1992), each representing about 300 km². Rock densities were adapted from a country-wide assessment of average bedrock densities in about 4800 km² map sheets (Puranen et al.,

1978). The database provided results on areal variation in heat production, and distinct contrasts between major geological units were seen. Heat flow values from 35 boreholes were correlated with the data, and heat flow-heat production relationships were studied using both glacial till and drill core heat production data. As similar geochemical till samplings had been carried out in northern Sweden and Norway, Kukkonen (1993) combined the data with the Finnish dataset (total of 1483 composite samples). It was also possible to use the regression line between heat production and heat flow to transform the heat production map to an estimate of heat flow in the study area.

An extensive sampling and analysis program in Finland was carried out by the Geological Survey of Finland in the 1990s (Rasilainen et al., 2007, 2008). A total of 6544 samples from bedrock outcrops were collected with a mini-drill and the samples were extensively analyzed for chemical compositions and petrophysical properties. The samples were also characterized for the lithology, age, and other geological parameters. Kukkonen and Lahtinen (2001) carried out a detailed analysis of a subset (1150 samples) of this dataset covering an E-W oriented band (120 km x 500 km) between latitudes 62° and 63° N. The study provided representative averages of heat production rate in the studied tectonic units, but also indicated that there is considerable heterogeneity and spatial variation in radiogenic heat production rates of the Precambrian lithosphere. Well-defined systematic variations of heat production rate values with either SiO₂ content, density or P-wave velocity were not found. The correlations appeared weak and scattered, and sometimes opposite with sign in the major rock groups (plutonic, metavolcanic and metasedimentary). The dataset in Kukkonen and Lahtinen (2001) is a subset of the database used in our present study.

In the present work, we study the radiogenic heat production of the bedrock surface in Finland using the extensive dataset of Rasilainen et al., (2007, 2008). As the samples represent directly the bedrock surface, we avoid the complications of earlier studies (Kukkonen, 1989a, 1993) using glacial till data.

The present dataset comprises 6544 samples and covers about 330,000 km², i.e. about one third of the area of the Fennoscandian Shield. The study area represents lithological units ranging in age from the Neoarchean basement to Paleoproterozoic mobile belts, and Mesoproterozoic granite intrusions. Previously published comprehensive national heat production data compilations are rare but include, for example, those of Australia (McLaren et al. 2003) and Norway (Slagstad, 2008).

2. Heat production data

The heat production values in this paper are based on the version 1.1 of the rock geochemical database of Finland, gathered by the Geological Survey of Finland (Rasilainen et al., 2007; 2008). The structure of this publicly available database has undergone no major changes after publication, although some small mismatches between the tabulated data and the manual of the database (Rasilainen et al. 2007) have been corrected. These include e.g. the replacement of FeO concentration by Fe₂O₃ concentration in the tabulated data. For the numerous applications of the database, the reader is referred to Rasilainen et al., (2008). The part of data used in this study is referred to as heat production data file (heatprod.dat) and follows the structure described in Table 1.

For calculation of heat production (A) [μWm^{-3}], we used the well-known equation of Rybach (1973):

$$A = \rho (9.52C_U + 2.56 C_{Th} + 3.48 C_K) \cdot 10^{-5} \quad (1)$$

where ρ is the rock density [kg/m^3] and C_U , C_{Th} and C_K are concentrations of U [ppm], Th [ppm] and K [%]. Density values applied were the actual rock densities measured in laboratory using weighing in air and water on the mini-drill cores gathered from the bedrock. As seen in the ternary plot (Figure 1), uranium and thorium are the main constituents in heat production, and potassium only plays a small role. The methods of chemical analysis have been reported in detail by Rasilainen et al., (2007), but in general, U and Th concentrations were determined using Inductively Coupled Plasma Mass Spectrometry (ICP-MS). The calculated K concentration was based on the measurement of potassium monoxide (K_2O) by X-ray fluorescence spectrometry (XRF).

The statistical variation of heat production parameters in our raw outcrop data is shown in Table 2. No data below the lowest reliable concentration (LRC) were taken into account. For U, this threshold was 0.08 ppm and for Th 0.13 ppm (Rasilainen et al., 2007). The number of outcrops where concentration was at the threshold was 234 in the case of U and 129 in the case of Th, if the precision of 0.01 ppm was used. Concentrations of K in typical Finnish rocks are typically larger, and the applied LRC in our study was 0.003%.

3. Heat production maps

Sampling locations in our heat production data file were expressed as rectangular coordinates in the Finnish Uniform Coordinate System (YKJ), yet differences between YKJ and EUREF-FIN coordinates are a few meters at most. Where necessary, we applied geographic EUREF-FIN coordinates (latitude and longitude). Heat production was then solved from Equation 1 and plotted in Figure 2. The ratio of thorium and uranium concentrations (Th/U) was also solved and plotted in Figure 3. As noted by Kukkonen and Lahtinen (2001) in central Finland, heat production can vary

over an order of magnitude in distances not more than a few kilometers. Therefore, it is imperative to average and possibly also interpolate data to get a generalized view of heat production and its constituents.

Although unprojected geographic coordinates are convenient in visualizing point data, they do not preserve area. This is not a problem as long as only point data are being handled. However, calculation of statistical parameters from data binned in regular latitude-longitude grid results in a biased situation where the areas closer to geographic poles are overrepresented (Veikkolainen et al., 2014). Therefore, we decided to calculate area-averaged statistics and to produce interpolated contour plots of heat production and its constituents using a regular grid on rectangular coordinates. In addition, we use original point data to investigate the possible relations between heat production and other parameters (P-wave velocity, rock density, silica concentration, ferric oxide concentration, etc.) with the aid of scatter plots. We also visualize metamorphic grade using box-and-whisker plots, and discuss its implications on heat production and Th/U ratio.

To reduce the effect on inhomogeneous sampling, we applied interpolation with a multiquadric radial basis function (RBF) in Scientific Python (SciPy), defined as follows (Hardy and Gofert, 1975):

$$\kappa(r) = \sqrt{1 + \varepsilon r^2} \quad (2)$$

where $\kappa(r)$ is a kernel function, $r=||x-x_i||$ is the Euclidian distance between points x and x_i and ε is an adjustable parameter which defaults to the approximate average distance between input nodes. A RBF does not require data to be presented in a form of a grid but suits unstructured data as well, making it

a good choice for interpolation of typically scattered geological data. The output of the function, however, is often represented in grid to allow convenient calculation of statistical parameters within the area of interest. In our interpolation, the input node coordinates were X (easting) and Y (northing) values from the heat production data file. The range of output coordinates was from 3075000 to 3745000 in X and from 6635000 to 7785000 in Y. The interval between cells in the output data grid was 10000 and therefore the total number of cells was 7888. Depending on what kind of RBF is applied, various undesirable boundary effects can arise (Fornberg et al., 2002). These may include physically impossible values in the output, e.g. negative heat production in a case where points with very small positive values are located close to an area with no data at all.

The appearance of the interpolated map in SciPy heavily depends on the smoothing parameter S , which scales the standard deviation of input data. If it is set to zero, the values at interpolation function at locations of the original data do not differ from values of the original data. Greater values result in a surface with less undulation, and larger differences between model and observations. Having tested various values of S , we ended up using $S=2$ in the production of maps as a viable compromise between the damping of heavily fluctuating high amplitude signal and the disappearance of bedrock features which would be detrimental to geological interpretation. The choice of interpolation method is always a compromise and depends on the quality of data to be interpolated. For example, magnetic maps are typically shown with great detail, but heat flow maps are more or less smoothed (e.g. Tao and Shen, 2008; Jaupart et al., 2014) because heat flow (as a diffusion signal) typically does not change abruptly at geological boundaries. To allow a meaningful spatial comparison between heat production and heat flow, we decided to interpolate both quantities in the same way.

For masking out grid cells outside our area of interest and for estimating how boundary effects affect our final estimate of heat production parameters, two criteria were applied separately. The loose criterion meant that all cells with at least one data point, and also nine surrounding cells were taken into account but other cells were left out before the calculation of statistical parameters (mean, median and standard deviation of ρ , C_U , C_{Th} , C_K and A) in our rectangular coordinate grid. This criterion ensured that the entire Finland was covered, but results in inclusion of some cells on the Baltic Sea and the neighboring countries as well. The total area covered by the 3997 cells was 399700 km², compared to the Finnish land area of 338400 km². The strict criterion was equivalent to dismissing all grid cells without any data points. This left us with an area of 3221 cells, 321100 km². Therefore it was evident that some spatial gaps remained also within Finnish borders. Using the loose and strict masking criteria separately, the mean, median and standard deviation for parameters were calculated in Table 3.

Using loose masking criteria, we produced five individual contour plots (Figures 4, 5, 6, 7 and 8) to illustrate the spatial variation of heat production parameters throughout Finland. To ease comparison with actual measurements (Figure 2), we also plotted locations of sampling sites. Because the masking criteria had little influence on the variation of parameters (Table 3), no separate maps representing strict masking criteria were produced. We also tested the influence of various smoothing parameters on the values of A , applying loose masking criteria only. These results are described in Table 4, yet no further maps were generated.

4. Heat flow – heat production relationships

The relation of heat flow and heat production is often described using Q-A plots:

$$Q = q_0 + DA \quad (3)$$

where Q is surface heat flow [mWm^{-2}], A is radiogenic heat production [μWm^{-3}] in the layer with the depth D [km], and q_0 is heat flow from deeper sources [mWm^{-2}], also referred to as reduced heat flow (Birch et al., 1968). Obviously q_0 and D are purely mathematical quantities and do not represent any physical boundary in the crust. Therefore, an important component of our study was to test if Q - A plots have any validity at all, even in a so-called heat flow province. For our Q - A relations, we obtained heat flow values from previous studies (Table 5) and determined heat production in corresponding locations on our interpolated map (Figure 9). Unlike Kukkonen (1993), we based our conclusions on paleoclimatically corrected rather than apparent uncorrected heat flow values, because the paleoclimatic effect is the major source of deviation from the steady-state thermal state in Fennoscandia (Kukkonen and Jöeleht, 2003). As a result of the glaciation-deglaciation cycle, raw heat flow values are typically lower than corrected ones, yet the estimated local dynamics of the past glacier result in large variations (Näslund et al., 2005).

Our study shows a Q - A relation of $Q = 33.79 + 5.919A$ in the case where heat flow data are corrected for paleoclimate, and $Q = 29.39 + 5.677A$ (Figure 10, Table 4) in the case where no correction has been made. Correlation coefficient was $r=0.35$ in the case of corrected, and $r=0.34$ in the case of uncorrected data. The number of heat flow determinations available was 44, compared to the number of 32 in the study of Kukkonen (1993) which also included data from northern Sweden. The Q - A relation of Kukkonen (1993) was $15.8 + 10.8A$, $r=0.61$, and no paleoclimatic corrections were applied to the data. In the analysis of Kukkonen and Lahtinen (2001), which was limited to a part of central Finland, the Q - A relation appeared $35.1 + 3.0A$, $r=0.76$ in the case of raw drill core data, and $31.7 +$

8.0A, $r=0.57$ in the situation where heat production averages within 10 km radius from drilling sites were applied. Averaging therefore greatly affected the shape of a Q-A plot in their study, and only the mean Q and A remained fairly similar. Unfortunately, the raw glacial till heat production database of Kukkonen (1993) was unavailable so we could not apply spatial interpolation methods to till data in the same way as we applied them to our outcrop data. Therefore quantitative spatial comparison of heat flow estimated from two different methods and datasets was not possible. However, it appeared that two points with high heat production in the rapakivi area (Elimäki and Loviisa; Kukkonen, 1989b) greatly affected the slope of our plot, and the influence of smoothing parameter was very important. Large values of S resulted in Q-A plots with smaller q_0 and a steeper slope, but the mean heat flow remained within 0.2 mWm^{-2} within the range of tested S values (Table 4). Although Q-A plots have certain potential in estimating mean heat flow, their shape is greatly affected by the way heat production data are handled. Therefore Q-A plots obtained from different studies cannot be compared without addressing a multitude of caveats.

5. Regional variation in heat production

An inspection of heat production results reveals notable regional differences in line with the general geology of Finland as a part of Fennoscandian Shield (Figure 11, e.g. Korsman et al., 1997; Rasilainen et al., 2008). In particular, the Subjotnian 1.67-1.62 Ga Wiborg and the 1.59-1.54 Ga Åland, Laitila and Vehmaa anorogenic rapakivi batholiths, and, remarkably, older granitoids of Lapland feature high heat production mainly associated with high U and Th content, and low rock density, below 2700 kg/m^3 . The largest part of southern Finland belongs to the Svecofennian domain, where bedrock is a complex assemblage of granitoids, migmatites and schists, and therefore has highly heterogeneous heat production rates. The highest values are found in late-orogenic granites in southern and southwestern Finland in western Uusimaa and the area of the Turku archipelago, in parts

of the late Svecofennian Granite–Migmatite zone (LSGM). North of these areas, variation is more subdued within the synorogenic 1.88-1.78 Ga Central Finland Granitoid complex (Rämö et al., 2001). Further to the north, Paleo- and Mesoproterozoic rocks are juxtaposed with the Archean basement.

The 2.13-1.76 Ga Central Lapland granitoid complex (e.g. Ahtonen et al., 2007; Lauri, 2013) features low bedrock density ($\rho < 2700 \text{ kg/m}^3$) and high heat production ($A > 2 \text{ } \mu\text{Wm}^{-3}$). To the south, the volcano-sedimentary 2.44-1.92 Ga Peräpohja schist belt (Ranta et al., 2015) has very low heat production rates in the range similar to that of Archean Karelian craton in the eastern Finland and some Svecofennian schist belts. The Central Lapland greenstone belt (Saverikko, 1987) is not much different in its thermal properties when compared to Peräpohja schists. The highest spot reading of heat production ($19.4 \text{ } \mu\text{Wm}^{-3}$) occurs in the 1.79-1.77 Ga Nattanen granite (Heilimo et al., 2009), as a result of high Th content. The Vainospää intrusion, located northeast of Lake Inari, is also of the Nattanen-type and owes much to its high heat production, ca. $3 \text{ } \mu\text{Wm}^{-3}$, to thorium, and has a thickness of ca. 6 km (Elo et al., 1989). Its age is also close to that of postorogenic granites in southern Finland, ca. 1.80-1.77 Ga (Heilimo et al., 2009).

Typically rocks with extremely high heat production ($A > 5 \text{ } \mu\text{Wm}^{-3}$) are granites with no metamorphic overprint, and their heat is mainly produced by the decay of U. However, U can be replaced by Th in the crystal lattices when high-temperature metamorphism occurs, resulting in decreased heat production rates (Hyvönen et al., 2005). Therefore the relation of metamorphic grade to heat production and Th/U ratio are important factors, not only because whole rock Th/U ratio has been found to have positive correlation with SiO_2 content (Kirkland et al., 2015).

In our raw data, the Th/U ratio varies between 0.02 and 253.77, with highest values in metamorphosed granitoids of northern Finland. On the other hand, lowest values occur in unmetamorphosed granites, yet not in rapakivi units but in Svecofennian complexes. There is no systematic dependence of heat production on metamorphic grade (Figure 12, Table 6) although a two-sample Kolmogorov-Smirnov test indicates that all ten possible comparison pairs are statistically distinct with 1% confidence level (Appendix A). The low heat production of greenschist facies rocks is notable, yet the number of data points is small (N=343) compared to that of amphibolite facies (N=2466) and unmetamorphosed (N=1496) rocks. Only 223 rocks represent granulite facies. For 1937 outcrops, the metamorphic grade is undetermined, but these represent mostly granitoids. A comparison of metamorphic grade and Th/U ratio (Figure 13, Table 6) reveals that granulite facies rocks have a high median Th/U ratio and just a few data with Th/U below 1. The Kolmogorov-Smirnov test also indicates that the granulite group is distinct from other groups with 1% confidence level. However, the greenschist and amphibolite facies groups feature similar Th/U ratios with 1% confidence level, and so do unmetamorphosed rocks as well as greenschist facies rocks (Appendix A).

The interpolated heat production (Table 3) appears slightly larger than raw average calculated from our dataset. This is due to granitoids, like those of the Wiborg batholith, being underrepresented in the heat production catalogue when compared to mafic and ultramafic rocks. The absence of dykes within rapakivi units further emphasizes their high heat production in the interpolated map. In the lithologic division, the eastern 1.67-1.62 Ga and western 1.59-1.54 Ga rapakivi granites are treated separately, yet their median heat production rates are nearly similar, $3.4 \pm 1.2 \mu\text{Wm}^{-3}$ and $3.3 \pm 1.0 \mu\text{Wm}^{-3}$. In the interpolated map (Figure 8), the Laitila rapakivi is poorly visible because in the north and east it is bordered by Satakunta sandstone-conglomerate unit which is cut by diabases. The heat production of the sedimentary unit is $1.4 \pm 0.4 \mu\text{Wm}^{-3}$ and that of the dykes $0.2 \pm 0.1 \mu\text{Wm}^{-3}$. High and low values appear to average out in the map, unlike in the case of larger rapakivi units, particularly

Åland which is surrounded by the Baltic Sea, an area without measurements. The Wiborg batholith is mainly bordered by Svecofennian microcline gneisses and supracrustal mica schists and gneisses, which have a median heat production over the nationwide average. Plotting heat production as a function of geological age (Figure 14) does not reveal an obvious distinction between Svecofennian and Archean domains, but the high heat production of the Mesoproterozoic rapakivi granites is emphasized in the Post-Svecofennian domain.

An alternative to interpolation is to plot data using weighting by geological units as done e.g. by Slagstad (2008) in Norway. Following this principle, we have gathered heat production and Th/U ratio by units of the bedrock map of Finland (Rasilainen et al., 2008) in Table 7. In Figures 15, 16, 17 and 18, we have plotted heat production, C_U , C_{Th} and C_K information on map polygons using ArcMap 10.3.1 software and SciPy. It appears evident from Table 7 that our interpolated heat production estimate is similar to that estimated using an area-weighted mean of respective geological units. Therefore applying spatial interpolation to estimate mean heat production may be plausible in areas where spot readings are available but geological units have not been digitized precisely enough to allow averaging by them. Figure 15 also implies that it is undesirable to plot heat flow as a function of area-weighted heat production in the respective bedrock unit, because most heat flow determinations have been carried out in areas with highly heterogeneous geology. Therefore an interpolated map is better for this purpose, yet the interpolation method greatly influences the output.

As seen in Table 7, the Th/U ratios vary from 1.37 to 13.77 between units, while the area-weighted mean is 7.2 ± 3.1 and simple arithmetic mean is 5.7 ± 7.1 . Rock units with smallest values are almost exclusively mafic and ultramafic rocks and schists, which cover small, scattered areas in the Svecofennian domain. Prominent units with high Th/U ratios are the Lapland Granulite Belt, the

Archean gneiss complexes, and the Central Lapland Granitoid Complex. The absence of units with area-weighted Th/U ratio > 8 in Svecofennian areas of southern and central Finland is remarkable, while Paleo- and Mesoproterozoic rocks of northern Finland often feature high values. Although there are a few high spot readings of Th/U > 8 e.g. in 1.84-1.82 Ga microcline granites in Häme and Uusimaa areas, they do not truthfully represent the entire unit. Granites in the rapakivi areas and granitoids in the Central Finland Complex typically have low to moderate Th/U ratios. In general, the area-weighted Th/U ratio is larger than the arithmetic mean for the same reasons which explain the difference between area-weighted and arithmetic mean heat production.

Finnish regions with high heat production are comparable with several other Precambrian areas such as eastern Gawler craton in Australia (Neumann et al., 2000) and the Lac de Gras units in Canada (Thompson et al., 1995). The minimum, mean and maximum values of heat production are 3.4, 7.5 and $17.0 \mu\text{Wm}^{-3}$ for eastern Gawler and 4.9, 8.1 and $15.9 \mu\text{Wm}^{-3}$, respectively. In the 0.93-0.92 Ga Post-Sveconorwegian granites, Slagstad (2008) found a mean heat production of $3.92 \pm 2.54 \mu\text{Wm}^{-3}$ and a maximum of $15.95 \mu\text{Wm}^{-3}$. Besides our study, his analysis of Norwegian heat production is one of the few comprehensive heat production studies based on outcrop data in northern Europe. Correlation of heat production to rock density has been also attempted in Norway, and although Slagstad (2008) found a slight decrease of A with increasing ρ , the scatter of data in the A- ρ plot appeared so large that no meaningful model could explain the data. In Finland, the situation is somewhat similar. In our data there is only one exception to the rule that outcrops with $A > 5 \mu\text{Wm}^{-3}$ have $\rho < 2800 \text{ kg/m}^3$. On the other hand, low ρ does not necessitate low A, because felsic rocks with low density feature a broad range of heat production values. The skewness of the A- ρ distribution is strongly positive, and a linear fit ($A=12.93-0.004193\rho$) is unsuitable in explaining the data as it leads to negative heat production values at high densities. The correlation coefficient is $r=-0.46$ (Figure 19).

P-wave velocities show a strong dependence on sample porosity. Porosity is most often due to naturally occurring microcracks in outcrops or drilling-induced fractures. Heat production was plotted as a function of seismic P-wave velocity, yet we first corrected the velocity data for sample porosity assuming that pores were saturated with water. For the correction, the equation of Wyllie et al., (1956) was applied:

$$v_m = \frac{1-\phi}{\frac{1}{v} - \frac{\phi}{v_f}} \quad (3)$$

Here v_m is corrected P-wave velocity, ϕ is sample porosity in the database, v is sample P-wave velocity from the database, and v_f is fluid velocity (1500 m/s). Data were assumed to represent laboratory conditions (room temperature and 1 atm pressure). The distribution, based on 5685 raw data entries, had $r=-0.28$ and the exponential fit was $A=e^{3.944-0.0004393v}$ (Figure 20). A Precambrian lithosphere model, where $A=e^{(-2.17v/1000)+12.6}$ has been presented, corresponding to pressure of 1 atm = 987 MPa (Equation 13 in Rybach and Buntebarth, 1984). Due to the scattered nature of data, models strongly deviate from each other and their predictive power is poor. Although we did not carry out separate analyses for different rock types, we could repeat the general conclusion of Kukkonen and Lahtinen (2001) using a dataset almost five times as large as theirs, i.e., no distinct relationship between P-wave velocity and heat production rate exists. This is in line with earlier observations from Superior craton, another Precambrian area with relatively similar characteristics (Fountain, 1986).

As noted by Slagstad (2008), heat production and silica (SiO_2) content have a positive correlation in Norway, most obviously in granites and granitic gneisses but very weakly visible in metasedimentary

rocks. Also our database-wide investigation reveals a sharp increase of heat production between SiO_2 concentration of 40% and 75%. The distribution had $r=0.35$ and the linear fit to the data appears $A=-1.168+0.03907s$, where s is SiO_2 content (%). However, samples with silica content higher than 80%, comprising 3.8% ($N=248$) of the entire database, show a tail which deviates from the general trend (Figure 21). None of these samples has a heat production over $2.0 \mu\text{Wm}^{-3}$. They are mostly metasediments and a vast majority ($N=195$) of them are quartzites. In the interval of $60\% \leq \text{SiO}_2 \leq 80\%$ ($N=4227$), as many as 1158 samples (27.4%) have A of $2.0 \mu\text{Wm}^{-3}$ or more, the majority ($N=642$) of them being granites and the rest being mostly other plutonic and metaplutonic rocks. The group with SiO_2 values less than 60% ($N=1990$) mainly consists of mafic and ultramafic plutonic and volcanic rocks. Only 126 samples (6.3%) in this group have A of at least $2.0 \mu\text{Wm}^{-3}$, and despite the heterogeneity in the subgroup, mica-bearing rocks form an important part of it. Slagstad (2008) found a similar behaviour in Norway, meaning that micas often carry U- and Th-rich minerals.

Plotting heat production against ferric oxide (Fe_2O_3) concentration (Figure 22) reveals that while high values of A clearly indicate a low amount of Fe_2O_3 , the opposite is not the case, but samples with a near-zero A are ubiquitous in the entire range of Fe_2O_3 content. The distribution has an apparent similarity to that observed when comparing heat production and rock density (Figure 19). The distribution of data in the A vs. Fe_2O_3 plot had $r=-0.38$. Fitting a line results in an equation $A=1.988-0.1222f$, where f is Fe_2O_3 content (%). Although an exponential fit to the Fe_2O_3 data, as well as to the rock density data, may be better than a linear one, it is hard to find a physical reason for this kind of fitting across a range of very different rock types. There appear to be 751 samples with Fe_2O_3 concentration of 10 % or more, all but a few of those representing mafic or ultramafic volcanic or plutonic rocks. The highest Fe_2O_3 concentrations in granites ($N=1043$) are slightly less than 10%, but in metamorphosed rocks of granitic origin, larger values occur.

6. Discussion

The mean surface heat flow of Finland falls below the upper limit of geologically estimated heat flow, namely 50 mWm^{-2} in the global area-weighted median heat flow map of Davies (2013), although geological domains alone are a poor proxy of heat flow. On the other hand, Shapiro and Ritzwoller (2004) published a global heat flow map based on a global seismic shear wave velocity model of the crust and the upper mantle. In their map, Finland falls between the heat flow range of $40\text{--}50 \text{ mWm}^{-2}$, with smallest values in the Svecofennian domain. Goutorbe et al., (2011) presented a series of eighteen observables used to build up a global heat flow estimate, although some of them, such as basin type, and age at start of rifting, are not applicable to Finland which lacks Phanerozoic sedimentary cover. However, information about thickness of lithosphere, tectonothermic age, topography, upper mantle velocity structure, upper mantle density anomaly, thickness of middle crust, thickness of lower crust, and heat production (median grid and provinces separately) were available for the Finnish territory. As seen in maps of Goutorbe et al., (2011), their method of best combination of observables produced a heat flow in the range of $40\text{--}45 \text{ mWm}^{-2}$ in Finland, while their similarity method results in a larger variation of heat flow worldwide, and the range of values in Finland is $35\text{--}50 \text{ mWm}^{-2}$, respectively. In the light of previous analyses, our interpolated heat flow estimate of $42 \pm 4 \text{ mWm}^{-2}$ appears reasonable. By coincidence, this value is similar to that of Archean cratons worldwide (Jaupart and Mareschal, 1999) although the proportion of the Archean Karelian domain of the Finnish bedrock is just 47.1% (Rasilainen et al., 2008).

Regardless of whether we applied paleoclimatic correction or not, the slopes of our Q-A plots are nearly similar. The validity of Q-A plots has been previously tested in Fennoscandia and Caledonides by Slagstad et al., (2009). They found an increasing trend after grouping heat production data by

geological domain, but no meaningful relationship in the case of individual data points. In the comparison study of batholiths of the United Kingdom (Webb et al., 1987), data for different units appeared as distinct concentrations in Q-A plot, yet with strikingly different depth scales. Our result gives additional proof for the hypothesis that Q-A plots are appropriate only in very limited areas with highly enriched radioactive plutons close to the surface, e.g. the Appalachians, where anorogenic granites produce a mean heat flow as high as $8.6 \mu\text{Wm}^{-3}$ (Birch et al., 1968). The functionality of Q-A plots is by no means related to the age of the lithosphere and they should not be applied in global analyses as done e.g. by Artemieva and Mooney (2001). Nonetheless, to estimate the depth of the upper crust enriched in radioactive elements, other measures such as the differentiation index (Perry et al., 2006) can be used. Fortunately, the mean heat flow and heat production appear to be fairly insensitive to changes in the shape of Q-A plot when different smoothing parameters are used.

Pressure-temperature (P-T) data from mantle xenoliths of eastern Finland (Kukkonen and Peltonen, 1999) has revealed a mantle heat flow of $11 \pm 4 \text{ mWm}^{-2}$. In the light of this value, the Q-A relationship applied by Kukkonen (1993) would indicate that in the areas with almost zero near-surface heat production, only $1\text{-}9 \text{ mWm}^{-2}$ of heat flow comes from the crust. Taking the paleoclimatic effect into account would raise these values not more than a few mWm^{-2} . If our Q-A ratio estimated from paleoclimatically corrected data is applied to all 6465 raw data points, they have an estimated mean Q of 41.9 mWm^{-2} with a standard deviation of 4.3 mWm^{-2} . Therefore we suggest that based on our data, $22\text{-}40 \text{ mWm}^{-2}$ of surface heat flow originates from the crust. In the analysis of Kukkonen and Lahtinen (2001), the crustal contribution to the total heat flow of 37 mWm^{-2} was 26 mWm^{-2} , but no error parameters were given. Putting our value to global rather than Finnish perspective is difficult because only a handful of areas have well defined crustal heat flow constraints. These are typically highly metamorphosed terranes. The value of 29 mWm^{-2} for accreted belts of Superior craton (Heaman et al., 2011) appears similar to the Finnish value, while younger areas such as Natal-

Namaqua belt and Appalachians feature larger values (e.g. Andreoli et al., 2006; Lévy and Jaupart, 2011). The high heat production in Natal-Namaqua, South Africa, is of particular importance because it challenged the long-lived hypothesis that high metamorphic grade leads to low heat production rates (e.g. Heier, 1965; Sandiford et al., 2002). Recent observations from Ivrea Verbano in Italy, Sierra de Quilmes in Argentina, and Mount Stafford, Reynolds Range and Broken Hill in Australia also show that heat production does not change with metamorphic grade (Alessio et al., 2018).

In the stratified sampling procedure (Lehtonen and Pahkinen, 1994) used by Rasilainen et al., (2007, 2008) to gather data, the sampling density was proportional to lithological variation in the geological map, and therefore homogeneous areas had less data than heterogeneous ones. Having applied weighted average in calculation of nationwide mean heat production to remove this bias, we may conclude that the mean near-surface heat production in Finland is $1.4 \mu\text{Wm}^{-3}$, an important new parameter for standard geotherms and clearly larger than global Archean ($0.56\text{-}0.73 \mu\text{Wm}^{-3}$) and Proterozoic ($0.73\text{-}0.90 \mu\text{Wm}^{-3}$) averages (Jaupart et al., 2016). To roughly estimate how largely the Finnish heat flow is a result of heat producing elements in the upper crust, data from granulite facies rocks from Turku, Pielavesi-Kiuruvesi, Varpaisjärvi and Lapland areas are available. The mean of their heat production is $1.2 \pm 0.7 \mu\text{Wm}^{-3}$, and the median is $0.9 \pm 0.7 \mu\text{Wm}^{-3}$ (Jöeleht and Kukkonen, 1998), but the distributions for all areas are strongly skewed. Although their associated metamorphic pressures yield a large depth range, ca. 14-40 km, it is nevertheless obvious that the high heat production in Finland is not limited to surface rocks. The heat production determined from granulite facies rocks worldwide is lower, $0.68 \pm 0.62 \mu\text{Wm}^{-3}$, but varies largely even between units with similar pressure ranges and ages (Hasterok and Chapman, 2011).

Unlike outcrop- and till-based studies of radiogenic heat production, airborne gamma ray surveys can conveniently cover large areas at a time. In Finland, a nationwide survey was carried out in years 1972-2004 (Hyvönen et al., 2005). However, interpretation of the airborne data requires a number of corrections (background correction, flight height correction, channel interaction correction etc.) which have a variable level of uncertainty. In addition, the resulting signal integrates the radiation from the aircraft, cosmic radiation, atmosphere, soil, vegetation, and bedrock. Although some success has been achieved in some areas with little vegetation and subdued topography, e.g. Western Australia (Bodorkos et al., 2004) and even in southwestern England (Beamish and Busby, 2016), outcrop measurements give the most valuable absolute spot readings. Due to overburden and water bodies, airborne surveys may severely underestimate heat production values, as observed e.g. in Sudbury region, Canada, where the heat production determined from outcrop samples was $2.9 \pm 2.5 \mu\text{Wm}^{-3}$ and that determined from airborne data was $0.8 \pm 0.6 \mu\text{Wm}^{-3}$ (Phaneuf and Mareschal, 2014). Uncertainties associated with these values are standard deviations, and due to the smoothing effect of flight altitude, the associated uncertainty is substantially smaller in airborne data than in outcrop data. Obviously, this does not take the systematic error of airborne measurements into account. Therefore airborne surveys are not an alternative to ground-based surveys, yet they can provide additional information.

An important task in studies of the internal thermal regime of the continental lithosphere is the estimation of crustal heat production and derivation of the subcrustal mantle heat flow value. The results shown in our study and those discussed in literature strongly imply that simplified schemes with Q-A plots or v_p -A relationships do not provide reliable estimates of the heat production, nor the mantle heat flow. The complexity of geochemical characteristics of U, Th and K in partial melting, and metamorphism makes the problem very challenging. In our view, the best results could be achieved by constructing lithological heat production models of the crust and upper mantle using

seismic velocity data from wide angle surveys (e.g. Luosto et al., 1989, 1990, 1994), lithological modeling of the velocities (e.g., Kuusisto et al., 2006; Brown and Juhlin, 2006), as well as compositional and pressure-temperature data and U-Th-K analyses of crustal and mantle xenoliths (e.g., Hölttä et al., 2000; Kukkonen et al., 2003; Kukkonen et al., 2008). Analyses of this kind are not possible everywhere, but gradual accumulation of case histories with real data will finally provide a better insight into the field of lithospheric heat production than simple models.

An important observation shown by modeling P-wave velocities with laboratory measurements of seismic velocities of different rock types (e.g. Christensen and Mooney, 1995) is that crustal velocity layers reported in wide-angle surveys cannot be represented with single rock types. Instead, mixtures of several rock types are needed (e.g. Kuusisto et al., 2006). The problem is therefore non-unique, but ambiguity can be reduced with geologically reasonable selection of rock types in the models, as well as using xenolith data wherever available (Kukkonen et al., 2008). Paleoclimatically corrected heat flow values determined in deep boreholes provide the surface boundary condition for calculating the lithospheric heat production budget, but knowledge on the subcrustal heat flow value then brackets the crustal heat production. The diffusive nature of heat flow requires that the study area is sufficiently large, devoid of large-scale heterogeneity and thermally equilibrated to allow estimating the total crustal heat production. The construction of such models is beyond the scope of the present paper, but our analysis provides fundamental data heat production values for future analysis.

7. Conclusions

The present study presents a detailed spatial variation in radiogenic heat production determined with 6465 outcrop samples covering about one third of the Fennoscandian Shield area. The vast majority

of the dataset represents rocks ranging in geological age from Mesoarchean (about 2.7 Ga) and Paleoproterozoic (2.2-1.8 Ga) to Mesoproterozoic (ca. 1.3 Ga). Our results show that radiogenic heat production is a highly variable with outcrop spot values having an arithmetic mean of $1.34 \pm 1.19 \mu\text{Wm}^{-3}$, and the range of $0.02\text{-}19.4 \mu\text{Wm}^{-3}$. The interpolated areal average of the study area is $1.42 \pm 1.41 \mu\text{Wm}^{-3}$. We attribute the high standard deviation values reflecting the geochemical characteristics of U, Th and K resulting in a skewed distribution of heat production. U represents 37%, Th 47% and K 16% of the total heat production, respectively. Heat production and its range of values show an increasing trend with increasing SiO_2 , and a decreasing trend with increasing Fe_2O_3 content and rock density, respectively. Post-Svecofennian rapakivi granites, and late/postorogenic Paleoproterozoic Svecofennian granitoids show the highest heat production values in the range of $3\text{-}5 \mu\text{Wm}^{-3}$. Due to large Th content of certain granulite facies rocks, high heat production is not exclusive to rocks with low degree of metamorphism. Heat production is not clearly dependent on geological age, metamorphic grade nor with seismic P-wave velocity, and its correlation with surface heat flow is weak ($r = 0.35$) due to heterogeneity of lithologies and diffusive smoothing. Models of the thermal state of the Finnish Precambrian lithosphere should be guided by seismic P- and S-wave in situ velocities, compositional data and U-Th-K analyses of potentially available crust and mantle xenoliths as well as mantle heat flow data derived from mantle xenolith geothermobarometry.

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Figures

Figure 1. Ternary scatter plot of heat production in Finnish data (N=6544) showing the relative proportions of U, Th and K in total heat production. The average proportions of U, Th and K are 36.7%, 47.0% and 16.3%. Density contours for 200, 300, 400, 500 and 800 data points are also shown.

Figure 2. Radiogenic heat production [μWm^{-3}] in our raw dataset (N=6465) mapped in latitude-longitude coordinates. Values exceeding the range of the legend are shown with fuchsia color (seen in online article only).

Figure 3. Th/U ratio (dimensionless) in our raw dataset (N=6465) mapped in latitude-longitude coordinates.

Values exceeding the range of the legend are shown with fuchsia color (seen in online article only).

Figure 4. Interpolated bedrock density [kg/m³]. Values exceeding the range of the legend are shown with fuchsia color (seen in online article only). Geochemical sampling sites are shown with dots.

Figure 5. Interpolated concentration of uranium [ppm]. Values exceeding the range of the legend are shown with fuchsia color (seen in online article only). Geochemical sampling sites are shown with dots.

Figure 6. Interpolated concentration of thorium [ppm]. Values exceeding the range of the legend are shown with fuchsia color (seen in online article only). Geochemical sampling sites are shown with dots.

Figure 7. Interpolated concentration of potassium [%]. Values exceeding the range of the legend are shown with fuchsia color (seen in online article only). Geochemical sampling sites are shown with dots.

Figure 8. Interpolated radiogenic heat production [μWm^{-3}]. Values exceeding the range of the legend are shown with fuchsia color (seen in online article only). Geochemical sampling sites are shown with dots.

Figure 9. Interpolated heat flow estimated from radiogenic heat production using Q-A relation for paleoclimatically corrected data with 2 as the value of smoothing parameter in the interpolation. Values exceeding the range of the legend are shown with fuchsia color (seen in online article only). Geochemical sampling sites are shown with dots.

Figure 10. Heat flow vs. interpolated heat production in Finland. Cross symbols represent raw heat flow data and circle symbols represent paleoclimatically corrected heat flow data (Table 5). Dashed line has been fitted to raw data and solid line to corrected data, respectively. The value of smoothing parameter in the interpolation is 2 in both cases.

Figure 11. Simplified geological map of Fennoscandian Shield and adjacent areas.

Figure 12. A box-and-whisker plot showing heat production of rocks by their metamorphic grade. Classes are same as in the Rock Geochemical Database of Finland: Undetermined (0; N=1937), unmetamorphosed (1; N=1496), greenschist facies (2; N=343), amphibolite facies (3; N=2466), and granulite facies (4; N=223). See Table 1 for explanations of symbols, and kstest.dat in Appendix A for Kolmogorov-Smirnov test results.

Figure 13. A box-and-whisker plot showing Th/U ratio of rocks by their metamorphic. See Table 1 for explanations of symbols, and kstest.dat in Appendix A for Kolmogorov-Smirnov test results.

Figure 14. Mean heat production as a function of geological age in geological domains of Finland. Upper and lower boundaries of age are those reported in Table 7. Also, error bars in heat production axis correspond to standard deviation in Table 7. Some rocks in groups 90 (carbonatites) and 101 (Amphibolite, diabase and gabbro dyke swarms) within the Post-Svecofennian domain have poor age constraints and a large distribution of ages.

Figure 15. Heat production [μWm^{-3}] by geological units in Finland plotted using data in Table 7. For clarity, dyke swarms are not plotted. Areas with no geochemical data are left blank. Heat flow sampling sites are shown with dots.

Figure 16. Concentration of uranium [ppm] by geological units in Finland plotted using data in heatprod.dat (Appendix A). For clarity, dyke swarms are not plotted. Areas with no geochemical data are left blank. Heat flow sampling sites are shown with dots.

Figure 17. Concentration of thorium [ppm] by geological units in Finland plotted using data in heatprod.dat (Appendix A). For clarity, dyke swarms are not plotted. Areas with no geochemical data are left blank. Heat flow sampling sites are shown with dots.

Figure 18. Concentration of potassium [%] by geological units in Finland plotted using data in heatprod.dat (Appendix A). For clarity, dyke swarms are not plotted. Areas with no geochemical data are left blank. Heat flow sampling sites are shown with dots.

Figure 19. Relation of heat production to rock density for all raw data (N=6465). A linear regression ($A=12.93-0.004193\rho$, where A is heat production in $\mu W m^{-3}$ and ρ is rock density in $kg m^{-3}$) is also shown.

Figure 20. Relation of heat production to seismic P-wave velocity for the part of raw data with velocity and porosity information associated (N=5685). The velocity data were corrected for sample porosity following Wyllie et al., (1956). The model suggested for Precambrian lithosphere ($A=e^{(-2.17v/1000)+12.6}$ at 100 MPa) by Rybach and Buntebarth (1984) is shown as a dashed line, and a corresponding regression ($A=e^{(-0.27v/1000)+1.78}$) where A is heat production in μWm^{-3} and v is corrected v_p) based on our data is shown as a solid line. The vertical axis is logarithmic. Two outliers with $v_p > 10000$ m/s remain outside the plotting area.

Figure 21. Relation of heat production to silica concentration for all raw data (N=6465). A linear regression ($A = -1.168 + 0.03907s$, where A is heat production in $\mu W m^{-3}$ and s is SiO₂ content in %) is also shown.

Figure 22. Relation of heat production to ferric oxide concentration for all raw data (N=6465). A linear regression ($A=1.988-0.1222f$, where f is Fe_2O_3 content in %) is also shown. ONE COLUMN

Tables

Column	Description
YCOORD	Y coordinate (northing) in YKJ
XCOORD	X coordinate (easting) in YKJ
GEOLAT	Geographic latitude [°] in EUREF-FIN
GEOLON	Geographic longitude [°] in EUREF-FIN
UNIT	Unit number in the bedrock of Finland. See Table 7 and Rasilainen et al., (2008) for details.
UNITAREA	Area of the unit [km ²]
U	Concentration of U [ppm]
TH	Concentration of Th [ppm]
RHO	Density [kg/m ³]
K	Concentration of K [%]
PVEL	Seismic P wave velocity [m/s]. ND = not determined.
METAM	Degree of metamorphism. 0 = not determined, 1 = unmetamorphosed, 2 = greenschist facies, 3 = amphibolite facies, 4 = granulite facies.
SIO2	Concentration of SiO ₂ [%]
FE2O3	Concentration of Fe ₂ O ₃ [%]
POR	Porosity [%]

Table 1. Description of data columns in our heat production data file (heatprod.dat in Appendix A).

	ρ [kg/m ³]	C _U [ppm]	C _{Th} [ppm]	C _K [%]	A [μ Wm ⁻³]
Mean	2762	2.00	8.97	2.21	1.34
Median	2723	1.41	6.57	2.08	1.11
Standard deviation	130.9	2.40	10.01	1.35	1.19
Minimum	2326	0.08	0.13	0.00249	0.0263
Maximum	3533	54.80	271.00	8.632	19.387

Table 2. Statistics of heat production parameters in our raw data.

	ρ [kg/m ³]	C _U [ppm]	C _{Th} [ppm]	C _K [%]	A [μWm ⁻³]	Q [mWm ⁻²]*
Mean	2753 / 2754	2.08 / 2.08	9.69 / 9.62	2.30 / 2.29	1.42 / 1.41	42.20 / 42.16
Median	2754 / 2755	1.90 / 1.91	8.50 / 8.39	2.21 / 2.21	1.32 / 1.31	41.59 / 41.57
Standard deviation	55.56 / 54.19	1.27 / 1.21	5.52 / 5.49	0.75 / 0.73	0.68 / 0.66	4.03 / 3.93
Minimum	2606 / 2606	0.17 / 0.17	0.21 / 0.70	0.40 / 0.40	0.16 / 0.16	34.71 / 34.71
Maximum	2973 / 2964	7.43 / 7.43	51.80 / 51.80	4.69 / 4.69	5.35 / 5.35	65.45 / 65.45

Table 3. Statistics of heat production parameters in our interpolated data. The first value given in a cell refers to that calculated using the loose filtering criterion (3997 grid cells) and the second value to that calculated from the strict filtering criterion (3211 grid cells) in rectangular coordinates. The value of smoothing parameter is 2 in all cases. *Q has been calculated from interpolated A values using the paleoclimatically corrected Q-A relationship, with 2 as the value of smoothing parameter in the interpolation. See also Figure 8.

Smoothing parameter	0.1	0.5	1	2	3	4	5	10
Mean of A	1.43 / 1.43	1.42 / 1.42	1.42 / 1.42	1.42 / 1.41	1.42 / 1.41	1.42 / 1.41	1.42 / 1.41	1.42 / 1.40
Median of A	1.27 / 1.27	1.29 / 1.28	1.30 / 1.30	1.32 / 1.31	1.32 / 1.32	1.32 / 1.32	1.33 / 1.32	1.33 / 1.33
Standard deviation of A	0.93 / 0.88	0.78 / 0.75	0.72 / 0.71	0.68 / 0.66	0.66 / 0.64	0.64 / 0.62	0.63 / 0.61	0.60 / 0.57
Minimum of A	-1.57 / -0.31	0.07 / 0.11	0.12 / 0.14	0.16 / 0.16	0.18 / 0.18	0.20 / 0.20	0.21 / 0.21	0.27 / 0.27
Maximum of A	10.41 / 10.41	6.50 / 6.50	5.58 / 5.58	5.35 / 5.35	5.14 / 5.14	4.97 / 4.97	4.82 / 4.82	4.30 / 4.30
Q-A relation	37.97 + 2.931A	35.95 + 4.382A	34.89 + 5.142A	33.79 + 5.919A	33.13 + 6.384A	32.65 + 6.721A	32.26 + 6.989A	30.98 + 7.873A
Heat flow	42.16 / 42.16	42.17 / 42.17	42.19 / 42.19	42.20 / 42.14	42.20 / 42.13	42.19 / 42.13	42.18 / 42.11	42.16 / 42.00

Table 4. The influence of smoothing parameter on interpolated heat production (A, [μWm^{-3}]) statistics. The first value given in a cell refers to that calculated using the loose filtering criteria (3997 grid cells) and the second value to that calculated from the strict filtering criteria (3211 grid cells) in rectangular coordinates. The Q-A relation calculated using heat flow data in Table 5, and mean heat flow calculated from the mean of A are also given.

Measurement site	Latitude [°]	Longitude [°]	Raw HFD [mWm ⁻²]	Corrected HFD [mWm ⁻²]	Heat production [μWm ⁻³]	Reference
Elimäki	60.62	26.48	34	39.7	4.08	Kukkonen (1989b)
Espoo	60.18	24.83	48.0 ± 0.5	49.9	1.80	Kukkonen (1989b)
Eurajoki	61.23	21.48	32.4	38.9	1.78	Kukkonen (1989a,b)
Hammaslahti	62.45	30.02	38.8 ± 2.7	39.2 ± 2.8	1.43	Järvimäki and Puranen (1979), Kukkonen (1987, 1989a)
Heinola	61.25	26.37	44.9 ± 1.2	50.9	2.94	Kukkonen (1993)
Honkamäki	64.13	26.9	32.1 ± 1.3	36.0 ± 1.2	2.12	Järvimäki and Puranen (1979), Kukkonen (1987, 1989a)
Hyrnsalmi	64.58	29.32	37.3 ± 0.1	39.8	3.89	Kukkonen (1993)
Ilomantsi	62.87	30.75	30.5 ± 0.8	35.0 ± 1.1	0.86	Järvimäki and Puranen (1979), Kukkonen (1987, 1989a)
Juuka	62.94	29.14	20.2 ± 6.5	30.2	1.11	Kukkonen and Jöeleht (2003)
Kangasniemi	62.03	26.58	38.0 ± 11.6	43.5 ± 13.6	0.73	Kukkonen (1988, 1989a)
Keitele	63.28	26.37	40.5 ± 2.9	44.7 ± 1.5	0.63	Kukkonen (1988, 1989a)
Kerimäki	62.02	28.95	34.7 ± 3.8	42.3 ± 3.9	1.19	Kukkonen (1988, 1989a)
Kisko	60.23	23.52	68.0 ± 7.6	73.5 ± 6.1	1.16	Kukkonen (1988, 1989a)
Kolari (mean of 3 measurement ranges)	67.55	23.93	30.4 ± 4.2	34.1 ± 4.3	2.30	Kukkonen (1989a)
Konginkangas	62.82	25.7	35.3 ± 0.2	40.2	1.53	Kukkonen (1993)

Kotalahti	62.57	27.62	37.0 ± 2.5	47.7 ± 4.8	1.03	Järvimäki and Puranen (1979), Kukkonen (1987, 1989a)
Kuhmo	64.22	29.93	24.3 ± 0.1	27.1	1.07	Kukkonen (1993)
Lavia	61.65	22.68	46.3 ± 1.7	53.9 ± 1.8	1.81	Kukkonen (1988, 1989a)
Liminka	64.85	25.43	43.8 ± 1.3	48.9 ± 2.0	2.96	Puranen et al., (1968), Kukkonen (1987, 1989a)
Lohja	60.27	24.08	38.4 ± 1.0	40.2 ± 2.1	1.71	Järvimäki and Puranen (1979), Kukkonen (1987, 1989a)
Loviisa	60.37	26.3	56.9	62.1	3.82	Kukkonen (1989b)
Luikonlahti	62.95	28.7	30.7	33.7	1.19	Järvimäki and Puranen (1979), Kukkonen (1987, 1989a)
Mäntsälä	60.6	25.17	68.7 ± 0.2	72.9	1.56	Kukkonen (1993)
Nivala	63.85	25.05	33.9 ± 3.2	34.9	0.80	Puranen et al., (1968), Kukkonen (1987, 1989a)
Nummi-Pusula	60.47	23.77	54.6 ± 6.5	61.5 ± 10.5	0.80	Kukkonen (1988, 1989a)
Otanmäki	64.12	27.1	31.5 ± 1.6	32.4 ± 0.4	1.70	Järvimäki and Puranen (1979), Kukkonen (1987, 1989a)
Outokumpu	62.72	29.07	~30	~40	1.14	Kukkonen et al., (2011)
Outokumpu-290	62.72	29.02	33	38	1.14	Kukkonen (1987, 1989a,b)
Outokumpu-737, -740, -741	62.78	29.22	33.7 ± 1.7	40.7 ± 1.7	1.23	Kukkonen (1988, 1989a)
Parainen	60.18	22.32	38.4 ± 2.4	45.0 ± 2.6	2.13	Kukkonen (1988, 1989a)

Parikkala	61.58	29.68	27.9 ± 2.6	35.5 ± 2.5	0.16	Järvimäki and Puranen (1979), Kukkonen (1987, 1989a)
Pielavesi	63.2	26.67	34.0 ± 2.4	30.1	0.36	Järvimäki and Puranen (1979), Kukkonen (1987, 1989a)
Pori	61.45	21.75	50.4 ± 2.1	52.5 ± 3.2	0.84	Kukkonen (1987, 1989a)
Pyhäjärvi	63.66	26.08	37.7 ± 2.2	43.2 ± 2.4	1.08	Kukkonen (1988, 1989a)
Ranua	66.1	26.17	25.2 ± 3.0	29.0 ± 3.6	0.37	Kukkonen (1989a)
Sievi	63.72	24.85	43.5 ± 0.3	48.1	1.21	Kukkonen (1993)
Siilinjärvi-157, -112	63.12	27.73	21.8 ± 3.1	27.8 ± 0.9	0.46	Järvimäki and Puranen (1979), Kukkonen (1987, 1989a)
Sodankylä	67.63	26.25	12.7 ± 3.7	17.7 ± 1.5	0.28	Kukkonen (1989a)
Sokli	67.82	29.33	41.6 ± 1.3	40.5 ± 2.3	0.36	Kukkonen (1989a)
Sääksjärvi	61.45	22.42	39.5	49.6 ± 0.9	0.91	Kukkonen (1989b)
Vihanti	64.38	25.08	31.7 ± 0.9	34.7 ± 0.9	0.57	Kukkonen (1988, 1989a)
Virtasalmi	62.07	27.57	27.2 ± 1.1	30.6 ± 3.3	0.38	Puranen et al., (1968), Kukkonen (1987, 1989a)
Ylistaro	62.95	22.53	49	55.5	1.49	Kukkonen (1989a,b)
Ylivieska	64.33	24.45	33.5 ± 0.3	39	0.54	Kukkonen (1993)

Table 5. Raw and palaeoclimatically corrected values for heat flow in the study area, and corresponding heat production values estimated from interpolation.

	Undetermined		Unmetamorphosed		Greenschist facies		Amphibolite facies		Granulite facies	
	HP	Th/U	HP	Th/U	HP	Th/U	HP	Th/U	HP	Th/U
Mean	1.51	7.12	1.60	4.26	0.64	4.12	1.18	5.19	1.13	12.10
Median	1.13	4.69	1.30	3.29	0.44	3.61	1.10	3.88	1.01	10.40
Standard deviation	1.38	9.58	1.28	3.89	0.64	2.80	0.89	5.14	1.47	13.01
Minimum	0.03	0.02	0.03	0.04	0.03	0.09	0.03	0.20	0.05	0.73
Maximum	12.21	253.77	15.07	60.33	2.79	24.67	9.39	63.67	19.39	118.86

Table 6. Heat production (HP) [μWm^{-3}] and dimensionless Th/U ratio (Th/U) by metamorphic grade (MG) for our raw outcrop data (N=6465). For a visual comparison, see Figures 12 and 13.

Unit code	Unit name	N	Tectonic age [Ga]	Area [km ²]	Mean HP [μWm^{-3}]	Median HP $\pm$ SD [μWm^{-3}]	Th/U ratio
	Total area of mapped units in Finland	6465	3.2-0.08	336223	1.34; 1.44 ¹	1.11 $\pm$ 1.19	5.73 $\pm$ 7.08; 7.19 $\pm$ 3.06 ¹
Post-Svecofennian domain							
3	Sandstones and conglomerates (Lauhanvuori)	1	0.7-0.5 (Paulamäki and Kuivamäki, 2006)	72.4	0.27	0.27	2.40
4	Siltstones and shales	1	1.50-1.27	650.9	1.04	1.04	8.05
5	Olivine diabases	18	1.27	479.5	0.24	0.22 $\pm$ 0.11	4.16 $\pm$ 0.76
6	Sandstones and conglomerates	4	1.50-1.27	909.2	1.31	1.36 $\pm$ 0.45	4.43 $\pm$ 0.53
7	Quartz porphyries	3	1.65-1.62	8.2	1.66	1.90 $\pm$ 0.86	5.17 $\pm$ 1.45
8	Rapakivi granites (Wiborg, Ahvenisto, etc.)	93	1.65-1.62	9523.8	3.55	3.38 $\pm$ 1.17	4.47 $\pm$ 2.00
9	Rapakivi granites (Vehmaa, Laitila, Åland)	49	1.59-1.57	3089.7	3.33	3.26 $\pm$ 1.04	5.44 $\pm$ 2.27
10	Gabbro-anorthosite (Ahvenisto)	9	1.65-1.62	123.4	0.60	0.49 $\pm$ 0.46	4.27 $\pm$ 0.92
11	Gabbro-anorthosite (Laitila?)	1	1.59-1.57	4.7	0.14	0.14	4.82
12	Granites (northern Finland)	29	1.80-1.77	940.7	4.17	3.90 $\pm$ 1.89	7.94 $\pm$ 4.51

13	Granites and associated rocks (southern Finland)	3	1.81-1.77	33.5	2.96	2.36 ± 1.07	4.87 ± 2.91
89	Alkaline intrusions	2	0.37	16.8	0.23	0.23 ± 0.080	8.69 ± 4.19
90	Carbonatites	4	2.02-0.36 (Kouvo and Tilton, 1966, Kramm et al., 1993)	61.0	0.88	0.83 ± 0.23	3.77 ± 0.92
91	Impact melt rocks (Lappajärvi)	1	0.08 (Schmieder and Jourdan, 2013)	20.5	1.65	1.65	5.00
101	Amphibolite, diabase and gabbro dyke swarms	101	2.50-1.00	3851.6	0.34	0.30 ± 0.23	4.76 ± 2.49
Svecofennian Domain							
Collision-related intrusions							
15	Granodiorites, tonalites and quartz diorites (central Finland)	814	1.89-1.88	44421.3	1.33	1.18 ± 0.83	3.87 ± 2.68
16	Gabbros and diorites	246	1.89-1.88	2751.9	0.55	0.50 ± 0.38	2.56 ± 1.08
Intrusions postdating main stage of crustal thickening							
14	Microcline granites	207	1.84-1.82	13371.0	2.86	2.45 ± 1.87	5.27 ± 5.65
22	Pyroxene granitoids	13	1.88-1.87	814.0	1.43	1.09 ± 0.86	4.48 ± 3.08
23	Granites (southern central Finland)	25	1.88-1.87	1768.2	1.99	1.80 ± 0.77	4.37 ± 2.49

24	Granites (central Finland)	258	~1.88	16584.2	1.99	1.82 ± 1.01	4.85 ± 4.63
Supracrustal sequences							
17	Quartzites (near Wiborg rapakivi)	2	1.90-1.88	35.3	0.52	0.52 ± 0.20	4.81 ± 0.41
18	Mica schists and mica gneisses	348	1.90-1.88	15883.8	1.81	1.78 ± 0.50	4.64 ± 1.98
19	Intermediate and felsic metavolcanic rocks and metasediments	84	1.90-1.88	2296.7	1.68	1.65 ± 0.86	3.60 ± 1.93
20	Mafic metavolcanic rocks	178	1.90-1.88	4130.1	0.60	0.47 ± 0.48	2.26 ± 0.94
21	Ultramafic metavolcanic rocks	3	1.90-1.88	26.1	0.11	0.12 ± 0.02	2.42 ± 0.95
25	Mica schists, intercalated arkosites and conglomerates	47	1.90-1.87	2327.6	1.37	1.23 ± 0.58	1.37 ± 0.58
26	Intermediate and felsic metavolcanic rocks with metasedimentary intercalations	81	1.89-1.88	1315.8	1.35	1.37 ± 0.74	2.95 ± 1.03
27	Mafic metavolcanic rocks	106	1.89-1.88	1792.8	0.79	0.66 ± 0.57	2.59 ± 1.56
28 ²	Mica gneisses and mica schists with black schist intercalations	386	1.90-1.87	22880.6	1.66	1.64 ± 0.46	4.75 ± 2.30

	(central-western Finland)						
30	Mafic metavolcanic rocks	41	~1.90	743.3	0.51	0.30 ± 0.66	2.51 ± 1.11
32	Pyroxene granitoids and mafic dykes	20	1.89	706.1	0.96	0.82 ± 0.40	5.70 ± 5.11
33	Intermediate and felsic metavolcanic rocks with metasedimentary intercalations	1	1.90-1.88	42.1	0.52	0.52	3.07
34	Mafic metavolcanic rocks	2	~1.90	104.4	0.26	0.26 ± 0.03	2.36 ± 0.36
35	Mica gneiss and mica schist with intercalated carbonate rocks	112	1.93-1.87	6197.2	1.41	1.43 ± 0.65	4.88 ± 4.41
36	Felsic and intermediate metavolcanic rocks	16	~1.92	396.9	0.74	0.76 ± 0.32	3.44 ± 1.82
37	Mafic metavolcanic rocks	56	~1.92	764.2	0.49	0.33 ± 0.45	2.71 ± 3.04
Pre-collisional intrusions							
38	Gneissic tonalites and granodiorites	18	1.93-1.91	659.2	0.98	0.76 ± 0.68	3.97 ± 2.15
Karelian Domain							
39 ²	Granites and granodiorites with	322	~1.8	24592.0	2.56	2.43 ± 1.54	9.93 ± 9.34

	gneissic inclusions (Lapland)						
40	Post-collisional quartzites and conglomerates	10	1.85-1.80	407.7	0.82	0.82 ± 0.20	3.97 ± 0.87
41	Post-collisional granites and granodiorites	37	~1.86	1291.9	1.05	0.90 ± 0.61	5.56 ± 4.14
42	Quartzites and conglomerates	6	1.95-1.85	521.1	1.11	0.62 ± 0.75	4.40 ± 1.65
43	Mafic and felsic metavolcanic rocks	3	~1.88	48.7	1.27	1.40 ± 0.30	4.89 ± 1.74
44	Granites	8	1.89-1.88	340.8	1.20	1.01 ± 0.53	10.13 ± 13.60
45	Quartzmonzodiorites, quartz monzonites and granodiorites	16	1.90-1.86	1560.4	1.99	1.76 ± 1.03	3.48 ± 1.13
46	Gabbros	14	1.95-1.85	95.6	0.57	0.43 ± 0.51	3.08 ± 0.92
47	Mica schists and intercalated black schists	116	2.00-1.95	7951.5	1.32	1.29 ± 0.25	4.51 ± 1.22
48	Banded iron formations	1	2.00-1.95	160.5	0.04	0.04	1.63
49	Mafic metavolcanic rocks with metasedimentary intercalations	33	2.5-2.3	2970.2	0.21	0.12 ± 0.28	2.80 ± 1.30

50	Gneissic alkaline granites	6	1.96-1.95	184.6	1.72	1.45 ± 0.94	4.48 ± 1.50
51	Serpentinites and other rocks of ophiolitic origin	12	1.96-1.95	198.4	0.07	0.04 ± 0.06	3.46 ± 4.54
52	Gabbros	19	2.15-2.00	402.9	0.22	0.10 ± 0.23	3.54 ± 1.83
53	Mica schists, black schists, conglomerates and arkosites	173	2.30-1.95	9371.4	1.66	1.49 ± 0.84	3.82 ± 1.53
54	Ultramafic metavolcanic rocks	24	2.30-1.95	946.2	0.12	0.05 ± 0.15	2.27 ± 1.22
55	Arkositites, mica schists and conglomerates	9	2.00-1.95	612.6	1.03	0.80 ± 0.44	8.25 ± 2.06
56	Carbonates and calc silicate rocks, black schists and metavolcanic rocks	77	2.50-1.95	3504.9	0.61	0.34 ± 0.64	3.55 ± 2.37
57	Mafic and felsic metavolcanic rocks	144	$\sim 2.2^4$	3353.3	0.34	0.18 ± 0.45	3.53 ± 1.82
58	Quartzites	70	$\sim 2.2^4$	2653.2	0.52	0.47 ± 0.56	6.79 ± 3.64
59	Gabbros	26	2.2	703.6	0.27	0.21 ± 0.16	4.29 ± 1.87
60	Quartzites, arkositites and mica schists (Lapland)	253	$\sim 2.2^4$	14280.3	0.95	0.72 ± 0.73	5.81 ± 2.78
61	Conglomerates, arkositites and diamictites	3	$\sim 2.1^4$	125	0.80	0.63 ± 0.27	5.88 ± 1.41

62	Mafic and ultramafic metavolcanic rocks	87	~2.3 ⁴	1864.4	0.51	0.48 ± 0.35	4.43 ± 1.55
Layered intrusions and other intracratonic igneous complexes							
63	Granites	5	2.45-2.3	73.9	4.13	4.24 ± 1.96	7.47 ± 3.25
64	Gabbros and peridotites	33	2.44	954.6	0.21	0.12 ± 0.27	4.27 ± 1.56
65	Intermediate and felsic metavolcanic rocks	14	2.5-2.3	1173.7	1.14	1.31 ± 0.45	4.75 ± 1.006
Syn- to late orogenic intrusive complexes							
66	Orthopyroxene diorites	1	2.74-2.65	85.9	0.14	0.14	1.44
67	Granodiorites, tonalites, quartz diorites, granites and syenites	122	2.74-2.65	6997.8	1.39	1.07 ± 0.94	9.53 ± 6.94
68	Leucocratic granites and granodiorites	35	2.74-2.65	1730.9	2.33	1.58 ± 1.84	9.78 ± 7.20
Greenstone belts							
69	Gabbros	4	3.0-2.7	17.0	0.54	0.58 ± 0.38	3.71 ± 0.56
70	Metaperidotites, serpentinites and soapstones	7	3.0-2.7	107.3	0.11	0.06 ± 0.11	5.17 ± 7.98
71	Ultramafic metavolcanic rocks	8	3.0-2.7	72.8	0.07	0.04 ± 0.09	2.40 ± 1.23

72	Mafic metavolcanic rocks	128	3.0-2.7	2678.2	0.16	0.09 ± 0.17	3.17 ± 1.92
73	Intermediate and felsic metavolcanic rocks	16	3.0-2.7	218.3	1.03	0.79 ± 0.87	4.90 ± 2.52
74	Metasedimentary rocks	56	3.0-2.7	2743.7	0.92	0.84 ± 0.63	5.24 ± 4.61
Gneiss complexes							
75	Paragneisses	52	3.1-2.6	3114.8	1.34	1.00 ± 1.00	6.73 ± 8.41
76	Tonalites, trondhjemites, granodioritic gneisses and migmatites	724	3.1-2.6	55413.3	1.20	0.88 ± 1.18	11.35 ± 14.22
Lapland Granulite Belt and Inari Complex							
77	Garnet-bearing paragneisses	160	2.5-2.0	11958.7	1.20	1.04 ± 1.66	13.77 ± 11.85
78	Orthopyroxene diorites	34	2.5-2.0	1013.6	0.38	0.21 ± 0.54	10.04 ± 19.76
79	Anorthosites	9	2.5-2.0	301.2	0.06	0.06 ± 0.02	2.79 ± 1.83
80	Gneissic granites, granite gneisses and hornblende gneisses	32	2.5-2.0	2332.8	0.69	0.55 ± 0.61	5.73 ± 6.00
81	Foliated gabbros and granodiorites	22	1.95-1.93	918.4	0.76	0.58 ± 0.74	2.80 ± 1.62

82	Paleoproterozoic mafic and felsic metavolcanic rocks	38	2.5-2.0	645.7	0.39	0.32 ± 0.37	2.91 ± 1.73
83	Paleoproterozoic metasedimentary rocks	30	2.5-2.0	1161.5	1.03	0.76 ± 0.81	5.29 ± 3.98
84	Granites	9	2.6-2.5	288.7	2.14	1.91 ± 1.32	7.59 ± 3.16
85	Gneisses and migmatites	58	2.73-2.50 (Meriläinen, 1976; Gaál et al., 1989)	3786.1	1.60	0.97 ± 1.61	7.86 ± 6.65
Caledonian Domain							
1	Caledonian sandstones and shales	4	0.5-0.4	118.7	0.95	0.87 ± 0.55	4.05 ± 0.79
86	Ordovician mafic-ultramafic complex of the Upper Allochton	2	0.49-0.44 (stratigraphic estimate, see e.g. Lehtovaara, 1989)	13.8	0.24	0.24 ± 0.29	2.12 ± 0.50
87	Metamorphic rocks of the Middle Allochton	4	~0.5 (stratigraphic estimate, see e.g. Lehtovaara, 1989)	158.8	1.16	1.04 ± 0.97	3.36 ± 0.34
88	Cambrian sedimentary rocks	6	0.54-0.49 (stratigraphic estimate, see e.g.	202.9	0.88	0.93 ± 0.47	3.11 ± 1.08

	of the Lower		Lehtovaara,				
	Allochton		1989)				

Table 7. Heat production and Th/U ratio by lithologic unit as calculated from our raw outcrop data (N=6465).

Note that ¹ indicates an area-weighted mean, other means are simple arithmetic means from point data within the unit. Tectonic ages are from the 1:100000 bedrock map of Finland (Rasilainen et al., 2008), unless indicated otherwise. The total area of mapped units in Finland reported here is smaller than the actual land area, due to the absence of data in a few geological units. ² Unit 28 here combines units 28 and 281 in Rasilainen et al., (2007). ³ Unit 39 here combines units 39, 391 and 501 in Rasilainen et al., (2007). ⁴ Age has been estimated as a weighted average of age groups in Rasilainen et al., (2007), but neglecting data in group 0 (no age information). For a map of mean heat production within all units, see Figure 15, and for a map of U, Th and K concentrations, see Figures 16, 17 and 18.

Graphical abstract