Radiogenic heat production analysis of Fennoscandian Shield and adjacent areas in Sweden

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SUMMARY

In northern Europe, radiogenic heat production of surface rocks has been extensively studied in Finland and Norway alike. This paper presents a heat production analysis of Sweden, based on a rock outcrop data compilation obtained from the Geological Survey of Sweden (SGU). The study area comprises Precambrian Shield, Caledonian and platform cover areas. Altogether 39 933 samples with uranium, thorium and potassium concentration (C_U, C_{Th} and C_K) and density (ρ) data were available. Heat production (HP) was calculated using raw point data, binning on a regular grid, and averaging by bedrock units in the geological map. Methods based on raw point data and grid-based binning resulted in HP values of 2.5 ± 4.1 and 2.5 ± 5.6 μW m^{-3}, respectively, while averaging by lithology produced a lower value of 2.4 ± 1.7 μW m^{-3}. Limiting the lithology-based averaging to Precambrian bedrock areas resulted in heat production of 2.4 ± 1.6 μW m^{-3}. Due to the small geographic extent of area covered by sediments, this is similar to the Precambrian-only value. Regardless of the calculation method, heat production in Sweden is considerably higher than the corresponding value for Finland. The Swedish platform cover had apparently the lowest heat production (1.0 ± 1.8 μW m^{-3}) of all units but the presence of Precambrian rocks below the sediments means that this value strongly misleads if used to represent the entire upper crust. Svecokarelian (Svecofennian) and Sveconorwegian rocks, which comprised 94.0 per cent of all individual observations, had heat production values of 2.6 ± 1.8 and 1.7 ± 1.4 μW m^{-3}, respectively. Although the Swedish data still have large spatial gaps when compared to Finnish data, most bedrock units in Sweden are covered. It is obvious that the higher heat flow of Sweden compared to that of Finland is caused by near-surface (i.e. upper crustal) heat production, and crustal differentiation in Sweden is also larger.

Key words: Composition and structure of the continental crust; Heat flow; Europe; Spatial analysis; Cratons; Crustal structure.

1 INTRODUCTION

Radiogenic heat production is one of the key geothermal parameters of the lithosphere. It has been studied with the help of airborne surveys, and laboratory measurements of samples from glacial till or from the underlying basement. Airborne surveys of radioactivity were initiated in Sweden in late 1960s due to the interest towards uranium prospecting, yet thorium and potassium concentrations have been also determined to estimate heat production in general. By now the majority of the Swedish land area has been surveyed using radiation measurements from a fixed wing aircraft with 30–60 m altitude and 200–800 m line spacing (Kock & Samuelsson 2011). The largest areas currently devoid of airborne U, Th and K data are located in the Caledonides, as seen in the online map provided by the Geological Survey of Sweden (SGU; https://apps.sgu.se/kartvisare/). On

the other hand, data from till measurements have been published in Geochemical Atlas of Sweden (Andersson *et al.* 2014), with U, Th and K concentration maps included therein.

2 DATA AND NORDIC PERSPECTIVE

In Nordic countries, the interest towards mapping heat production using outcrop data has been manifested by surveys of Norwegian (Slagstad 2008) and Finnish (Veikkolainen & Kukkonen 2019) bedrock outcrop data. No study based on Swedish outcrop data has been undertaken yet, despite the presence of an abundant lithogeochemical database at SGU. It incorporates measurements from prominent lithologies of the country, allowing the calculation of heat production (HP). For this purpose, we used the equation of

Rybach ([1973](#)):

$$HP = \rho(9.52\,C_U + 2.56\,C_{Th} + 3.48\,C_K) \times 10^{-5}\,[\mu W\,m^{-3}], \quad (1)$$

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 [per cent], respectively. These radiogenic isotopes account for *ca.* 98 per cent of heat production in rocks. As many as 40 306 samples had this information, compared to the number of 6465 samples in the Finnish lithogeochemical database (Rasilainen *et al.* [2007](#)). However, the Finnish data are relatively evenly distributed throughout the country, despite the stratified sampling procedure which favours areas with small-scale lithological variation. The distribution of Swedish data is much more uneven, with some areas entirely devoid of data. Also in Norway, the situation is closer to that of Sweden than to that of Finland (Slagstad [2008](#)). Various interpolation methods, such as radial basis functions (RBF; Fornberg *et al.* [2002](#)), can be applied to deal with the problem of uneven data. In Finland, RBF interpolation has provided a mean heat production of $1.4 \pm 1.2\,\mu W\,m^{-3}$, compared to the value of $1.3 \pm 1.2\,\mu W\,m^{-3}$ calculated using the arithmetic average and standard deviation from point data (Veikkolainen & Kukkonen [2019](#)). On the other hand, Slagstad ([2008](#)) averaged Norwegian heat production data in ArcGIS software by using actual geological unit sizes as weighting factors, instead of applying any interpolation. This procedure is also applied in our paper.

Because Swedish bedrock has been adequately documented with lithogeochemical codes, we used a separate compilation of 10 963 density measurements in addition to 40 306 determinations of C_U, C_{Th} and C_K data. The data compilations partly overlapped, and therefore a number of density values could be directly associated with C_U, C_{Th} and C_K data from same localities, yet not necessarily from same samples. To combine density data with radiogenic element concentration data, we used sample codes from both data compilations and $X–Y$ coordinates in SWEREF99 TM system with $15°00'$E as a central meridian and 0.9996 as a scale factor. Both X and Y were in metres, not in kilometers, and to avoid negative X values, 500 000 m had been added to each X coordinate value. The precision of coordinate data was 1 m both in the case of density data and element concentration data, yet in some cases, different rock types appeared at same localities. A typical case is a Precambrian granitic basement cut by narrow dykes, such as those in the 1526–1497 Ma Ragunda rapikivi formation close to Caledonides (Piper [1979](#); Persson [1999](#)) and those of the coeval Rödö complex (Moakhar & Elming [2000](#); Andersson & Förster [2003](#)) on the east coast. Mainly because of duplicate measurements of element concentrations from same locations and even from same samples, as many as 23 260 (57.7 per cent) of all C_U, C_{Th} and C_K data could be attributed to actual density measurements. For the rest of the radiogenic element data, we calculated the mean density for their respective source rocks and applied that value in eq. ([1](#)), in place of the actual ρ value from the locality. Some rare source rocks, such as metasyenitoids and peridotites, were represented by C_U, C_{Th} and C_K data but not by ρ data and were left out from further investigation because densities of rocks vary from 2519 to 3510 kg m^{-3} and therefore the presence of ρ data was required to ensure consistency in methodology. As many as 39 933 of 40 306 (99.0 per cent) element concentrations could be assigned either to actual ρ data from same locations, or to mean ρ data from similar lithology, regardless of location. We used this data set as a basis in our subsequent analyses. For unaveraged heat production values calculated using eq. ([1](#)), see Appendix A.

Before visualizing heat production by lithological polygons in ArcGIS as previously done in the case of Norway and Finland (Slagstad [2008](#); Veikkolainen & Kukkonen [2019](#)), we decided to average multiple data from same locations for the purpose of visualizing point data by their coordinates. The number of unique $X–Y$ coordinate pairs with C_U, C_{Th}, C_K and ρ data turned out to be 15 208. Before any further analyses, we averaged values of heat production parameters (C_U, C_{Th}, C_K and ρ) for each site using a simple arithmetic mean (Table [1](#)), converted rectangular coordinates to geographic ones and plotted data in maps (Figs [1–3](#)). While studying Th/U ratio remains important for understanding metamorphism (Hyvönen *et al.* [2005](#)), our Swedish data has no consistent information about the metamorphic grade of rocks, and also, the ratio calculation can easily become biased when either C_{Th} or C_U or both are very close to detection threshold. Values below the threshold were treated as zero in the original Swedish data and their use in Th/U ratio calculation results would result in zero, or division error. Therefore we did not produce a Th/U map because it would have not included all data present in individual concentration maps. Also, we were unable to produce box plots of Th/U ratio and heat production by metamorphic grade in the way done for Finnish data. In Finland, high Th/U ratios are common in highly metamorphosed granitoids (Veikkolainen & Kukkonen [2019](#)), but the correlation between heat production and metamorphic grade is weak in Finland and also globally (Hasterok *et al.* [2018](#)).

The Swedish sampling site with the largest amount of raw data, that is 19 entries from gneiss granites and other granitoids, had SWEREF99 TM coordinates 467 082, 6 322 974 and was situated in the 1713 + 2/–3 Ma Alvesta pluton of the Trans-Scandinavian Igneous Belt (TIB; Johansson [1990](#); Högdahl *et al.* [2004](#)). However, the spatial density of data in the immediate vicinity of this point is small. Parts of the 2.44–1.96 Ga Svecofennian area close to Stockholm and parts of the 1.14–0.90 Ga Sveconorwegian area close to the west coast (Balling [2013](#); Sadeghi *et al.* [2013](#)) have been sampled more densely, and so are the more northerly rapakivi granite areas (Persson [1999](#); Andersson & Förster [2003](#)) too. Unfortunately, the Caledonian orogeny, which represents a unique tectonothermal age in Sweden, is very poorly represented in terms of data density, and the northern Swedish Caledonides are entirely devoid of data.

In the Swedish data, differences between heat production values calculated using density data from sampling location, and heat production values calculated using mean densities from the respective rocks were generally small. If density data were unavailable, an estimated average density from same rocks could be reasonably used. Applying the value of 2.65 kg m^{-3} (Lindén *et al.* [1983](#)) as mean upper crustal rock density for Finland and Sweden as a whole in the heat flow—heat production study of Näslund *et al.* ([2005](#)) is therefore not an oversimplification. In our compilation, the heat production determined from mean density of each lithology was on average just 0.02 $\mu W\,m^{-3}$ smaller than that determined from the sample density. The distribution of these differences had a standard deviation of 0.33 $\mu W\,m^{-3}$. The largest negative differences were –2.83, –1.68, –1.29, –1.11 and –0.81 $\mu W\,m^{-3}$, and the largest positive differences were 1.30, 0.98, 0.84, 0.83 and 0.60 $\mu W\,m^{-3}$ in the raw data. Except for a brief comparison of measured rock density and heat production, we decided to use mean densities of lithologies in analyses of this paper.

In our spatial analysis, we applied a grid with lower and upper limits of 292 500–907 500 m in X direction (easting) and with 6 152 500–7 622 500 m in Y direction (northing). The dimensions of an individual cell were 5000 by 5000 m and therefore the total number of cells was $126 \times 298 = 37\,548$. To concentrate on areas with an adequate number of data points, we binned our unstructured data to this grid. After assigning each $X–Y$ coordinate pair in the

Table 1. Heat production (HP) constituents in raw data before and after averaging by sampling site coordinates.

	Before averaging ($N = 39\,933$)	After averaging ($N = 15\,208$)	After averaging and grid binning (loose; $N = 9954$)	After averaging and grid binning (strict; $N = 5421$)
Mean $C_U \pm$ SD [ppm]	4.61 ± 14.65	4.60 ± 20.84	4.65 ± 15.94	4.63 ± 14.89
Mean $C_{Th} \pm$ SD [ppm]	15.03 ± 16.62	14.65 ± 14.79	15.07 ± 16.70	14.92 ± 16.10
Mean $C_K \pm$ SD [%]	3.26 ± 1.40	3.24 ± 1.35	3.26 ± 1.40	3.27 ± 1.39
Mean $\rho \pm$ SD [kg m^{-3}]	2698.8 ± 88.6	2702.4 ± 89.8	2699.0 ± 88.8	2698.6 ± 88.4
Mean HP $\pm$ SD [μW m^{-3}]	2.50 ± 4.12	2.47 ± 5.53	2.52 ± 4.43	2.50 ± 4.17

After preliminary averaging, values were dependent on whether loose or strict grid binning was used. SD means standard deviation.

data to a certain grid cell, we produced a set of grid cells appropriate for subsequent analysis (data mask) and left the remaining cells without attention. In the loose binning, not only cells with actual data points were included in the mask, but also nine surrounding cells in each case. This meant that the maximum possible distance from a data point to the farthest edge of the mapped area was $2 \times \sqrt{2} \times 5000\,\text{m} = 14\,140\,\text{m}$. The total number of grid cells where heat production parameters was to be calculated in this scheme was 9954. The density of sampling sites was $15\,208/9954 = 1.5$ per grid cell, that is one site per 16.4 km^2.

In the situation where all cells with no data were left out of analysis, the number of cells accepted for heat production analysis was only 5421. In this strict binning, the density of sampling sites was $15\,208/5421 = 2.8$ per grid cell, that is one site per 8.9 km^2. This value is much higher than the density of one site per 52 km^2 of data (Rasilainen *et al.* 2007) in the analysis of the Finnish heat production (Veikkolainen & Kukkonen 2019), yet the Finnish data covered the all major geological units of the country in a much more consistent way without significant spatial gaps. We tabulated Swedish heat production constraints in the case of loose binning and in the case of strict binning as well (Table 1). In loose binning, 40.5 per cent (380 200 km^2) of grid cells had values for ρ, C_U, C_{Th} and C_K, and in strict binning, 14.4 per cent of cells (135 525 km^2) had the same information. For the visual comparison of data coverage of these binning options and resulting heat production values, the reader is referred to Appendix B. In both cases, binning does not take any actual geological constraints into account, but it is only used to calculate averages within fixed cells.

ur The Swedish ρ, C_U, C_{Th} and C_K data was based on commonly applied methods, that is weighing samples in air and water, Inductively Coupled Plasma Mass Spectrometry (ICP-MS), and X-ray fluorescence spectrometry (XRF). We did not analyse the relation of heat production to various properties such as seismic *P*-wave velocity or concentrations of silica and ferric oxide in the way done by Veikkolainen & Kukkonen (2019), who failed to find any systematic correlations of that kind in Finland. Detailed Swedish geochemical surveys have been carried out in areas like the Bergslagen mining district in northern Svealand (Kumpulainen *et al.* 1996) and Kristineberg deposit in the Skellefteå group (Hannington *et al.* 2003). Wilson & Åkerblom (1982) determined eight areas of granites with anomalously high heat production; (A1) southern Norrbotten, (A2) northern Västerbotten, (B) Hotagen, (C) Bergslagen, (D) Bohus, (E) Gothenburg, (F) Götemar and (G) Blekinge. In particular, the Halen granite of Götemar area turned out to have extremely high C_U (27 ± 5 ppm) and C_{Th} (80 ± 6 ppm) values, while its C_K

is also high (5.0 ± 0.1 per cent), but not exceptional. Landström *et al.* (1979) also determined high values for the Halen granite; 4.4 per cent for C_K, 23.7 ppm for C_U and 61.1 ppm for C_{Th}, leading to a heat production of 10.7 μW m^{-3}. The term 'granite' is sometimes used as a generalization of rocks with silica content over 65 per cent (McLaren & Powell 2014), but in this paper, we refer to granites *sensu stricto* rather than *sensu lato*, in line with classification in the original Swedish lithogeochemical data.

For analysing heat production by actual lithotectonic areas, we used the 1: 1000 000 bedrock map of Sweden (https://apps.sgu.se/kartvisare/kartvisare-berggrund-1-miljon.html), available in ArcGIS shapefile format (shp). The map incorporated 147 lithotectonic areas, yet not all of them were represented by heat production data. The total number of polygons within these areas was as large as 8800, although 6994 of them were devoid of heat production data points. The remaining 1806 polygons, however, covered an area of 355 838 km^2, compared to the area of 249 276 km^2 of empty polygons. The all 8800 polygons together comprised an area much larger than the Swedish land area, because a couple of of them extended to the sea. In particular, size of polygon, which included Gotland, was 30 825.4 km^2, almost ten times the actual land area of the island (3183.7 km^2). To avoid bias caused by seafloor in area-weighted heat production estimate, we reshaped this area, and therefore the platform cover shrinked from 34 933.5 to 7291.8 km^2. From Phanerozoic areas of Öland and Scania, no data were available but neither did heat production polygons cover those areas. In Proterozoic (post-1.8 Ga) magmatic and sedimentary provinces, one column obviously included sea area. We removed this part and recalculated the polygon area, shrinking it from 3566.5 to 809.6 km^2. The reduction in area is small and the operation was mainly done to improve the appearance of the map. The total area of Proterozoic (post-1.8 Ga) magmatic and sedimentary provinces also changed from 23 057.8 to 20 300.9 km^2. With these two changes taken into account, the total area of units with heat production data decreased from 355 837.8 to 328 196.1 km^2. For a general view of Swedish geological units and subunits, the reader is referred to Fig. 4.

Statistics of heat production parameters were calculated within each polygon, and areas of particular interest were taken into a more detailed investigation. Polygons with the largest number of data are listed in Table 2. All polygons belonged to six main tectonic units: Blekinge–Bornholm orogen, Caledonides, Platform cover, Proterozoic (post-1.8 Ga) magmatic and sedimentary provinces, Svecokarelian orogen and Sveconorwegian orogen. All polygons had distinct area identification codes (IDs).
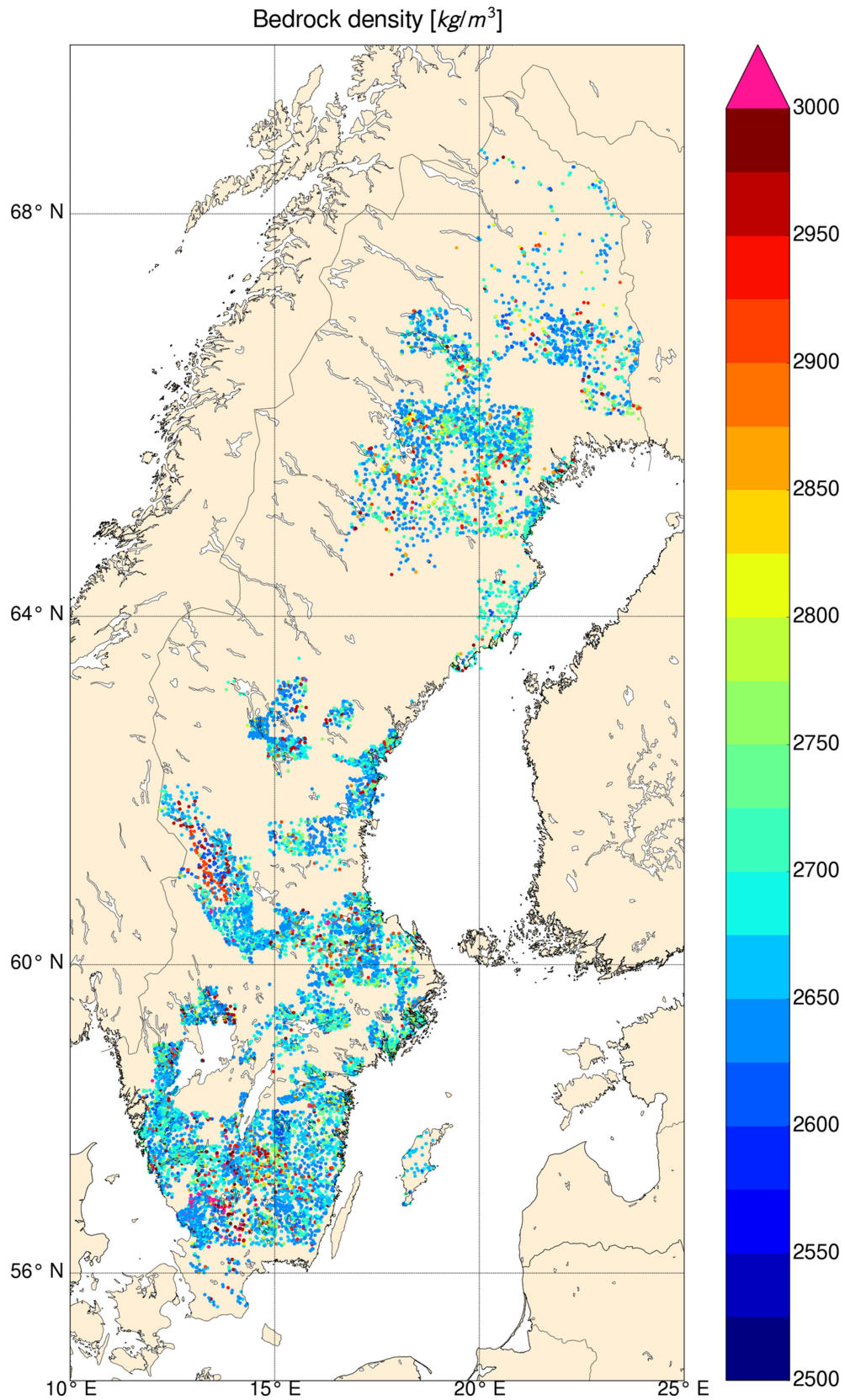
Figure 1. Bedrock density by individual data sites ($N = 15\,208$). For sites with more than one initial value, site-level average has been used. Data © SGU.
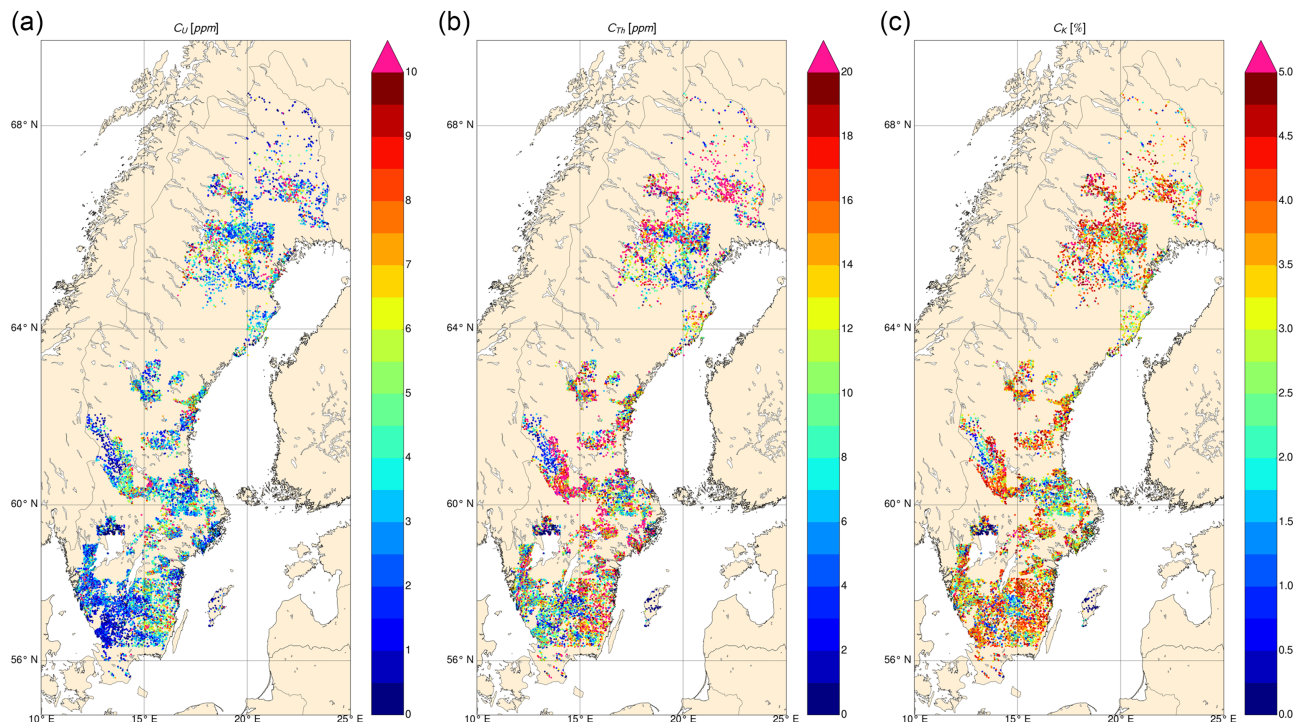
Figure 2. Concentration of (a) uranium (b) thorium and (c) potassium by individual data sites ($N = 15\,208$). For sites with more than one initial value, site-level average has been used. Data © SGU.

3 RESULTS

Analysing the Swedish data by main tectonic units (Table 3) reveals several interesting features. The highest area-weighted mean heat production occurs in the Caledonides, yet this is most likely a sampling bias. Caledonide polygons with at least one data point cover an area of 12 166 km^2, yet the spatial distribution of the 134 data points is highly uneven, with the northern Caledonides being almost devoid of data. A polygon with a size of 7676 km^2 in the southern part of the Swedish Caledonides features a high mean heat production 4.03 ± 3.47 µW m^{-3}, yet only nine measurements have been used to determine this value. Close to the Norwegian border, a small polygon with the size of 132 km^2 only is represented by 30 data points with the mean heat production of 1.18 ± 0.21 µW m^{-3}. However, to the southwest observations are more abundant in an area dominated by Jotnian sandstones. Right east of the Caledonides, a polygon consisting of granites, granodiorites, syenitoids, quartz monzodiorites and metamorphic equivalents in the Bothnia-Skellefteå unit has just 2 samples in an area of 6936 km^2. As many as 37 620 of 39 918 observations (94.2 per cent) and 1661 out of 1806 polygons (92.0 per cent) belong to Svecokarelian and Sveconorwegian tectonic units, which had heat production values of 2.6 ± 1.8 and 1.7 ± 1.4 µW m^{-3}, both higher than estimated average in the upper 12–14 km layer of the crust globally, *ca.* 1.6 µW m^{-3} (Huang *et al.* 2013; Rudnick & Gao 2014).

In the Swedish bedrock map, main units are divided into subunitswhich consist of distinct rock types. However, Proterozoic (post-1.8 Ga) magmatic and sedimentary provinces, platform cover, Caledonides and Blekinge–Bornholm orogen have only one subunit. On the other hand, Sveconorwegian bedrock consists of four subunits (Idefjorden terrane, upper unit of eastern segment, middle unit of eastern segment, lower unit of eastern segment) and all Svecokarelian bedrock to six subunits (Bergslagen, Bothnia-Skellefteå, Ljusdal, Norrbotten, Småland and Överkalix; Fig. 4, Appendix C).

The Blekinge–Bornholm orogen is also the southernmost exposed part of the Fennoscandian Shield, located south of the Småland-Blekinge deformation zone (SBDZ), the. Most rocks in the area crystallized at 1.75–1.77 Ga, yet thermal overprinting occurred at 1.45–1.40 Ga (Johansson *et al.* 2005). The area-weighted mean heat production in Blekinge rocks is 2.36 ± 1.08 µW m^{-3}, slightly lower than the Svecokarelian average of 2.63 ± 1.78 µW m^{-3}. The 1.83–1.82 Ga Oskarshamn-Jönköping belt (Mansfeld *et al.* 2005), which consists of calc-alkaline intrusions, volcanic rocks and coarse-grained clastic metasediments, has lower heat production compared to the surrounding TIB rocks. To the north, the 1.8 Ga Småland subunit of Svecokarelian orogen has an area of 23 974 km^2 and an area-weighted mean heat production of 2.55 ± 1.40 µW m^{-3}. In the more northerly 58 658 km^2 Bergslagen subunit, the corresponding heat production value is 2.72 ± 1.90 µW m^{-3}. Especially in central-western Bergslagen, 1.85–1.75 Ga granites and pegmatites with heat production over 4 µW m^{-3} are common. Bergslagen is bordered by the Ljusdal subunit in the north, characterized by 1.96–1.84 Ga rocks with a dominance of 1.87–1.84 Ga metamorphic granitoids. This part of Svecokarelian Sweden has an area-weighted value of 2.41 ± 1.29 µW m^{-3}. The larger Bothnia-Skellefteå subunit has a greater diversity in rock types, which is also reflected in the larger standard deviation of heat production (2.48 ± 1.64 µW m^{-3}). The corresponding value for the more northerly Norrbotten subunit is 3.13 ± 2.52 µW m^{-3}, and for the Överkalix subunit, 2.24 ± 1.58 µW m^{-3}. In the Sveconorwegian part of Sweden, the western Idefjorden terrane had an area-weighted mean heat production of 1.95 ± 1.71 µW m^{-3}. Put together, the three other more easterly Sveconorwegian subunits feature a slightly lower value, 1.65 ± 1.22 µW m^{-3}. The southern part of the Eastern Segment, where heat production is lowest, very high Th/U ratios are common. In Sveconorwegian area, only the eastern part represents reworked crust of the TIB, opposite to the western part which is
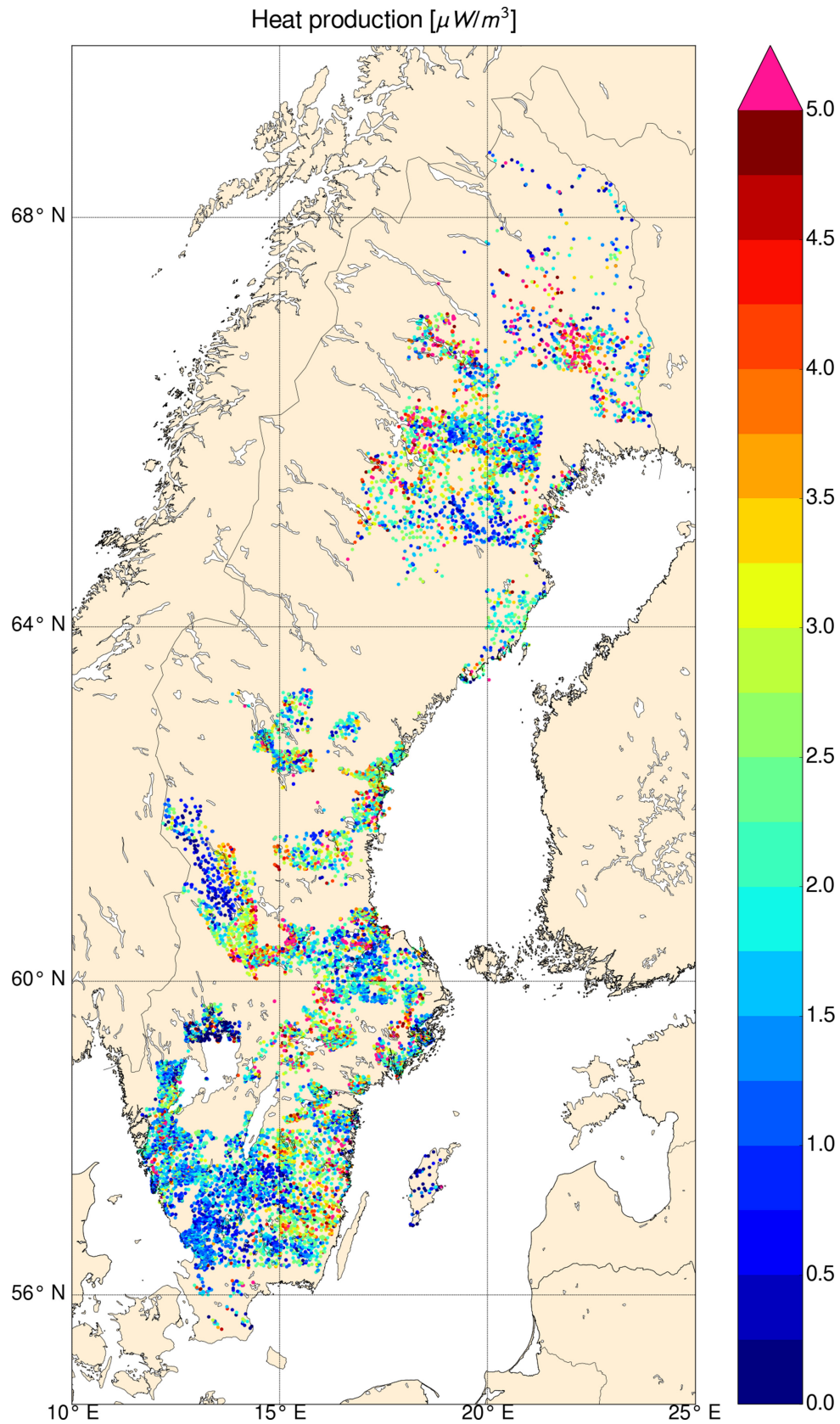
Heat production [$\mu W/m^3$]

Figure 3. Heat production by individual data sites ($N = 15\,208$). For sites with more than one initial value, site-level average has been used. Data © SGU.
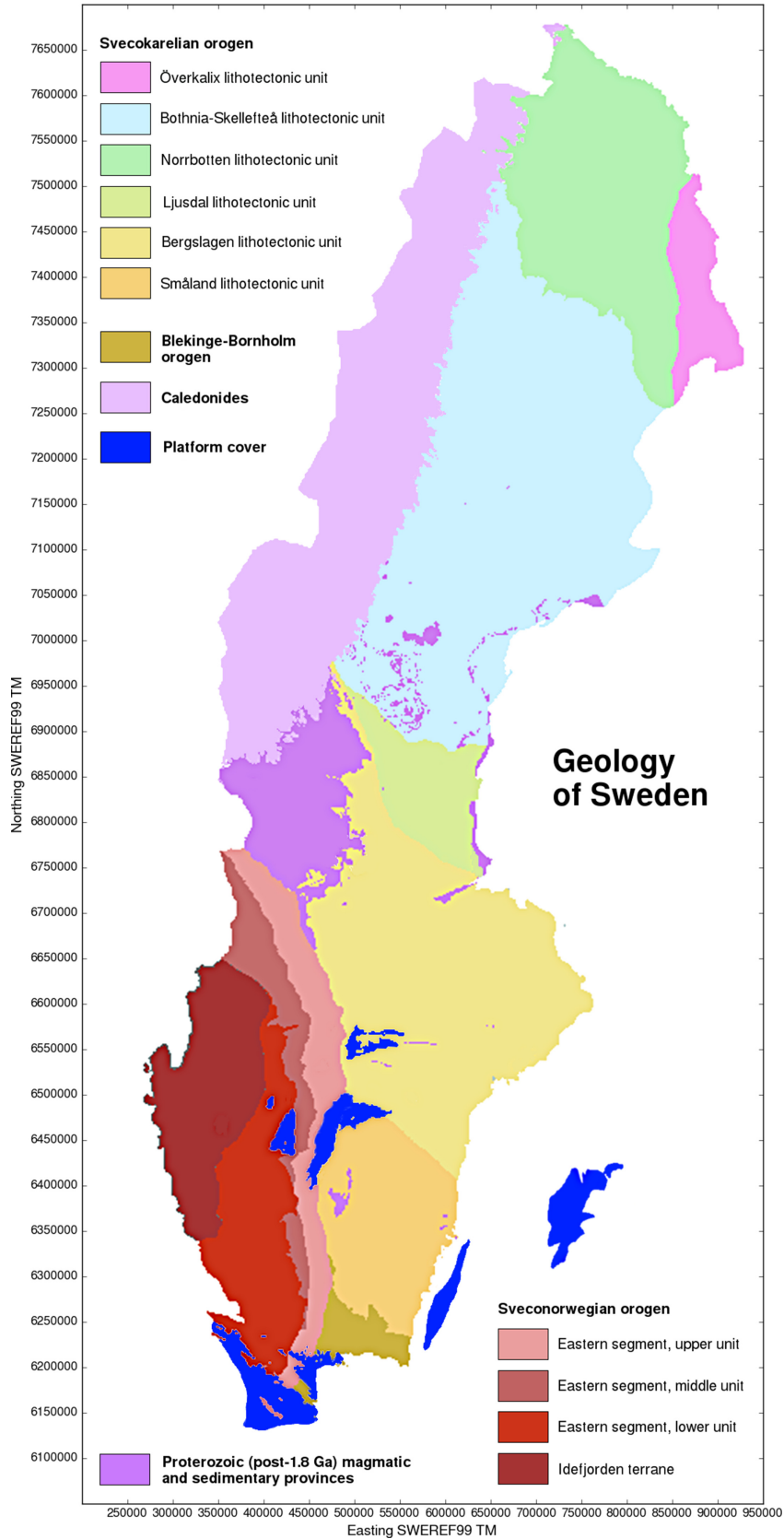
Figure 4. Swedish geological units (bold font) and subunits (normal font). All Swedish land area is shown, including polygons with no heat production data.

Table 2. Swedish map areas with the greatest number of heat production data points.

Area ID	Rock type	N	Area [km^2]	Mean HP $\pm$ SD [μW m^{-3}]
1057	Granitoid and subordinate syenitoid (*ca.* 1.91–1.87 Ga), metamorphic; Svecokarelian orogen; Bergslagen lithotectonic unit	3159	24 142	2.31 $\pm$ 2.21
847	Granite, granodiorite, syenitoid, quartz monzodiorite and metamorphic equivalents (1.8 Ga); Svecokarelian orogen; Småland lithotectonic unit	2605	17 975	2.63 $\pm$ 1.50
7838	Granitoid (1.6–1.5 Ga), metamorphic; Sveconorwegian orogen; Idefjorden terrane	2200	13 296	1.92 $\pm$ 2.03
1135	Metagreywacke, mica schist, graphite- and/or sulphide-bearing schist, paragneiss, migmatite, quartzite, amphibolite (*ca.* 1.96–1.87 Ga); Svecokarelian orogen; Bothnia-Skellefteå lithotectonic unit	1760	29 687	2.53 $\pm$ 2.22
6815	Granitoid to syenitoid migmatitic gneiss (1.7 Ga); Sveconorwegian orogen; Eastern Segment, lower unit	1175	8874	1.35 $\pm$ 0.91

Area IDs are from the geological map of Sweden, available in ArcGIS shapefile format from the Geological Survey of Sweden.

Table 3. Heat production by main Swedish tectonic units.

Main tectonic unit	Subunits	N_p	N_d	Area [km^2]	Mean HP [μW m^{-3}]
Blekinge–Bornholm orogen	Blekinge–Bornholm orogen	14	226	3180.6	2.36 $\pm$ 1.08
Caledonides	Caledonides	13	134	12 166.4	2.89 $\pm$ 2.38
Platform cover*	Platformal sedimentary cover rocks	16	201	7291.8	0.95 $\pm$ 1.80
Proterozoic (post-1.8 Ga) magmatic and sedimentary provinces	Proterozoic (post-1.8 Ga) magmatic and sedimentary provinces	102	1737	20 300.9	1.88 $\pm$ 0.81
Svecokarelian (Svecofennian) orogen	Bergslagen lithotectonic unit, Bothnia-Skellefteå lithotectonic unit, Ljusdal lithotectonic unit, Norrbotten lithotectonic unit, Småland lithotectonic unit, Överkalix lithotectonic unit	1364	28 172	216 243.0	2.63 $\pm$ 1.78
Sveconorwegian orogen	Eastern segment, lower unit; Eastern segment, middle unit; Eastern segment, upper unit, Idefjorden terrane	297	9448	66 256.5	1.74 $\pm$ 1.37
All main units		*1806*	*39 918*	*325 439.2*	*2.37 $\pm$ 1.65*
*Precambrian main units***		*1777*	*39 583*	*305 981.0*	*2.38 $\pm$ 1.62*

Subunits are also listed. N_p = number of polygons, N_d = number of data points, Area = total area of tectonic unit, Mean HP $\pm$ SD = mean heat production and standard deviation calculated as a weighted averages, using polygon area as a weighting factor.

*The majority of the platform area consists of seafloor rather than land. The most important land areas are Gotland and parts of Scania, but heat production data are available from Gotland only.

**Precambrian-only data exclude Caledonides and platform cover. For a map of these units and subunits, see Fig. 4, yet note that polygons without heat production data are also shown therein.

younger (Bingen *et al.* 2008; Roberts *et al.* 2013; Slagstad *et al.* 2018).

The largest Swedish areas with high heat production turned out to be concentrated in the Norrbotten subunit, representing 1.88–1.75 Ga tectonothermal ages on the geological map. There are 121 polygons with a mean heat production of 5.0 μW m^{-3} or more, with a total area of 13 039 km^2, visible in fuchsia color in Fig. 5. The vast majority of these polygons represented Svecokarelian tectonothermal age, with a total area of 12 540 km^2. They were present in all six Svecokarelian subunits, with the exception of Ljusdal. The rest
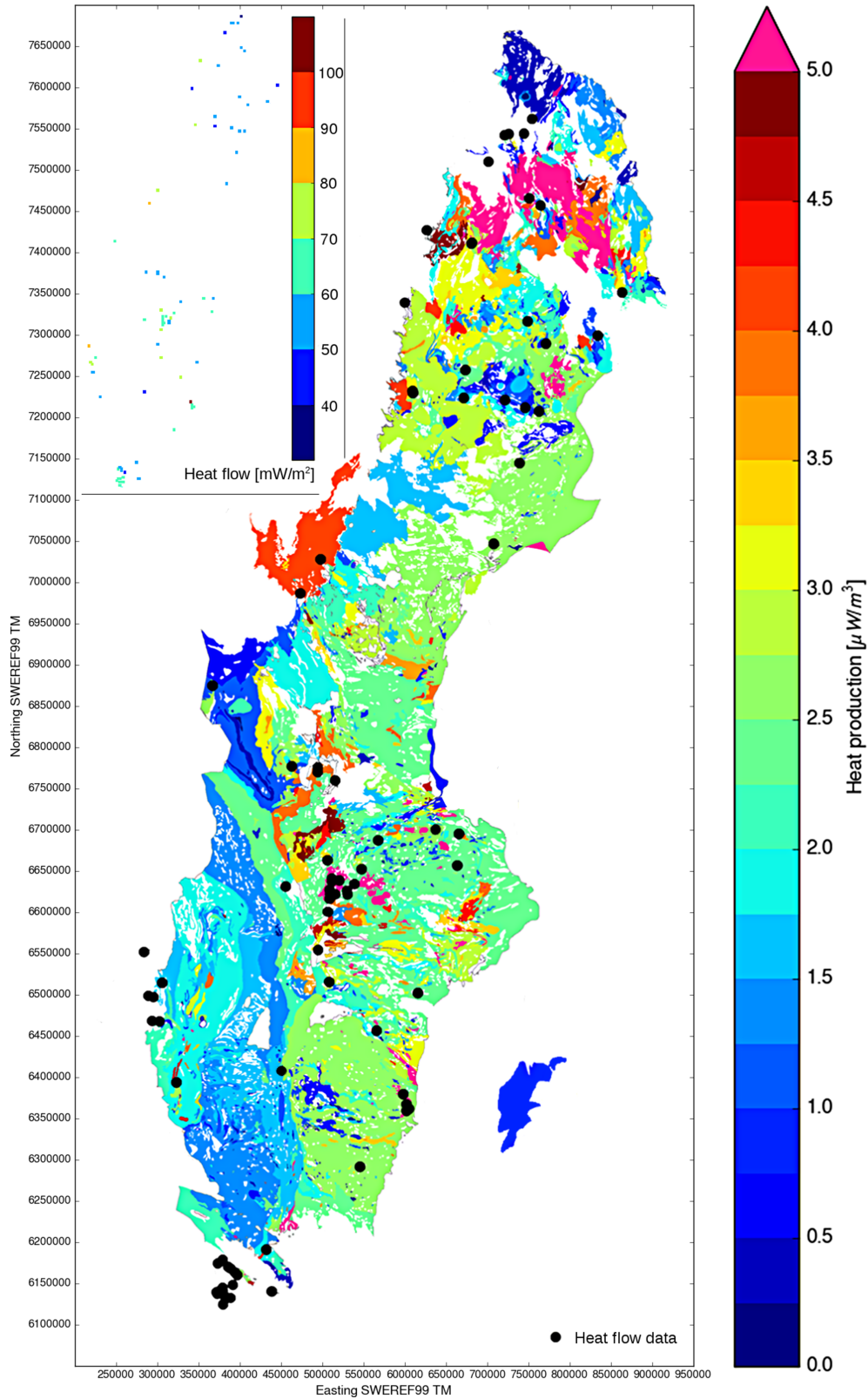
Figure 5. Heat production by geological unit polygons in Sweden. Heat flow sites ($N = 86$) are shown with dots. The subplot indicates heat flow values binned using the 10 km grid. For a more detailed description of areas with high heat production (over 5 μW m^{-3}), see Appendix C, and for a more detailed description on heat flow data, Appendix D. Data © SGU.

were Sveconorwegian (193 km^2), or belonged to other post-1.8 Ga igneous and sedimentary provinces (204 km^2), platformal sedimentary cover rocks (11 km^2), or Blekinge–Bornholm orogen (91 km^2). In southern Sweden, the western area composed of Sveconorwegian rocks is distinct with its low heat production, while the eastern part composedof Svecokarelian and Blekinge–Bornholm orogen rocks has higher values. Most polygons with high heat production, over 5 μW m^{-3}, are represented by only a few samples and are also small in area. The majority of them are also Svecokarelian, falling within a narrow age range (Appendix C). An investigation of polygons with heat production of 5–10 μW m^{-3} reveals a 1.85–1.75 Ga granite-pegmatite area in Norrbotten, with an area of 1242.8 km^2 and heat production of 5.3 ± 4.7 μW m^{-3} determined from 257 samples. A nearby area, also representing 1.85–1.75 Ga granite-pegmatites, has an area of 4040.3 km^2 and heat production of 6.1 ± 5.3 μW m^{-3} determined from 213 samples. In Norrbotten, the third major area with high heat production (5.0 ± 3.9 μW m^{-3}) is represented by 133 samples on an area of 1481.1 km^2. On the other hand, an extremely low heat production of 0.5 ± 0.3 μW m^{-3}, is apparent in the 3.20–2.65 Ga rocks of the far northern Sweden, comparable to Finnish Archean areas (Veikkolainen & Kukkonen 2019). Actually, the only Swedish sedimentary area with a substantial number of heat production determinations, namely Gotland, has a higher heat production than the northernmost part of the country (Table 1).

The choice between two binning options did not appear to affect heat production much. The value of 2.52 ± 4.43 μW m^{-3} obtained from loose binning after site-level averaging is essentially the same as the value of 2.50 ± 4.17 μW m^{-3} obtained from strict binning after site-level averaging. In an analysis of Finnish and Swedish earthquake data, Veikkolainen *et al.* (2017) concluded that the apparently nonexistent link between terrestrial heat flow and seismic cutoff depth requires that any major heat flow variations must result from shallow lying (i.e. upper crust) heat producing units. The Swedish heat production data, despite not covering the entire country, covers most major Swedish lithologies. Therefore sampling bias is unlikely to explain the higher heat production in Sweden compared to that in Finland. However, calculation of heat production from mapped Swedish tectonic units using weighted averages of unit sizes results in a slightly smaller value (2.37 ± 1.65 μW m^{-3}) compared to grid-based result. After polygon modification described in Section 2, this value does not involve seafloor which would bias the result, yet the presence of Precambrian rocks below the Phanerozoic cover means that results from Gotland only represent the surface (Sopher *et al.* 2016). Leaving the Phanerozoic parts, that is Caledonides and platform cover, out of analysis leads to a unit-weighted heat production of 2.38 ± 1.61 μW m^{-3}. This is also close to the value obtained from grid-based binning and obviously a more realistic value for the upper crustal heat production in Sweden, even though the thickness of the upper crust is poorly constrained globally and varies within a large range of 2–16 km globally (Hasterok & Chapman 2011).

In the Finnish data (Veikkolainen & Kukkonen 2019), different interpolation options greatly affected the slope of linear heat flow—heat production (Q-A) plots, but estimated mean heat flow was subject to minor changes only. Although the uneven and impractical distribution of heat flow data in Sweden does not allow a reliable determination of Q-A plots except for a very limited data from granitoids with high heat production (Pinet & Jaupart 1987), it is obvious from point data and interpolated maps (Slagstad *et al.* 2009; Veikkolainen *et al.* 2017) that heat flow in Sweden is larger

than that in Finland. The geotherm representing high surface heat flow in Fennoscandia, namely 60 mW m^{-2} was related to the upper crustal heat production constraint of 2.1 μW m^{-3} in Veikkolainen *et al.* (2017). Given the uncertainties inherent in determination of one-dimensional geotherms, this values is surprisingly close to our average Swedish heat production rates which are in the range of 2.1– 2.5 μW m^{-3}. Unlike data in this study, the Swedish part of the heat flow data compilation of Veikkolainen *et al.* (2017) does not include the heat flow determination made for the proposed site for a spent nuclear fuel repository at Forsmark (Sundberg *et al.* 2009), nor for the previously suggested alternative site of Laxemar (63.3 mW m^{-2}, also in Sundberg *et al.* 2009). Neither does it incorporate the recent heat flow determination from the *ca.* 1820 m deep borehole in Lake Vättern (47.0 mW m^{-2}, Sundberg *et al.* 2016), important because it is located far from other boreholes in southern Sweden. For Laxemar, a mean heat flow of 61.0 mW m^{-2} of Sundberg *et al.* (2016) and the previous result (Hurter & Hänel 2002) was used as the data point value in the calculation of mean Swedish heat flow. No palaeoclimatic corrections were available for Vättern, but the depth behaviour of heat flow in the diorite section of the borehole makes it reasonable to assume that the heat flow constraint (47 mW m^{-2}) from the deepest measured section of the hole (1700–1800 m) is closest to a value undisturbed by long-term climate variations. We used this constraint as a reasonable approximation of palaeoclimatically corrected heat flow. Put together, Swedish heat flow values have a mean Q = 62.8 ± 12.4 mW m^{-2} calculated from palaeoclimatically corrected point data and Q = 52.0 ± 11.4 mW m^{-2} from uncorrected point data. From the Finnish data gathered by Veikkolainen *et al.* (2017), the corresponding values are Q = 42.1 ± 11.3 and 37.3 ± 11.0 mW m^{-2}. Palaeoclimatic disturbance is the most obvious source of uncertainty in heat flow determinations of northern Europe (Čermak *et al.* 1993; Slagstad *et al.* 2009; Majorowicz & Wybraniec 2010) and therefore palaeoclimatically corrected values should be preferred over uncorrected ones despite the great uncertainty on glacial history and basal thermal conditions of ice sheets (Näslund *et al.* 2005). Detailed descriptions of application of ground surface temperature models are available only for a few boreholes, such as Forsmark and Laxemar (Sundberg *et al.* 2009), yet these are too shallow to record the entire depth range of palaeoclimatic disturbance (Kukkonen & Jõeleht 2003).

In Fig. 5, heat flow sites are shown on a map with heat production calculated for each polygon and also in a subplot with a colour bar. Polygons without heat production constraints are left blank. It is obvious that consistent comparison of heat flow and heat production is not as straightforward as it is in Finland, where all lithological units have been mapped adequately in a geochemical database (Rasilainen *et al.* 2007). Apparently, in far southern sediment-covered area of Sweden the lack of heat production data is most serious. South of Trans-European Suture Zone, heat flow has been determined on 19 sites (Hurter & Hänel 2002). All of these are outside polygons with heat production data available. Even if heat production constraints from surface rocks of this area are available, these may give misleading results for comparison with heat flow, because lithosphere is not sedimentary by volume. It has been estimated that globally only 4 per cent of lithospheric volume is sedimentary although sediments cover 73 per cent of the Earth's surface (Wilkinson *et al.* 2009)).

Spatial gaps in heat production data are apparent in the south, but also in northernmost Sweden, which has been the most important target to exploration geophysics and geology. For example, heat flow in Kiruna is 51 mW m^{-2} as determined from five boreholes (Parasnis 1982), but no heat production values for this well-known

mining area are available. On the other hand, as many as three heat flow determinations (69, 69 and 76 mW m^{-2}) are available from amphibolite facies granite of Malingsbo (Malmqvist *et al.* 1983) in central Sweden, known for its high heat production (9.6 ± 1.9 μW m^{-3} as determined from the unit polygon). Also, 10 measurements are available at distances less than 20 km from the border of the same granite area, yet on unit polygons with heat production of just 2.3–2.4 μW m^{-3}. Exceptionally high heat flow of 108.7 mW m^{-2} has been determined in 1.87–1.91 Ga quartzite-dominated lithology in Solstad mine (Eriksson & Malmqvist 1979 compared to the value of 62.6 mW m^{-2} from Kråkemåla (Hurter & Hänel 2002) only 13 km apart. A little farther (19 and 20 km) from Solstad, the Avro and Laxemar heat flow values (61.5 and 63.3 mW m^{-2}) resemble those of Kråkemala although Kråkemala hole is situated on a unit polygon with mean heat production of 6.1 ± 0.1 μW m^{-3}, only slightly smaller that of the unit polygon of Solstad, 7.3 ± 9.2 μW m^{-3}. The granitoid area where Avro and Laxemar holes are located, is by its large extent one of the most prominent ones in the geological map of Sweden and has a heat production of 2.6 ± 1.5 μW m^{-3} (Table 2).

In the Sveconorwegian Idefjorden granite-pegmatite area which extends past Norwegian border, four Swedish heat flow sites are not located on any polygon with heat production data available. Unfortunately, these also include the borehole drilled to 4-km-thick granite body in Bohus, of particular importance due to its very high heat flow of 76 mW m^{-2} (Landström *et al.* 1980). Heat production values obtained from Norwegian Idefjorden units (Slagstad 2008), exceed the Sveconorwegian average obtained from our Swedish data analysis (1.74 ± 1.37 μW m^{-3}). The average obtained from 385 determinations from the Norwegian part of the Sveconorwegian orogen is very similar, 1.73 ± 1.45 μW m^{-3} (Slagstad 2008). This is notable, because any substantial difference would raise concerns that values from these two national data sets are not comparable due to methodological or sampling bias. In the Norwegian Caledonides, 167 determinations from intrusive rocks have yielded a value of 1.73 ± 1.45 μW m^{-3} and 561 determinations from metasedimentary and metamafic rocks a value of 1.40 ± 1.39 μW m^{-3} (Slagstad 2008), smaller than in Sweden but within the standard deviation of the very small Swedish data set. From Finnish Caledonides, 16 determinations are available (Rasilainen *et al.* 2007) and these show heat production even more lower than that in Sweden, from 0.24 to 1.16 μW m^{-3} depending on subunit (Veikkolainen & Kukkonen 2019). The small number and uneven spatial distribution of Swedish and Finnish samples is the most likely explanation for difference. Comparison of Fig. 5 in our paper and the Finnish geologically averaged heat production (Fig. 15 in Veikkolainen & Kukkonen 2019) shows that in the northern Svecokarelian (Svecofennian) parts of both countries, heat production values remain more or less similar across the country border, thus proving that also Swedish and Finnish data sets can be compared.

For studying the relation between heat production and rock density, we applied 23 127 value pairs, for each of which a density value had been determined directly, not as a mean of the respective rock unit. We separated granitoids (*N* = 14 124) and another data set of sediments and metasediments (*N* = 1642) from the rest of data (*N* = 7361). For calculation of heat production, we used the measured density of the rock instead of the mean density of the rock unit, unlike in other parts of our analysis. Unmetamorphosed granites (*N* = 7218) formed more than half of our granitoid group. However, a part of rocks (*N* = 1971) in granitoid group are likely to be somewhat metamorphosed. These include gneiss granites (*N* = 1185), gneiss granitoids (generic; *N* = 162), gneiss granodiorites (*N* = 473) and gneiss tonalites (*N* = 151). Fig. 6

shows that the granitoid group has a peak of high heat production values (over 5 μW m^{-3}) in the density range of 2550–2700 kg m^{-3}, but in the sedimentary and metasedimentary group, no such peak is visible but the distribution is relatively flat. In the group of other rocks, a slight decrease of heat production as a function of density is apparent. This is not unexpected, since pegmatites (*N* = 175) do not belong to granitoid group but may have high heat production as well. Otherwise the high heat production values in this group are represented by a variety of rocks such as mylonites, paragneisses, rhyolites and even volcanic rocks.

In Sweden, heat production values over 5 μW m^{-3} are almost exclusive to rocks with density less than 2800 kg m^{-3}, typical of felsic lithology. Altogether 20 samples had heat production over 25 μW m^{-3}, and for clarity, these are not shown in plots. Also, one sample has a density over 3600 kg m^{-3} and was left out of plots. Mean density and its standard deviation in granitoid group was 2665.5 ± 67.2 kg m^{-3}, in sedimentary group 2702.5 ± 76.8 kg m^{-3}, and in the group of other rocks 2765.1 ± 147.7 kg m^{-3}. Mean heat production rates in these groups, as determined using directly measured rock densities, were 2.64 ± 1.96, 1.88 ± 1.83 and 1.88 ± 1.86 μW m^{-3}. Similar heat production rates in two groups is merely a coincidence resulting from the fact that the third group, i.e. other rocks, has a very wide range of lithologies from rhyolites to basalts. In Fig. 6, linear fits are visible just to show the general trend, as it is not possible to predict heat production from rock density. This conclusion is similar to that drawn by Slagstad (2008) in the case of Norwegian data, and Veikkolainen & Kukkonen (2019) in the case of Finnish data. Not surprisingly, histograms of radiogenic element concentrations appear skewed to the right in case of C_U and C_{Th}, and to the left in case of C_K, as seen in Fig. 7. Globally, heat production increases as a function of felsic and alkali content in igneous rocks, both in plutonic and volcanic ones (Hasterok & Webb 2017), and Sweden makes no exception to the rule.

Ternary diagram of normalized heat production is shown in Fig. 8. We left out all point data with heat production of exactly 0 μW m^{-3}, meaning that 39 364 data entries remained. Average proportions of heat production from U, Th and K appeared to be 42.4, 40.8 and 16.8 per cent. The values of U and Th are slightly different from their Finnish counterparts of 36.7 and 47.0 per cent, while the value of K is almost same as the Finnish result 16.3 per cent (Veikkolainen & Kukkonen 2019). The variation of K content appears to be smaller between different geological units, and the general role of K in heat production is small. The proportion of U, however, appears to be highly variable, as it is in Finnish data, and this emphasizes the importance of studying Th/U ratio rather than K/Th or K/U ratios which have been recently investigated globally (Hasterok *et al.* 2018). Contours indicate that the majority of Swedish heat production values fall within a narrow range of U, Th and K values, reminiscent of what has been observed in Finland and also globally. Given the small proportion of Phanerozoic rocks in Finnish and Swedish data compilations, it may be even possible to generalize this result to various other areas dominated by Precambrian lithology.

4 DISCUSSION

Our observation that heat production in Sweden is larger than in Finland is essential for further understanding of lithospheric structure in Fennoscandian shield and adjacent units. The crustal differentiation index (Perry *et al.* 2006) is therefore also larger in Sweden than in Finland, particularly if the same Moho heat flow constraint of 12 ± 3 mW m^{-2} (Kukkonen & Peltonen 1999; Kukkonen &
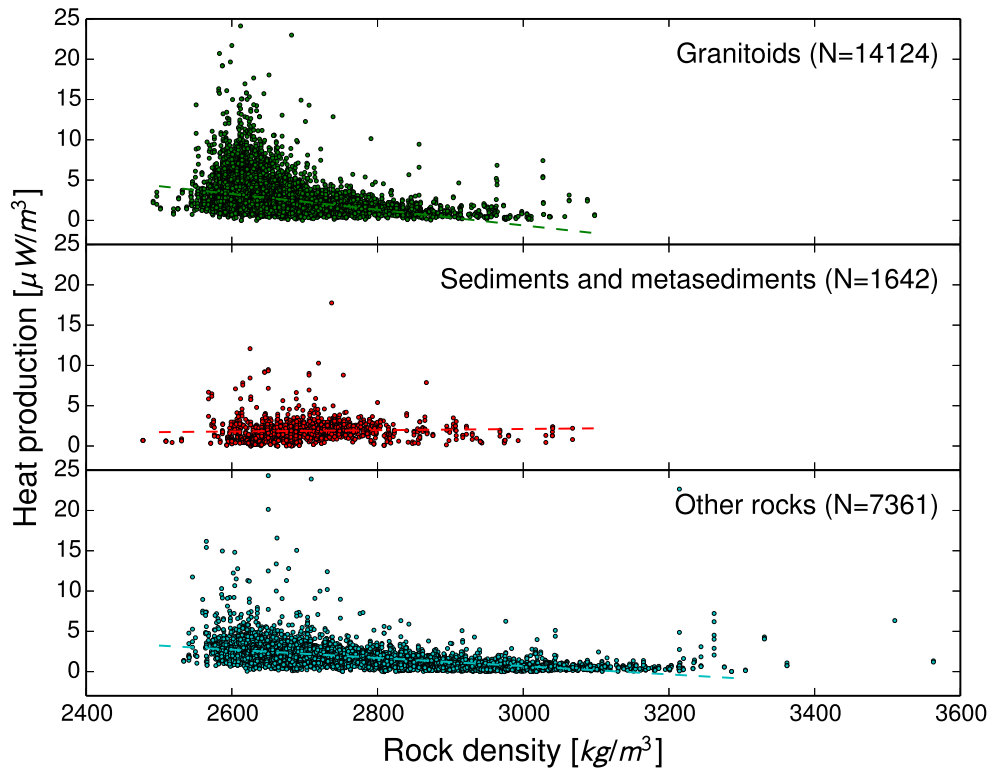
Figure 6. Heat production by rock density in three groups of rocks with directly measured densities. Dashed lines show linear fits to data points, yet these only indicate the general trend. Data © SGU.
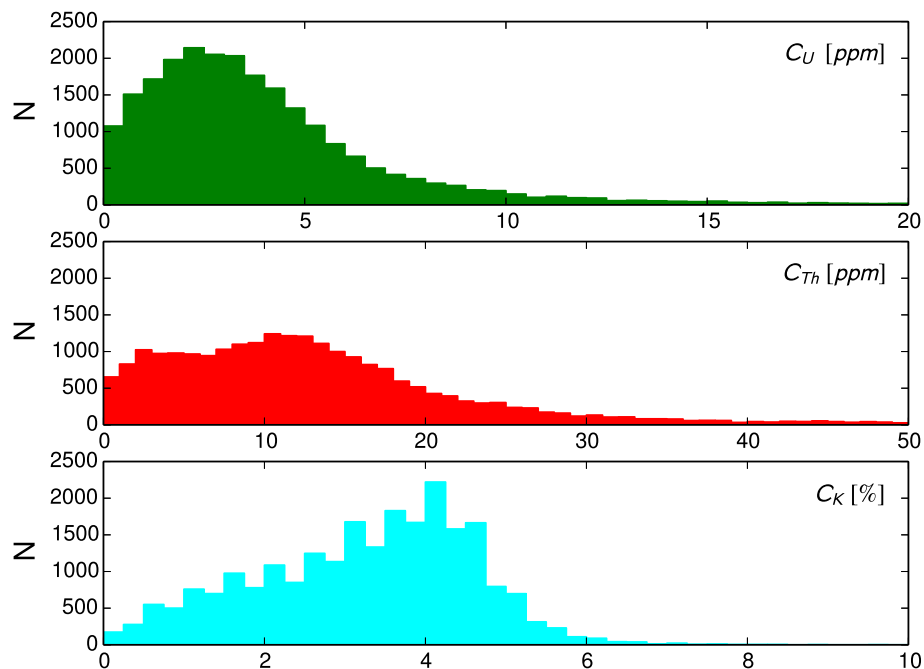

Figure 7. Histograms of radiogenic element concentrations for rocks with directly measured densities ($N = 23\,127$). Bin size is 0.5 ppm for C_U, 1 ppm for C_{Th} and 0.25 per cent for C_K. For clarity, large outlier values with $C_U > 20$ ppm, $C_{Th} > 50$ ppm and $C_K > 10$ per cent are not shown. Data © SGU.

Lahtinen 2001; Kukkonen *et al.* 2003) is valid for the entire shield. Despite variations in Moho depth in the shield area (Grad & Tiira 2012; Grad *et al.* 2014; Bagherbandi *et al.* 2015), Moho heat flow outside the Caledonides should be nearly similar throughout the shield, given the absence of elevation contrasts. However, the lack of

heat production constraints in several Swedish areas with high heat flow, the absence of heat flow determinations in areas of strongly enriched crust in northern Sweden, and the poor knowledge of the thickness of the upper crustal heat producing layer impair our ability to draw detailed conclusions on heat production. The problem of
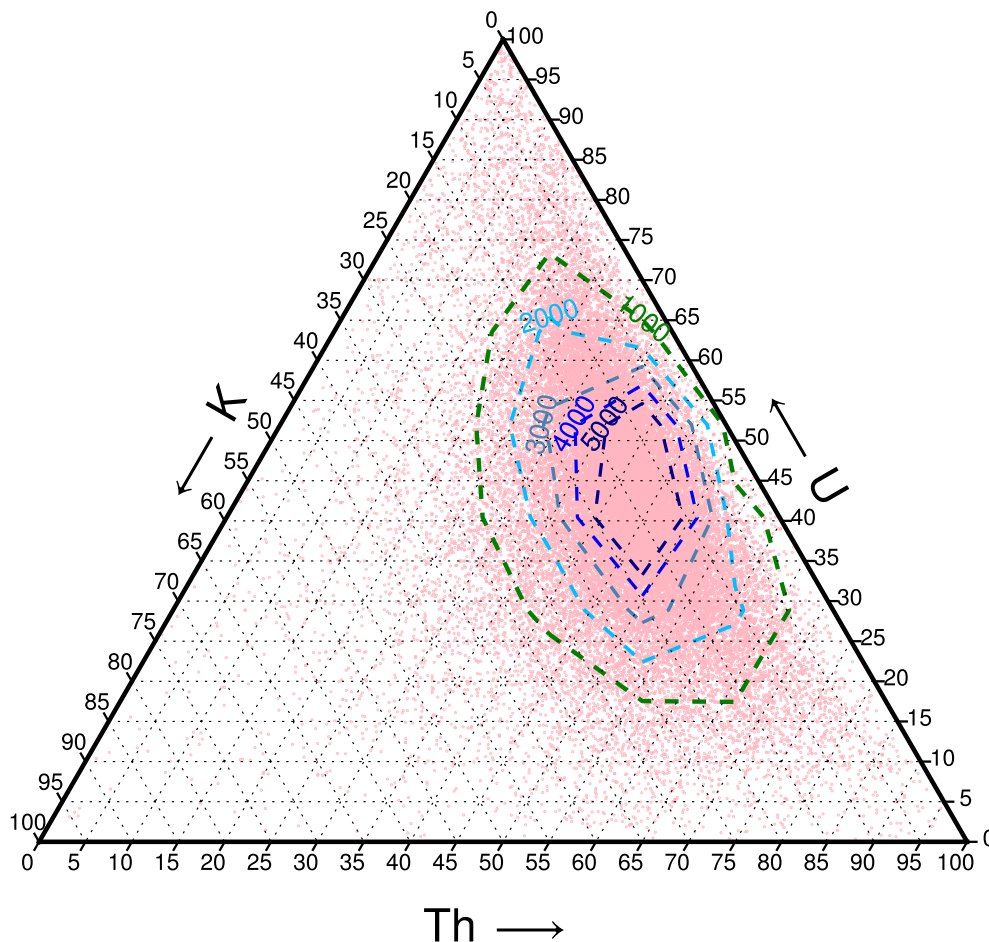
Figure 8. Ternary plot of proportions of U, Th and K in raw Swedish heat production data ($N = 39\,364$). No data with zero heat production are included. Density contours for 1000, 2000, 3000, 4000 and 5000 data points are also shown. Data © SGU.

spatial gaps in the Swedish data remains until a new sampling campaign is launched, although inversion of other geophysical data may give clues about heat production in areas without outcrops (Hokstad *et al.* 2017). Thus far, generalization is needed, and it has been done also in other countries with certain economically interesting areas of high heat production. For example, in Australia more than 80 per cent of radiogenic element concentration data of Proterozoic rocks have been obtained from the North Australian Craton. Large variations of heat production in Precambrian areas are not exceptional, but have been observed e.g. in Australia (McLaren & Powell 2014) and in India (Menon *et al.* 2003; Singh *et al.* 2014) as well.

In determination of heat production, airborne gamma ray surveys are often preferred over laboratory measurements due to the better spatial coverage of measurements obtained from flights. For example, the heat flow map of Näslund *et al.* (2005) over Finland and Sweden is based on airborne gamma ray data from Sweden, geochemical data from 1054 Finnish glacial till measurements (Kukkonen 1989) and linear Q-A relationship (Birch *et al.* 1968). The resulting mean heat flow value 49 mW m^{-2} obtained for two countries (Näslund *et al.* 2005) is similar to that obtained by Veikkolainen *et al.* (2017). Because heat flow in Figs 1 and 2 of Näslund *et al.* (2005) was directly proportional to heat production, a qualitative comparison between our heat production map and maps of Näslund *et al.* (2005) is possible. Most northern Swedish areas with high heat production (Figs 6 and 8 in our paper) are barely visible as areas with high heat

flow in maps of Näslund *et al.* (2005) but conversely, in the southeastern part, heat flow maps show high values in large areas unlike our heat production maps do. The problems of interpreting airborne radiometric data were discussed recently by Phaneuf & Mareschal (2014), who observed that the mean heat production determined from airborne data ($0.8 \pm 0.6 \, \mu\text{W m}^{-3}$) of Sudbury region, Canada, was significantly lower than that determined from laboratory measurements ($2.9 \pm 2.5 \, \mu\text{W m}^{-3}$) from rocks of the same area. Even though Näslund *et al.* (2005) only included airborne measurements from exposed bedrock, these cover only a small fraction of the measurement area even in glaciated areas such as Sweden and Finland, and therefore the problem of uneven sampling remains, although airborne surveys can conveniently cover large areas.

5 CONCLUSIONS

Our analyses of heat production from outcrop samples in the SGU lithogeochemical database were based on three methods: (1) calculation from point data after averaging values at exactly same SWEREF 99 TM coordinates; (2) using regular grid with 5 km bin size and (3) calculating values within actual geological units. Regardless of method, mean heat production stays within the range of $2.3 \ldots 2.6 \, \mu\text{W m}^{-3}$, but the value obtained by averaging by geological units ($2.4 \pm 1.7 \, \mu\text{W m}^{-3}$) is probably the most useful, especially in cases where comparison with Finnish (Veikkolainen & Kukkonen

2019) and Norwegian (Slagstad 2018) heat production maps needs to be done. Despite spatial gaps in point data, most tectonic units and subunits are adequately covered, and data are coherent with those obtained from neighbouring countries.

The outcome of this study confirms previous assumptions of higher heat production and surface heat flow in Sweden compared to those of Finland (Näslund *et al.* 2005). Both Finnish (Veikkolainen & Kukkonen 2019) and Swedish heat production studies are based on analyses of radiogenic element concentrations from outcrop samples from largest national data compilations available. The vast majority of heat production data from both countries originates from Precambrian rocks, and leaving the small Phanerozoic part out of analysis makes no obvious difference. Following the tradition of till geochemical analyses of two or more Fennoscandian countries (Gustavsson *et al.* 1994; Edén & Björklund 1995), it may be feasible to combine Swedish, Finnish and also Norwegian heat production data in a common database after a thorough comparison of analytical procedures used to obtain results in national databases. The presence of bedrock outcrops and the absence of platform cover in the majority of land area in these countries makes it convenient to generalize measurement results from surface rocks to greater depths in order to study the composition of the lithosphere using mixtures of rock types at different depths, although this requires additional seismic evidence on the layer structure of the lithosphere (Kuusisto *et al.* 2006).

SUPPORTING INFORMATION

Supplementary data are available at *GJI* online.

Appendices: Unaveraged heat production data at SWEREF 99 TM coordinates are tabulated in Appendix A. Heat production plots based on two binning options described in the text are shown in Appendix B. Swedish bedrock units with exceptionally high heat production (over 5 μW m^{-3}) are listed and described in Appendix C. Heat flow data are tabulated in Appendix D.

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