DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2014/28

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Contents

1. Abstract

This report presents the results of a compilation of geochemical and radiometric data for uranium in Greenland stored at GEUS. Acquisition of six different data types, i.e. stream sediment fine fraction, stream sediment heavy mineral concentrate, stream water, rock, airborne gamma-spectrometry and ground scintillometry, are described, their quality is commented, and the spatial distribution of samples and recorded U data are shown in maps of entire Greenland. The data set based on systematically sampled, treated and analysed stream sediment has the most extensive coverage corresponding to c. 75 % of ice-free Greenland.

Colour symbol plots or contoured grids of U values of the individual data sets together illustrate that the background variation of U across Greenland has several clearly defined areas of uranium enrichment, with South Greenland being the most pronounced. A comparison with a map of main lithotectonic units demonstrates that elevated to high uranium values are derived from 1) parts of the Archaean basement where rocks are in amphibolite facies and are intruded by late granites and pegmatite, 2) Palaeoproterozoic supracrustal sequences with abundant migmatites and late granites, 3) Mesoproterozoic metasediments in East Greenland intruded by Palaeozoic granites, 4) Mesoproterozoic alkaline igneous complexes in South Greenland. In many cases the elevated background for U reflects occurrences of rocks with high abundance of U-bearing accessory minerals.

The highest U values in the data sets, the U anomalies, indicate where mineralisation with uraninite has occurred. Such mineralisation is known within rocks of at least three different settings and ages in South Greenland: 1) Palaeoproterozoic sediment-hosted mineralisation, 2) Vein-type mineralisation of Mesoproterozoic age hosted by Palaeoproterozoic granite, and 3) Magmatic-type uranium mineralisation associated with highly differentiated magmas of Mesoproterozoic peralkaline intrusive complexes. Elsewhere in Greenland, uraninite and secondary uranium minerals are associated with pegmatites, acid volcanic rocks and fractures or shear zones within such rock complexes. Uraniferous pyrochlore is associated with a Neoproterozoic carbonatite.

2. Introduction

With the establishment in 1955 of the Danish atomic energy commission (AEK), headed by the nuclear physicist and Nobel Prize winner Niels Bohr, the Danish government took active steps to stimulate peaceful use of nuclear energy in Denmark. The initiative also stimulated uranium exploration in Greenland, then an integral part of Denmark, and The Geological Survey of Greenland (GGU, since 1995 merged with The Geological Survey of Denmark to form The Geological Survey of Denmark and Greenland, GEUS) was commissioned to carry out government supported uranium exploration activities in Greenland.

In 1965, when a new licensing system for mineral exploration in Greenland was introduced, the government continued to exert control of uranium resources in Greenland by having the general practice of excluding radioactive materials from issued exploration licences to commercial companies. Two Danish mining and exploration companies however, Kryolitselskabet Øresund A/S and Nordisk Mineselskab A/S had obtained their exploration permissions long before that, and their mineral exploration programmes included uranium in parts of Greenland.

When Denmark in 1972 joined the European Economic Community (EEC, later to be replaced by the European Union, EU), the EURATOM agreement imposed the member states to provide an overview of their uranium resources. This resulted in extra government and EEC financing that allowed GGU to undertake reconnaissance to regional scale uranium exploration in large parts of Greenland.

Active uranium exploration led by GGU ceased in 1986, following the 1985 decision by the Danish government to omit nuclear power from its energy supply policy. However thereafter, uranium (U) was routinely determined as part of multi-element analyses of samples collected during mineral exploration and geological research. Now the data from the uranium exploration programmes together with those accumulated over time give a good overview of the distribution of uranium in Greenland.

This report presents the result of a compilation of data for U concentrations in rocks and surface materials (stream sediment, soil and water) acquired by and archived by GGU/GEUS. It gives a description of data acquisition, quality and comparability, together with coverage maps and maps of the spatial distribution of U concentrations for individual data types. The main features of the U variation are discussed in relation to crustal domains and known uranium mineralisation. In addition, this report provides a comprehensive list of references concerning Greenland U data and mineralisation outside the well-studied, large, low-grade U deposit at Kvanefjeld in South Greenland.

Additional data from multi-element analyses, including U, of samples from Greenland exist in company reports and published research, but such data have not been systematically recorded by GEUS.

A general introduction to the geology of Greenland is given in Henriksen et al. (2009), and an evaluation of geological environments in Greenland with potential to host uranium deposits is given by Keulen et al. (2014), and that report contains literature references to the geology of uranium occurrences mentioned in the present report.

3. Main Uranium exploration activities in Greenland

3.1 Kvanefjeld

Owing to the early recognition of U-Th rich igneous rocks at Kvanefjeld (see location in Map 1) in the Mesoproterozoic Ilímaussaq peralkaline igneous intrusion, this area attracted detailed investigations from 1955 to 1983 (Sørensen et al. 1974, Nielsen 1981, Bondam 1995, Sørensen 2001, Rose-Hansen et al. 1986, and references to articles (in Danish) listed in the bibliography dealing with the early activities of AEK and GGU).

The investigations at Kvanefjeld comprised geological and radiometric mapping, drilling, drill hole logging, core analyses, driving of adits, ore processing tests, feasibility studies, and environmental impact studies. The present report does not concern U data for Kvanefjeld, for which the reader is referred to references mentioned in Rose-Hansen et al. (2001) and to the Greenlandic Ministry of Industry and Mineral Resources (MIM) or the present license holder, Greenland Minerals and Energy Ltd., regarding contemporary data for U resources of the Ilímaussaq intrusion.

3.2 Reconnaissance and regional surveys

This section provides a short overview of main activities. References to investigations and results are given in later sections and in the bibliography. The exploration programmes were carried out in collaboration between GGU and personnel from AEK's research laboratory, Risø National Laboratory (Risø), except for one undertaken by Nordisk Mineselskab A/S, see below.

1950's and 1960's: GGU mapping teams in South Greenland carried Geiger counters. Data are documented in unpublished field diaries and field reports archived at GEUS. The information obtained has been superseded by the regional U exploration carried out 1979-1980.

1971-1977: The East Greenland uranium exploration programme comprised airborne gamma ray spectrometry with subsequent ground studies of detected anomalies, regional scale drainage geochemistry (stream sediment and stream water), local scale soil geochemistry and ground gamma ray spectrometry in selected anomalous areas. Data documentation of detailed studies mostly unpublished.

1970-1984: Nordisk Mineselskab A/S operated in East Greenland 1970-1984 where their mineral exploration programme included regional geochemical surveys mainly relying on heavy mineral concentrates from stream sediment, soil and scree. Exploration for uranium was part of the activities, and they made ground checks on a number of U anomalies identified by GEUS and their own surveys. The findings are described in Harpøth et al. (1986). After the closure of the company in 1991, GEUS obtained rights to store and use their data (Thomassen & Tukiainen 2009, Thomassen 2009). The results of U analyses of rocks and heavy mineral concentrate of stream sediment and scree samples are presented in this report.

1975-1979: In Southern West Greenland the regional uranium exploration comprised airborne gamma ray spectrometry with subsequent ground studies of anomalous areas (Secher 1980 and reports listed in bibliography).

1979-1986: Regional uranium exploration programmes covering South Greenland (Syduran and Syduran extension, 1978-1983, Sydex 1984-1986). The regional airborne gamma ray spectrometric and drainage geochemical surveys (stream sediment and stream water) were followed by comprehensive studies of U-mineralised sites including ground scintillometry and gamma ray spectrometry, magnetic profiling, trenching, rock sampling, mineralogical and chemical analyses, and isotopic age dating (Armour-Brown et al. 1980, 1981a, Steenfelt & Armour-Brown 1988 and project reports listed in bibliography).

Dedicated uranium exploration was abandoned from 1986 onwards, but U was determined in analytical packages using instrumental neutron activation (INA) and inductively coupled plasma spectrometry (ICP) methods. Thus, U data are available from all stream sediment samples and most rock samples collected for mineral exploration and research purposes since 1990.

4. Data acquisition

4.1 Geochemical data

Geochemical data for U have been acquired for a large number of samples representing four different sample media (Table 1): Stream sediment, heavy mineral concentrates of stream sediment, stream water and rock.

4.1.1 Stream sediment and equivalent sample media

Following initial orientation studies on the application of stream sediment for U exploration in the early 1970s, systematic sampling and analysis of the fine grain size fraction of stream sediment at reconnaissance to regional scale was carried out from 1974 to 1976 in northern East Greenland, followed by a survey of South Greenland 1979 to 1980. In addition, local sampling of stream sediment and soil was carried out at many of the sites defined as U anomalies by airborne gamma ray spectrometry in East, West and South Greenland in order to further localise and characterise the source of the anomaly (see bibliography).

From 1981 onwards, systematic low-density sampling and analysis of the fine fraction of stream sediment was conducted within the Geochemical Mapping Programme for Greenland (Steenfelt 1987, 1993, 1999) with U being one of the many major and trace element concentrations determined in the samples. Although stream sediment is the preferred sample medium, soil or lake shore sediment has been sampled as substitute in (rare) low-relief areas where proper streams are absent. In very steep topography typically along glaciers, samples of scree have been collected as substitute for stream sediment. Substitute samples were treated in the same way as stream sediment with analysis of the fine fraction.

Sampling, sample preparation and analysis has largely followed the same protocol since 1981, although sampling density has varied according to logistic and budgetary conditions (typically, remote areas are sampled less densely), see Steenfelt (1999, 2001a,b) for details on sampling, preparation and analysis. Literature references to results and interpretations of individual surveys are listed in the bibliography.

For samples from East and West Greenland 1972-1977 the analysed fine fraction was below 0.18 mm. From 1979 (South Greenland) onwards the < 0.1 mm fraction was preferred for analysis.

Samples from the regional U exploration projects were first analysed for U by delayed neutron counting (DNC) at Risø. From 1990 onwards, all samples for the Geochemical Mapping Programme were analysed for a multi-element suite by instrumental neutron activation (INA) at commercial laboratories, and samples analysed earlier for U and a few other elements were reanalysed by INA to provide multi-element data from areas already covered. This has resulted in a large number of samples with U determined twice so that the comparability can be documented.

Map 2 shows the location of stream sediment samples collected for geochemical mapping and analysed by INA together with that of samples collected in local exploration for U or other elements. Map 3 shows location of samples analysed by DNC in regional and local surveys.

GEUS stream sediment samples fine fraction (including soil and lake sediment samples)	
Geochemical mapping analysed by INA	11629
Regional exploration analysed by DNC	5645
Local exploration analysed by INA or ICP	1433
Local exploration analysed by DNC	1189
Stream sediment samples (sensu lato), heavy mineral fraction	
GEUS samples analysed by INA	705
Company samples analysed by INA:	
NunaMin Nassuttooq region	1396
NunaMin Nuuk region	1166
NunaMin South Greenland	1847
NordMine	2451
GEUS stream water samples	
Samples analysed by UA3	6183
Analysed by DNC after pre-concentration with $Fe(OH)_3$	1166
Uummannaq region analysed by ICP-MS	210
South East Greenland analysed by ICP-MS	850
Rock samples	
GEUS samples analysed by INA	6961
GEUS samples analysed by DNC	1311
GEUS samples analysed by gamma ray spectrometry	615
GEUS samples analysed by ICP	1032
Nordmine samples analysed by INA	1166

Table 1 *U data inventory for Greenland. Number of samples with digital sample location analysed for U as of December 2013. See radiometric data in Table 2. NordMine: Nordisk Mineselskab A/S. NunaMin: NunaMinerals A/S. For abbreviations of analytical methods see text. Sample locations are seen in Maps 2–7.*

4.1.2 Heavy mineral concentrate

Heavy mineral concentrates (HMC) of stream sediment samples have been used in exploration for gold, tungsten or other heavy mineral. Stream sediment is most commonly used as sampling media, but also residual overburden (soil s.l.), or scree have been used, and concentrates have been prepared by panning or other mechanical treatment in the field or by mineral separation in the laboratory.

A large number of the samples have been analysed by INA thus providing data for U. GEUS' database contains U concentrations for 705 HMCs. In addition, GEUS has published data acquired by two commercial companies, Nordisk Mineselskab A/S and Nuna-Minerals A/S (formerly Nunaoil A/S), see Table 1 and Map 4.

All available U data from heavy mineral concentrates are presented here. However, it should be observed that the data from the individual HMC campaigns are not directly comparable because sampling, sample size and processing varied. More information about methods and results are given in GEUS' mineral resource evaluations for large areas of West and South Greenland (Schjøth et al. 2000; Schjøth & Steenfelt (eds) 2004; Thorning et al. 2011), and in Harpøth et al. (1986) and Thomassen (2009) regarding East Greenland HMC.

4.1.3 Stream water

Owing to the mobility of U6+, surface and ground water have found application already in the early days of geochemical U exploration (Wenrich-Verbeek 1977 and references therein). The first method applied in Greenland used 1 litre stream water samples in which preconcentration of U was made by co-precipitation with ferric hydroxide followed by analysis of the precipitate for U using DNC. A total of 2103 stream water samples collected in East Greenland was analysed this way (Asmund & Steenfelt 1976; Steenfelt & Kunzendorf, 1979).

A fairly large number (c. 900) of stream water samples were collected at high density within anomaly areas in East Greenland, but their location has not been digitised. A number of 278 samples (55 with digital location) in West Greenland were analysed in the same way, see Map 5.

The U exploration project covering South Greenland used 100 ml stream water samples collected at the same sites as stream sediment samples and they were analysed by a Scintrex UA-3 laser analyser (Armour-Brown et al. 1982b). The conductivity and F- concentration of the samples were also determined (Armour-Brown et al. 1983a; Steenfelt & Dam 1982). Stream water data are presented in Armour-Brown et al. (1983a) and Olesen (1984), but were not included in Thematic Map Series for South Greenland (Thorning et al. (eds) 1994), or the mineral resource evaluation of Schjøth et al. (2000).

The UA-3 analyser was used from 1979 to 1990 to determine U concentrations of 6183 stream water samples collected during the Geochemical Mapping Programme (Map 5). The results are published in the Open File Reports on individual surveys, see bibliography.

Selected water samples from two areas in northern West Greenland were analysed by inductively coupled plasma mass spectrometry (ICP-MS) including U. These data have not been published previously.

Stream water samples from Southeast Greenland were analysed by ICP-MS including U. Data have not been published previously.

There has been no earlier attempt to compile and present all U data from stream water samples in Greenland, mainly because it is not straightforward to compare results from individual surveys and because there is a general hesitancy towards the quality of water analytical data, see section 5. However, since considerable parts of Greenland have actually been covered by stream water samples (Map 5), and since results for U of individual surveys were meaningful, it seems justified to present the overview that the compiled data can provide.

4.1.4 Rock samples

Until the 1970s, whole rock analyses made to assist geological mapping were primarily determining major element oxides by XRF, which did not include determination of U. During the U exploration campaigns 1972 to 1986, powdered rock samples were analysed for U by Risø National Laboratory (Risø) using Delayed Neutron Counting for U and/or laboratory gamma ray spectrometry (GAM) for U, Th, and K (expressed as equivalent U and Th, see section on gamma ray spectrometry below).

From 1990 onwards, many rock samples collected for mapping and mineral exploration purposes were routinely analysed using multielement analytical packages, primarily INA because this method gives good results for Au and REE. INA also includes determination of U concentrations. Increasingly inductively coupled plasma emission or mass spectrometry (ICP-ES or ICP-MS) methods (also determining U) has taken over from INA for rock samples. Although U data were rarely used in the interpretation of petrogenesis or mineralisation, their number accumulated and the data now provide a documentation of the common (background) U variation in rocks across Greenland.

The compilation contains data for rock samples with digital location (Map 6). Many GEUS rock samples collected before 1980 lack digital location. Rock samples collected by Nordisk Mineselskab A/S (Thomassen & Tukiainen 2009) and analysed for U are included in the compilation.

4.2 Radiometric data

4.2.1 Airborne gamma ray spectrometric surveys

In a country like Greenland with almost no infrastructure, an airborne survey is an attractive way to obtain a first overview of the distribution of radioactive elements. The advantage is that many areas in Greenland are sparsely covered with vegetation, so that good response

from the rock surface is recorded. The disadvantage is that the mountainous terrain in many parts of surveyed areas in Greenland prevented linear flight routes because the instrumentation required that ground clearance was kept low to obtain sufficient detector response to gamma rays from the surface. Contour-flying was therefore applied in the surveys at regional scale performed over large areas of East, West and South Greenland (Map 7). The surveys were performed using fixed-wing aircrafts in East and West Greenland and helicopter in South Greenland (Table 2).

Airborne gamma ray spectrometry

Region	Year	Spectrometer	Detector volume	Ground clearance	Line kilometres
East Greenland	1971	4-channel	0.8 l	50 m	7000
	1973-1974	4-channel	11 l	100 m	20000
West Greenland	1975	4-channel	11 l	100 m	18000
	1976	4-channel	11 l	100 m	12000
South Greenland	1979	4-channel	7.4 l	30 m	14000
	1996	256-channel	16.8 l	60 m	

Ground radiometry

West Greenland scintillometer measurements	4851
South Greenland scintillometer measurements	2204

Table 2 *Acquisition of radiometric data for Greenland.*

An essential part of the gamma-radiation recorded by the U and Th channels of the spectrometer is emitted from daughter products, ^{214}Bi and ^{208}Tl respectively, produced during radioactive decay of ^{238}U and ^{232}Th in rocks. Careful calibration allows the recorded counts per second to be recalculated to equivalent ground concentrations of Th and U, expressed as eU ppm and eTh ppm, when the assumption is made that the ^{238}U and ^{232}Th decay series are in equilibrium. In order to compare measured total radiation levels between surveys, the radiation in counts per second have been recalculated and expressed in Ur. One Ur is defined as the radioactivity equivalent of one part per million of uranium in radioactive equilibrium. Instruments were calibrated at large concrete pads at Risø (Løvborg et al. 1981), and further information on equipment and data presentations can be found in Løvborg et al. (1976) and Breiner et al. (1976).

East Greenland. An airborne gamma ray spectrometric survey conducted 1971 is described in Nielsen & Løvborg (1976). The survey of 1973 (continued in 1974) used instrumentation built at Risø with analogue recording (Nielsen & Larsen 1974). Data were later

digitised (punch tapes), however data were never transferred to an up-to-date electronic format and the flight routes were not digitised. Many of the recorded anomalies were followed-up by helicopterborne and ground scintillometry, detailed geochemical surveys and rock sampling (Nielsen & Steenfelt 1975, Steenfelt 1976, Steenfelt & Nielsen 1978, Steenfelt & Kunzendorf 1979). The results of the local investigations have not been published in detail, largely because none of the targets located in East Greenland seemed economically viable at the time, and because the priority targets for U exploration shifted to South Greenland. The main results of the East Greenland gamma ray spectrometric survey in terms of response from lithology and mineralisation are described in Nielsen & Steenfelt (1977) and Steenfelt (1982). A few internal GGU reports and field diaries contain additional information.

West Greenland. Airborne gamma ray spectrometric surveys 1975 and 1976 used the same gamma ray spectrometer and fixed-wing airplane as the East Greenland survey, but the data obtained were digital from the beginning and the flight routes were drawn on topographic maps at scale 1:250 000 and then digitised (Secher 1976, 1977). Data were transferred to magnetic tapes that were partly damaged, unfortunately, during storage. Finally, most of the data were restored and are now available (see Tukiainen et al. 2003). This reference also contains more information on instrumentation and survey specifications and it presents data for total radiation (Ur), K, eTh and eU as coloured dots along flight lines.

Grid maps of eU ppm, eTh ppm, K % and total radiation in Ur are presented in the GEUS resource evaluations for West Greenland (Schjøth et al. 2000, Schjøth & Steenfelt (eds) 2004, Thorning et al. 2011).

In both East and West Greenland a helicopter equipped with a high-sensitivity scintillometer was commonly used to zoom in on anomalous areas before ground work was undertaken.

South Greenland. Airborne radiometric data are available from project Syduran and from project AEM Greenland 1996. The data include measurements from helicopter of the radiation from uranium, thorium, potassium and of total radiation.

The instrumentation and survey specifications for the Syduran project are described in Armour-Brown et al. (1982). A Scintrex GAD-6 four-channel gamma ray spectrometer (7.413 litre NaI(Tl) crystal) installed in a helicopter was flown along contours at a nominal height of 30 metres over the terrain. Data were recorded on magnetic tape and has later been transformed to electronic format.

The survey results are presented in Armour-Brown et al. (1983a), Olesen (1984), Steenfelt & Armour-Brown (1988), Thorning et al. (1994). Grids based on data from the Syduran project were calculated at 1 060 metres grid cells using the minimum total curvature method, and contoured grid maps of eU ppm, eTh ppm, K % and total radiation in Ur were presented in Schøth et al. (2000).

An 256-channel Exploranium GR820 gamma ray spectrometer was used in the airborne combined electromagnetic and gamma ray spectrometric survey “Project AEM Greenland 1996”. The less steep topography of these small survey areas (see Map 7) allowed that data were collected at a nominal ground clearance of 60 metres along flight lines spaced 200 metres apart and with orthogonal control lines at intervals of 2 000 metres. Survey specifications and maps are reported in Stemp (1997) and grid maps are also presented in Schjøth et al. (2000).

4.2.2 Ground measurements

The total gamma-radiation was routinely measured by scintillometer at stream sediment sampling sites for the Geochemical Mapping Programme of West and South Greenland. In South Greenland the scintillometer was Geometrics BGS-2, in remaining Greenland Saphymo SPP2. Data for South Greenland were reported in Ur (Unit of radiation) based on calibration and calculations made at Risø, while SPP2 readings were reported in counts per second (cps). In the compilation made for the geochemical atlas of West and South Greenland (Steenfelt 2001a), a conversion from Ur to cps was estimated based on readings performed on calibration pads at Risø.

Detailed 4-channel gamma ray spectrometric ground surveys have been made at radioactive areas to document the size and character of the U-enrichment or mineralisation. A survey in Randbøldal, East Greenland (location Map 7), has been reported in Sørensen (1976), but several other small surveys have not been published or reported. Detailed surveys performed in South Greenland are described in the Syduran and Sydex project reports. A survey covering Tikiusaaq carbonatite in southern West Greenland (Map 7) is reported in Steenfelt et al. (2007b).

5. Data evaluation

This section comments on the quality of the analytical data sets and the comparability between data from different analytical methods. In addition, it is evaluated to what extent the data can reliably be used to document regional variation and to identify and quantify areas with anomalously high U concentrations. It is obvious that where the range in measured values is large, the distinction between high and low areas is significant and reliable and little affected by sampling or analytical noise. Table 3 illustrates the data ranges as percentiles of the frequency distributions. An impression of the ranges in background distribution is also gained by looking at the colour scales of Maps 8-14. The strength of the anomalies is illustrated here by comparing the highest, i.e. uppermost 1 % of the values, with the upper end of the background distribution expressed as the 75th percentile.

	Stream sediment		**Rock**	
	geochemical mapping	exploration		
Method	INA	DNC	INA	DNC
Number	11629	6778	6961	1298
25 perc	1.4	2.2	0	0.8
50 perc	2.8	4.5	0.8	3.3
75 perc	6.1	16.1	2.6	21.2
95 perc	36	107	10	584
99 perc	120	336	28	3702
max	1400	965	3500	38800
Ano/bckgr	20	21	11	175

	Airborne gamma spectrometry			**Heavy mineral concentrate**			**Stream water**			
	WG 75	WG 76	SG 79	GEUS	NordMine	NunaMin	SG,WG	SEG	UReg	EG
Method				INA	INA	INA	UA-3	ICP	ICP	DNC
Number	85397	64067	222069	705	2451	4408	6183	850	210	1111
25 perc	0.45	0.45	1.5	0.6	0.0	1.6	0	0.00	0.01	0.02
50 perc	0.85	0.94	2.65	4.5	0.0	5.1	0.0	0.0	0.0	0.0
75 perc	1.4	1.6	4.1	10.6	0.0	11	0.3	0.0	0.2	0.1
95 perc	2.8	3.2	7.4	37	19	33	1.7	0.2	1.7	0.3
99 perc	4	5.2	14	109	47	72	6.5	0.4	6.0	0.8
max	13.3	14.4	197	280	1100	210	82.2	1.6	13.6	3.3
ano/bckgr	2.9	3.3	3.4	10		7	21.6	14.1	27.6	13.5

Table 3 *Statistical parameters, i.e. maximum (max) and percentiles (perc) of the frequency distribution of U values recorded by different sample media and analytical methods. Water concentrations in ppb, all other in ppm. The ratio between 99th and 75th percentile is used here as a measure of anomaly to background contrast (ano/bckg). For abbreviation of analytical methods see text. WG: West Greenland, SG: South Greenland, SEG: Southeast Greenland, EG: East Greenland, UReg: Uummannaq region. NordMine: Nordisk Mineselskab, NunaMin: NunaMinerals.*

Stream sediment. The reproducibility of stream sediment data from Greenland is good as shown by systematically collected duplicate samples (see e.g. Steenfelt & Kunzendorf 1979, Steenfelt 1987). The analytical methods for U based on nuclear techniques, DNC and INA, provide total concentrations of U with high precision and accuracy and insignificant bias over time (Steenfelt 1999). Lower detection limit is commonly 0.5 ppm for INA (varies between laboratories) and 0.1 ppm for DNC. There is strong correlation between results obtained by the two methods and between INA data from different laboratories (Steenfelt 1999). The regional variation in U concentrations displayed by the stream silt is therefore reliable and significant (Map 8). The data exhibit strong anomaly-to-background contrast (Table 3).

HMC. All data represent analysis using INA, but samples from individual surveys were treated differently so that while the U variation within each survey appears (Map 9) reliable, the variation between surveys may not be significant. The U concentration range is narrow compared to that of the fine fraction of stream sediment, and the anomaly-to-background contrast is small.

Stream water is a homogeneous medium, and duplicate samples have shown that measured U concentrations are reproducible (Steenfelt & Kunzendorf 1979). However, the amount of dissolved components including U may display seasonal and regional variation. The electrical conductivity measured in all stream water samples provides an indication of the degree of dilution and that can be used in evaluating U concentrations (Steenfelt & Dam 1982).

The UA-3 instrument seems to have had calibration problems between some surveys, expressed as a slight shift in background concentrations. Hence, while identification of anomalies is reliable, small variations in background data are not. Likewise, data obtained by different methods are not directly comparable. The degree of comparability between surveys has not been studied.

The data provided by ICP-MS are considered reliable, but no test has been made to compare the values with those obtained by UA-3 or DNC. In general, the water data should be considered reliable in outlining U enriched districts, because they show strong anomaly/background contrast, but less pronounced trends should be evaluated with care.

For the purpose of this presentation, stored data have been retrieved and are adjusted where obvious differences between data sets can be ascribed to bias among methods. In result, the general background and anomaly levels are made comparable among surveys. It is emphasised that the data presented in Map 10 should be regarded as a preliminary attempt to provide an overview.

A more accurate evaluation of the stream water results is warranted and should consider the relationship between U concentrations and electrical conductivity measured in almost all stream water samples from Greenland. Data analysis has shown that U concentrations in stream water are generally correlated with conductivity, as are other components measured in the water (Steenfelt & Kunzendorf 1979; Steenfelt & Dam 1982).

Rock samples. The samples with U data determined by INA and ICP are not representative of common rocks, and the relative abundance of certain rock types is biased by excess samples of mafic volcanic assemblages, preferred in mineral exploration, and unusual

rocks like carbonatite and kimberlite, relative to common felsic plutonic rocks of the basement. Many of the samples analysed by DNC and GAM are collected at radioactive “hot spots” detected by the regional airborne gamma ray spectrometry and stream sediment surveys during uranium exploration projects so that these datasets are biased towards high values.

DNC and INA analyses are preferred because they give accurate total concentrations, but the values determined by ICP are generally good and the method has a low detection limit (some laboratories have 0.05 ppm). The database only contains 70 samples for which U has been determined by both ICP and INA, and for which values are above lower detection limit. The correlation is acceptable, but not as good as between DNC and INA. A correlation between values determined by DNC and GAM suggests that the precision for GAM is lower than for DNC.

X-ray fluorescence data (XRF) for U determined in rock samples are registered in the database, but they have poor quality and should not be used.

Gamma ray spectrometry is an indirect method of determining U concentrations that requires equilibrium between radioactive decay products to give correct data. Owing to the nature of data recording, airborne gamma ray spectrometer data are vulnerable to instrument performance, atmospheric pressure, calibration, etc. (IAEA 2003), and it is recognised, when the data from Greenland are studied in detail, that there have been occasional problems with equipment stability. Further, recalculation to ppm in rocks is based on modelling and the level may not be accurate. However, the relative regional variation and outlining of high and low areas are considered reliable.

6. Spatial distribution of uranium in Greenland

Spatial distribution maps of U for entire Greenland are presented here for the first time. Stream sediment and ground radiometric data have been compiled and presented for West and South Greenland (Steenfelt 2001); otherwise compilations have been made for specific regions within West and South Greenland as mentioned in the section on data acquisition.

Two sets of maps have been made, one (Maps 8–14) illustrating the general variation in the majority of the samples, the background variation. The other set (Maps 15–19) showing the location of the highest values, the anomalies, recorded in the data sets.

The large coverage and relatively regular spacing and analytical consistency of stream sediment, airborne and ground radiometric data invite presentation as colour contoured grids (Maps 8, 13 and 14), while dot maps have been preferred to illustrate the variation in stream sediment HMC, stream water and rock (Maps 9–12) because of the heterogeneity of sample distribution and data involved.

The contoured grid map of eU concentrations (Map 13) combines data from 1975, 1976 and 1979 that have been screened for negative values in the eU data records and for values outside defined intervals in measured height above ground (ground clearance). The map represents 381533 data points.

6.1 Background variation

The unbiased, systematically acquired data from stream sediment, stream water and airborne gamma ray spectrometry document the natural variation in U concentrations of rock complexes across large areas of Greenland. The stream sediment data (Map 8) are the most complete and most reliable in terms of data quality, and presently they serve as the best overview for the entire Greenland. Comparing the distribution patterns for eU obtained by airborne gamma ray spectrometry and U in stream water with the stream sediment background map within southern West and South Greenland convinces that the three methods show similar distribution patterns.

Ground radiation (Map 14) is a fourth data set illustrating background variation. The total radiation is dominated by contributions from Th and K and by experience, the U concentration is only moderately correlated with total radiation. Nonetheless, the general variation in total radiation provides information on occurrences of relatively radioactive environments.

HMC and rock data provide supplementary information where they are available. Since the HMC method is designed to isolate heavy accessory minerals, the variation (Map 9) can be interpreted to show abundance of U bearing minerals such as allanite, monazite, zircon, and pyrochlore. Rock samples (Maps 11 and 12) with elevated U confirm the presence of U-enriched rocks in the regions of elevated concentrations outlined by stream sediment, stream water and radiometry as well as low levels in many rocks within the low-background regions of Map 8.

All the background variation maps display clear patterns of high and low areas and they all emphasise the pronounced uranium enrichment in South Greenland. A comparison of the

distribution patterns with major lithotectonic units of Greenland (Map 1) shows that the lowest values for U in the datasets characterise areas dominated by 1) Archaean crystalline basement of the North Atlantic craton (NAC) and of the northernmost Caledonian fold belt of East Greenland, where the rocks are at granulite facies metamorphic grade and represent mid- to deep crustal level, 2) Palaeozoic shelf deposits of the Franklinian Basin in North Greenland dominated by carbonate and sandstone, 3) Palaeogene mafic volcanic rocks in West and East Greenland (although stream sediment data do not cover much of this lithology, see Map 2).

Provinces of elevated U can be correlated with 4 different lithotectonic settings:

1. Within the Archaean basement, high U background occur at the margins and central part of the NAC and in the Rae craton, where orthogneiss and supracrustal rocks are at amphibolite facies metamorphorphic grade and where they are intruded by late to post kinematic granites and pegmatites. In the Nassuttooq region there are monazite bearing pegmatites (Secher 1980; Steenfelt et al. 2007a), the Nuuk region features allanite-rich late Archaean pegmatites and Qôrqut granite complex (shown in Map 1), and in the southern NAC elevated U and radioactivity can be related to the late Archaean Neria granite and migmatised Isorssua mica schists (Steenfelt 1994). The reason for the elevated U observed where amphibolite facies orthogneisses of the Rae craton occur is not known in detail.
2. High background values for U characterise Palaeoproterozoic Ketilidian and Rinkian supracrustal sequences. Common to the two areas are high proportions of metasediments in the supracrustals and abundant migmatitic veining and pegmatites. The Ketilidian U enrichment is described in Steenfelt et al. (2000), while the Rinkian province of high background has not been clearly demonstrated before the present compilation.
3. High U background in the East Greenland Caledonian fold belt is associated with tracts of Silurian and Devonian granitic intrusive and effusive rocks derived by melting of Mesoproterozoic metasediments (Nielsen & Steenfelt 1977, Steenfelt 1982).
4. Mesoproterozoic alkaline igneous complexes and carbonatites in South Greenland are enriched in radioelements including U and contribute to the high U background over South Greenland.

In summary, the provinces of elevated to high U background mainly reflect 1) rock complexes with elevated abundance of U-bearing refractory minerals, allanite, monazite, etc. which again reflect the result of crustal differentiation of U through crustal melting and granite magmatism. 2) Intrusion of alkaline magmas and carbonatites. It is observed that South Greenland comprises three settings, Archaean, Palaeoproterozoic and Mesoproterozoic, with elevated U.

It is considered worth mentioning that a possible formation of high grade unconformity-type or vein-type U mineralisation is favoured by the availability of U in high background environments.

6.2 Uranium anomalies

The highest U values recorded in each data set are extracted and presented as anomalies in Maps 15–19. The anomaly thresholds for the data populations of each set are generally chosen as the 99th percentile, see Table 3, if not otherwise described here.

Stream sediment anomalies (Map 15) are defined at two levels, above 120 ppm and above 340 ppm. The lower level corresponds to the upper 1 % of the frequency distribution for samples collected during geochemical mapping. The upper level corresponds to the upper 1 % of the frequency distribution of samples collected in local sampling in uranium mineralised areas.

Stream sediment contains refractory accessory uranium minerals derived from weathered rocks, but in addition the sediment picks up material from eroded and weathering U-mineralised shear and fracture zones of U-rich minerals such as uraninite, pitchblende, brannerite etc. and secondary U-minerals. Where this has happened, U concentrations of the sediment may reach very high values. Most stream sediment anomalies occur in South Greenland in areas where mineralisation with uraninite is known.

HMC data (Map 16) have weak contrast between background and anomaly, arguably because U-rich heavy minerals such as uraninite and secondary U-minerals are unstable in the secondary environment. In fact, HMC U anomalies indicate above normal abundance of resistant U-bearing accessory minerals such as allanite, monazite, zircon or thorite/thorianite hosted by granitic rocks.

Stream water (Map 17) has been shown to have a higher anomaly to background contrast than stream sediment (Steenfelt & Kunzendorf 1979) and is very suited as sampling medium at regional scale uranium exploration in Greenland, provided that the degree of dilution due to seasonal or other changes can be monitored. Despite the differences in analytical techniques used for water samples, the anomalies are well defined, and their location in the high-U regions outlined by stream sediment adds evidence for the presence of fracture-type or vein-type U mineralisation. The level above 2 ppb is added to show the clustering of high values in certain regions, where they could be indicative of U mineralisation.

Rock samples (Map 18) with more than 100 ppm U are clearly beyond the range for common rocks and the orange symbols may represent samples of pegmatite, carbonatite or peralkaline igneous rocks or weakly mineralised samples. Rock samples with above 500 ppm are taken to indicate occurrences with U-rich minerals, and those above 5000 ppm are from high grade U occurrences.

Anomalously high values recorded by gamma ray techniques from the air or on ground (Map 19) are defined in relation to the frequency distribution of recorded values within individual surveys, because the results are obtained with different survey specifications. The symbols in East Greenland represent approximate locations of anomalies shown in Nielsen & Steenfelt (1977, Fig. 7) and they comprise high values in both total radiation and high values in the U-channel of the spectrometer. The pattern of high values mainly reflects occurrences of magmatic rocks with unusually high content of uraniferous accessory minerals, e.g. pegmatites, granites, peralkaline rocks, carbonatites. In southernmost South Greenland, additional occurrences of disseminated uraninite hosted by Palaeoproterozoic metasediment are recorded as gamma spectrometry anomalies.

6.3 Uranium mineralisation

The uranium exploration programmes, see bibliography and Keulen et al. (2014), have documented that mineralisation with high-U minerals like uraninite has occurred in areas of high U background in East, southern West and South Greenland. This is illustrated by the distribution of the anomalies, in stream sediment, stream water and rock samples (Maps 15–18).

The most pronounced U enrichment has taken place in South Greenland, where three types of mineralisation have been recognised:

1) Uraninite/pitchblende mineralisation hosted by Palaeoproterozoic Ketilidian metasediment and migmatite. This type is reflected by anomalies in airborne gamma ray spectrometry and stream sediment, and confirmed by rock concentrations of above 5000 ppm U (Metased. zone in Map 18). It has been studied at a few localities (Nielsen & Tukiainen 1980; Armour-Brown 1986), but is assumed to be more widespread (Armour-Brown 1986; Steenfelt & Armour-Brown 1988). The age of the uraninite in one occurrence correspond to the intrusion age of a late Ketilidian granite-monzonite-norite suite (1740 Ma, Armour-Brown 1986).

2) Vein-type mineralisation of Mesoproterozoic age hosted by fracture zones within Palaeoproterozoic granitic rocks. This is the type indicated by the many stream sediment and stream water anomalies in the Granite zone of Map 18. The mineralised occurrences have been studied in some detail where small lenses of pitchblende in fractures along major fault zones have been traced intermittently over several kilometres. Most common minerals are botryoidal pitchblende, secondary U-minerals and brannerite (Nyegaard et al. 1986; Steenfelt & Armour-Brown 1988).

3) Magmatic-type uranium mineralisation associated with highly differentiated magmas of Mesoproterozoic peralkaline intrusive complexes, known as the Gardar magma province. The mineralisation forms large, low-grade (200-400 ppm U) type deposits in Ilímaussaq and Igaliko intrusive complexes, that are clearly reflected in airborne gamma-spectrometry (Map 19 and Tukiainen et al. 1984; Steenfelt et al. 2000), but they do not give as high values in stream sediment and rocks as the uraninite bearing mineralisation mentioned above. Minor U and Th enrichments are located in other Gardar complexes (Armour-Brown et al. 1982b).

It is obvious and emphasised by the present compilation of U data that South Greenland represents a favourable environment for uranium mineralisation, where early enrichment is documented in Archaean upper crustal rocks, subsequent enrichment occurred in Palaeoproterozoic sediments, and at least two events (Late Ketilidian and Gardar) of remobilisation and precipitation of high-grade U minerals has taken place in favourable structural traps. Considering the abundance of U in South Greenland, it remains a possibility that a Palaeproterozoic unconformity type uranium deposit has been formed and is now preserved somewhere, probably at depth, since none of the known surface occurrences can be described as unconformity type. Such deposit could have contributed U for remobilisation during the recurrent post Palaeoproterozoic events of heating and tectonic disturbances that affected South Greenland.

The exploration activities in East Greenland by GGU and Nordisk Mineselskab A/S identified a number of minor occurrences of uraninite and secondary uranium minerals during

follow-up of anomalies from airborne gamma ray spectrometry and drainage geochemistry (Harpøth et al. 1986; Nielsen and Steenfelt 1977). Rock samples with more than 5000 ppm U are from the most studied occurrences, Arkosedal, Hochwacht and Randbøldal (Map 18). They are all associated with fracture zones related to major N-S fault systems developed during post Caledonian (Palaeo- to Cenozoic) crustal extension (Steenfelt 1982).

Follow-up of many anomalies in Nuuk region, southern West Greenland, identified abundant pegmatites enriched in allanite and rare euxenite, but also uraninite hosted by pegmatite and adjacent mafic metavolcanic rocks close to a major shear zone (Secher 1980, Steenfelt et al. 2007a and unpublished data).

A few rock samples enriched in uraniferous pyrochlore and having more than 5000 ppm U have been collected in fractures zones within the fenitisation halo of the Neoproterozoic Sarfartoq carbonatite in West Greenland (Secher 1986).

The province of high background and a few anomalies in the Uummannaq region, West Greenland, are recorded in stream sediment and stream water data, ground radioactivity and rock samples. Nielsen (1980) mentions elevated U values in rock and sand samples, but otherwise this region has not been recognised as uranium enriched before this compilation, and it has not been investigated with regard to U mineralisation. The region is underlain by interleaved Archaean orthogneiss and Palaeoproterozoic supracrustal rocks representing shelf and slope deposits. Rock samples with elevated U were mainly collected during gold and zinc exploration (Thomassen & Lind 1998; see also Steenfelt et al. 1998 and references therein).

7. Conclusion

The compilation, description and presentation of available data on U will benefit an explorer or researcher with an interest in uranium in Greenland.

The geochemical background variation for U recorded by five types of sample media displays distribution patterns for elevated uranium that identify where upper crustal rock assemblages are preserved in the Precambrian basement of Greenland. Such areas are characterised by the presence of granitic rocks and pegmatites enriched in U-bearing accessory minerals and are the result of crustal fractionation of U through crustal melting and granite magmatism. High background areas are considered fertile for the formation of unconformity- or vein-type U deposits during later reworking and hydrothermal activity.

The spatial distribution of U anomalies clearly identifies areas with high-grade U mineralisation and potential to host economic deposits and emphasise the extraordinary abundance of high U samples in South Greenland.

8. Bibliography and references

The bibliography is divided into three categories 1) reports and papers dealing with uranium exploration and investigation of uranium mineralisation in Greenland, 2) reports and papers on geochemical mapping and exploration in which data for U are presented, and 3) selected papers in Danish describing the initiation of uranium exploration in Greenland. A few additional and cited references on geology and methodology are listed immediately below. References cited in the text of the report are marked with an asterisk.

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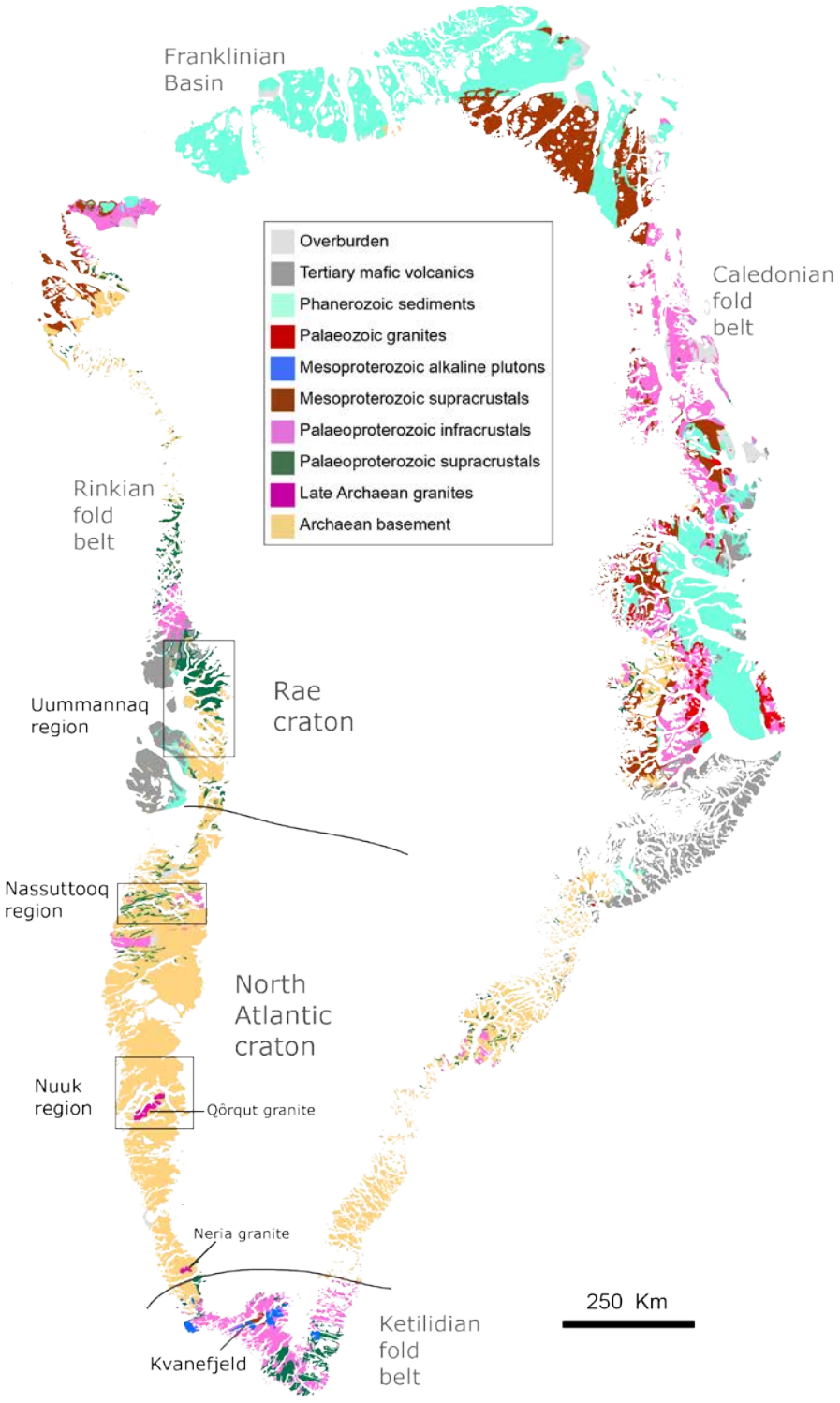

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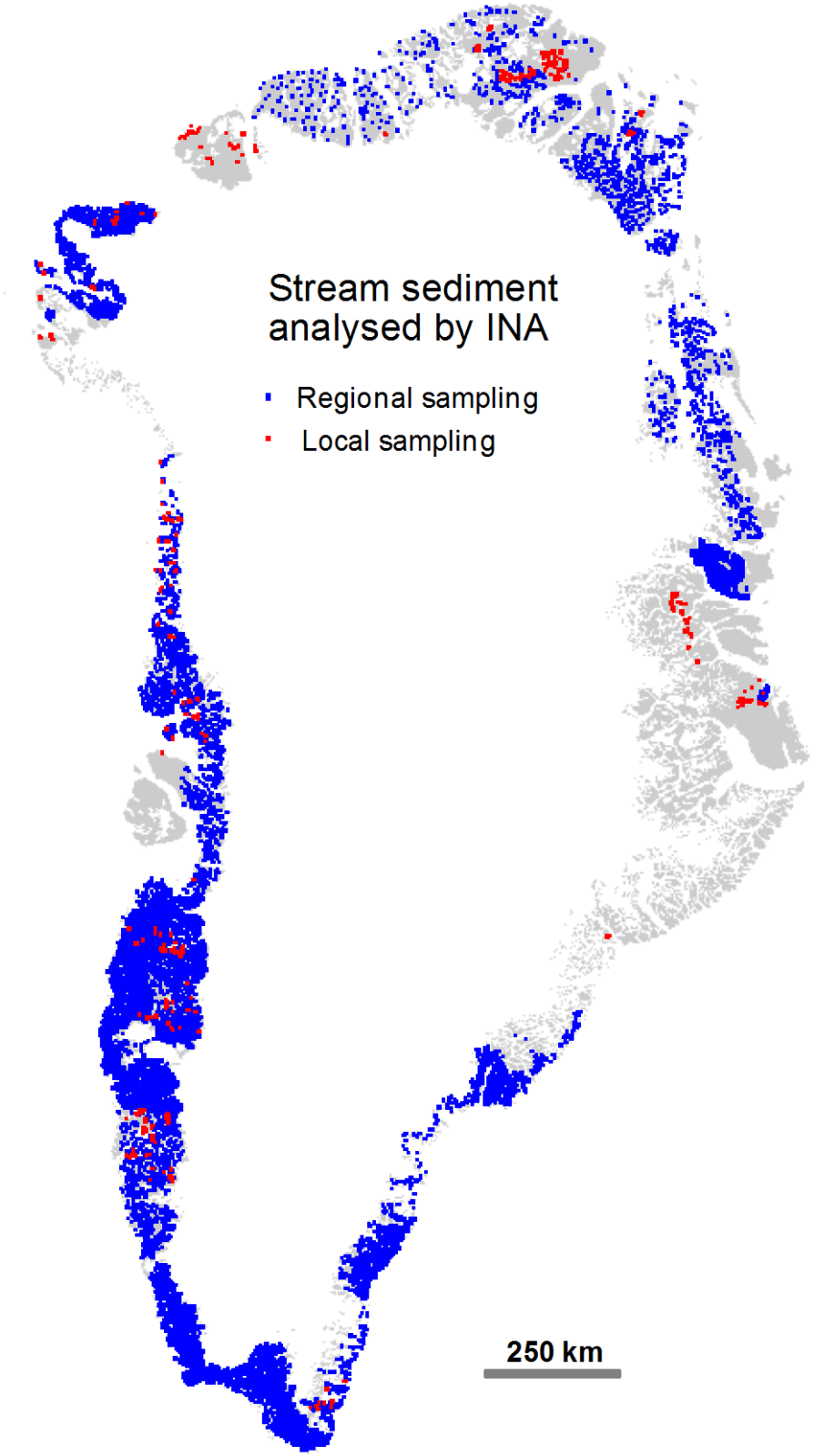

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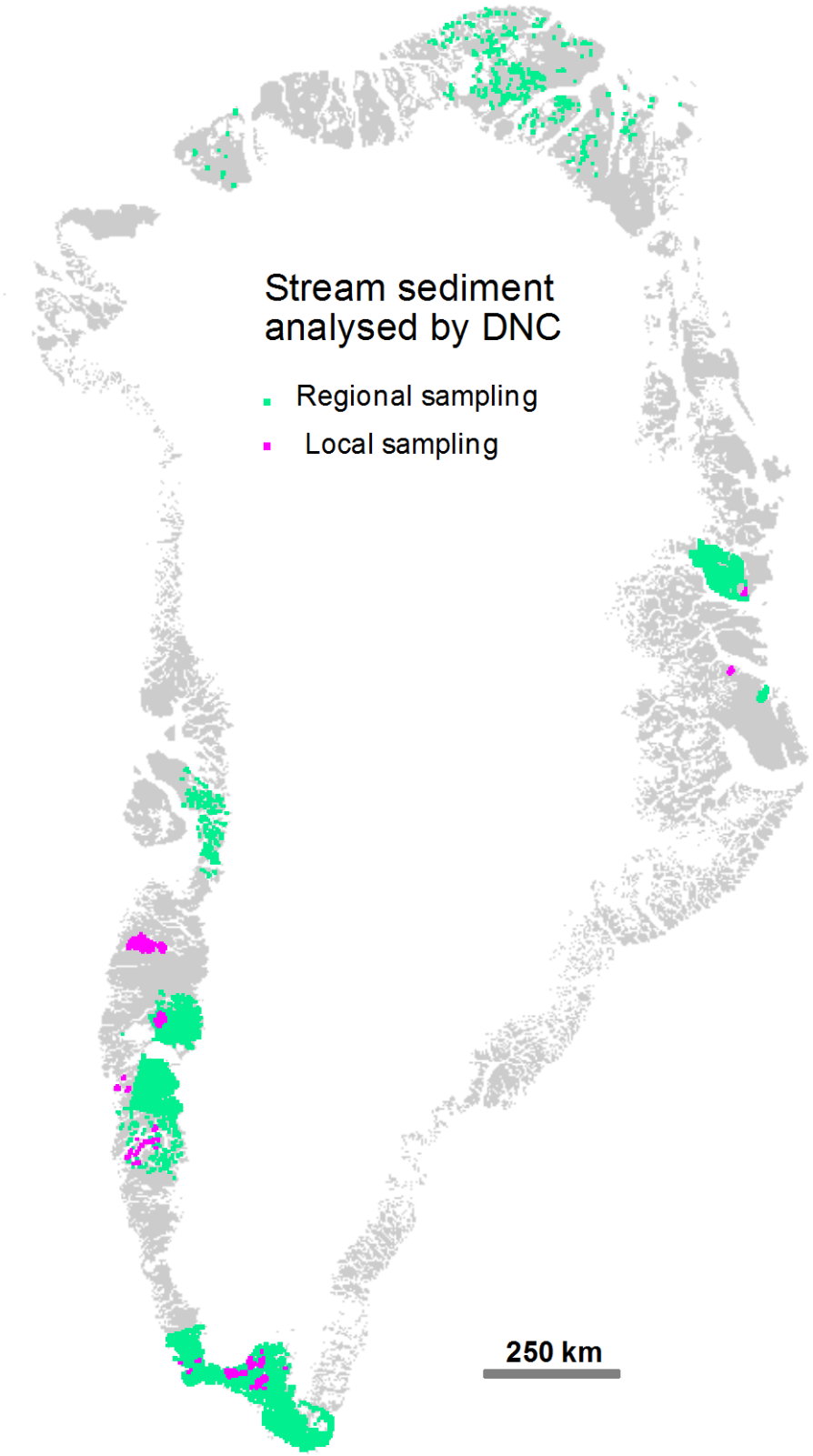

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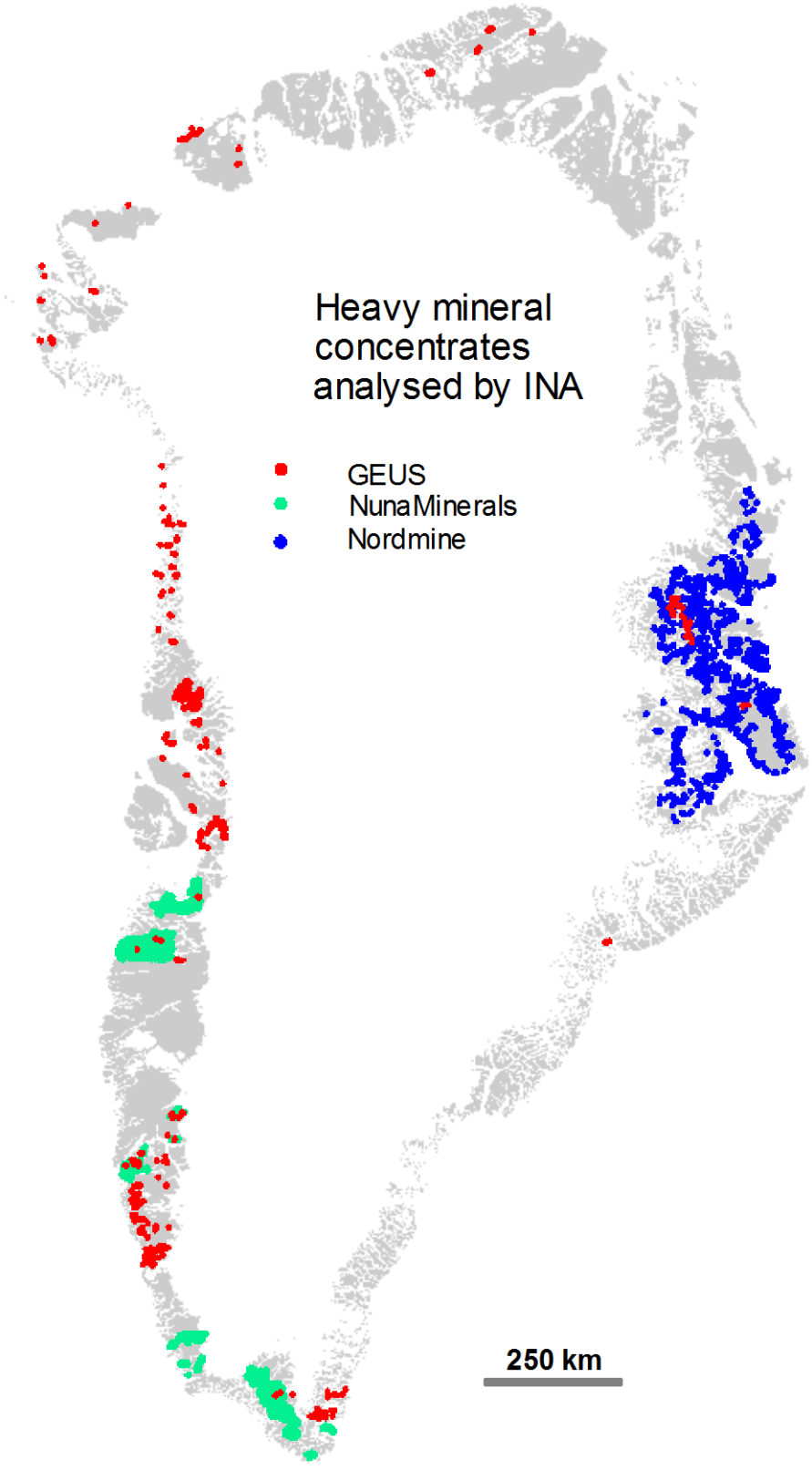

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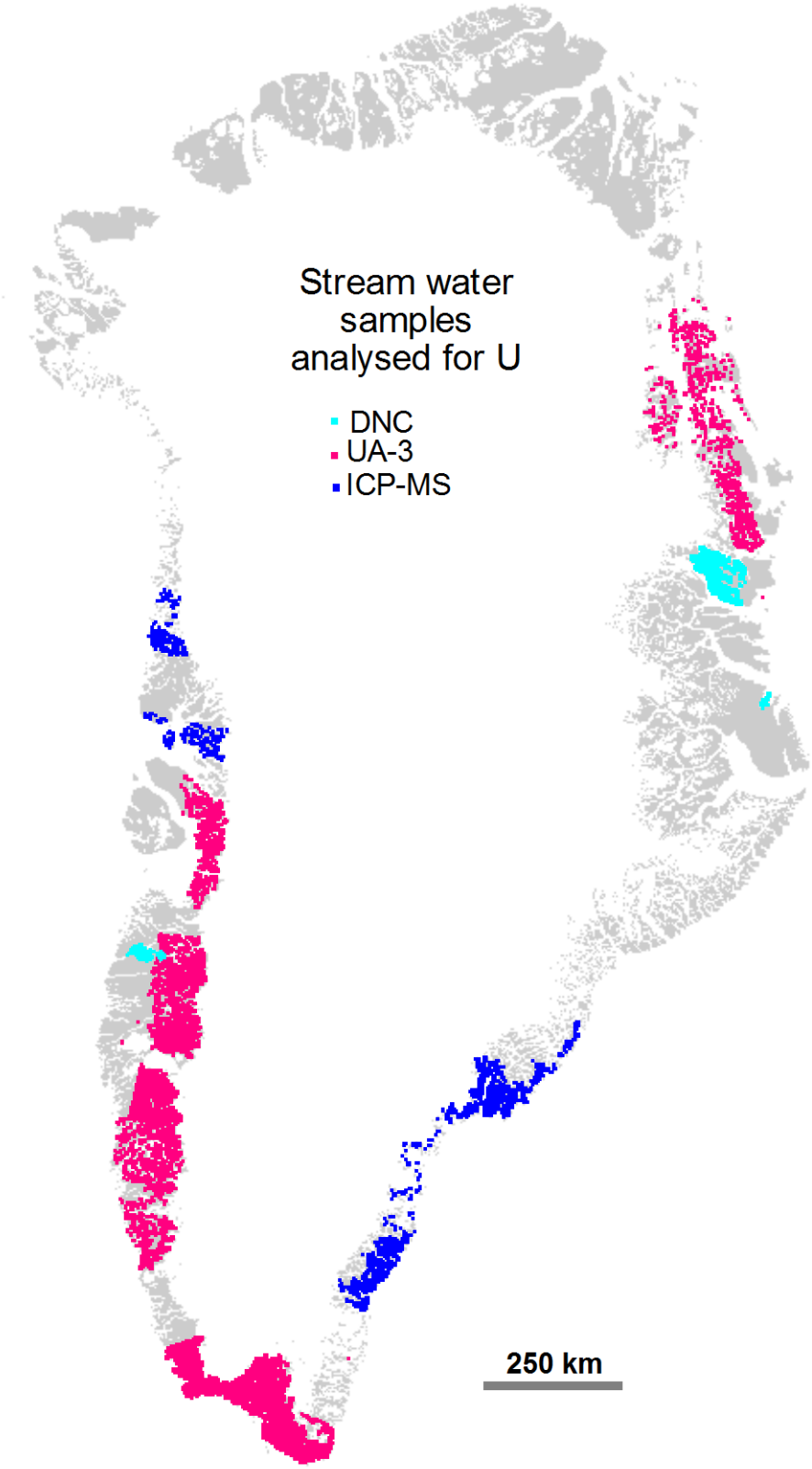
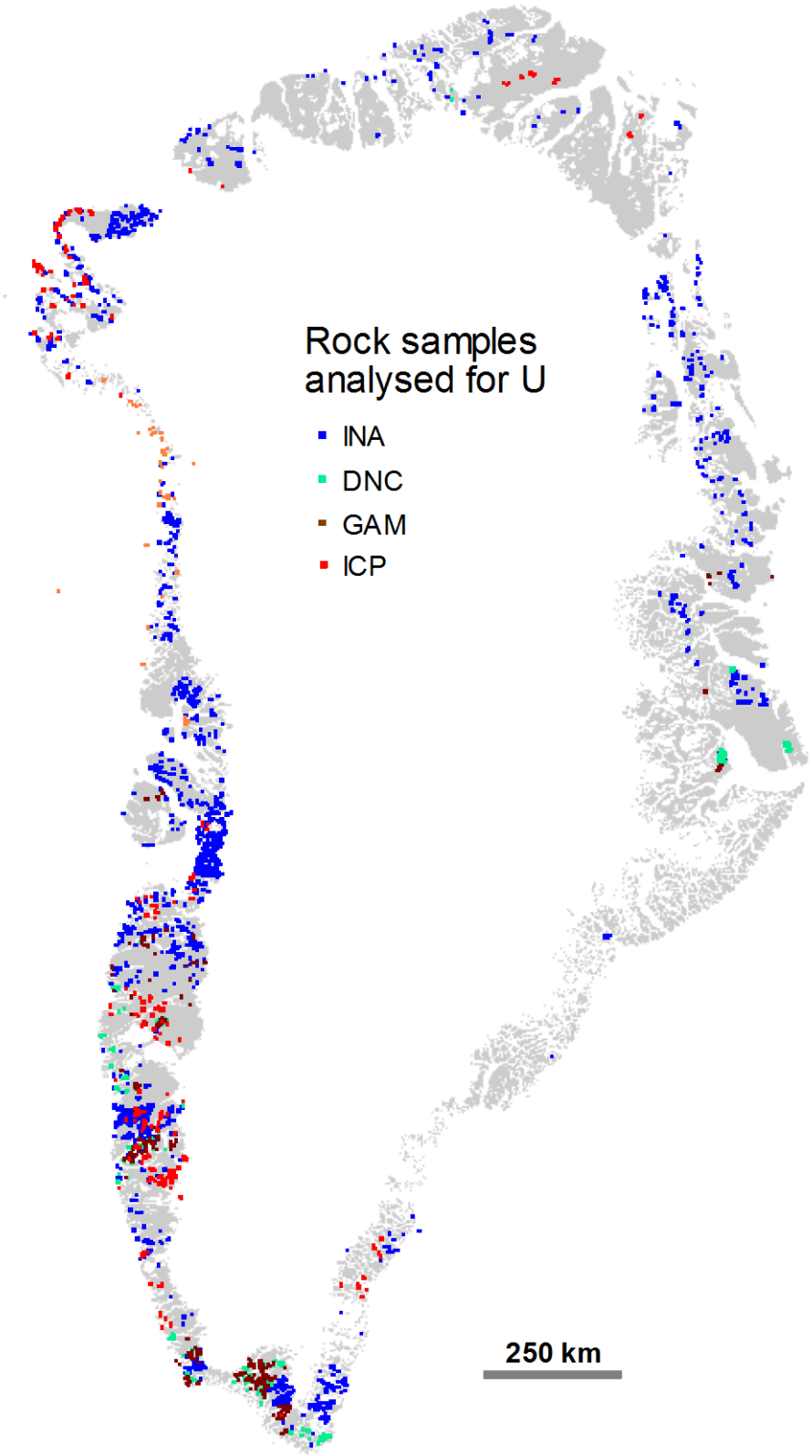


Map 5. *Location of stream water samples analysed by delayed neutron counting (DNC), laser scintillometry (UA-3), or inductively coupled plasma mass spectrometry, see text for more details.*



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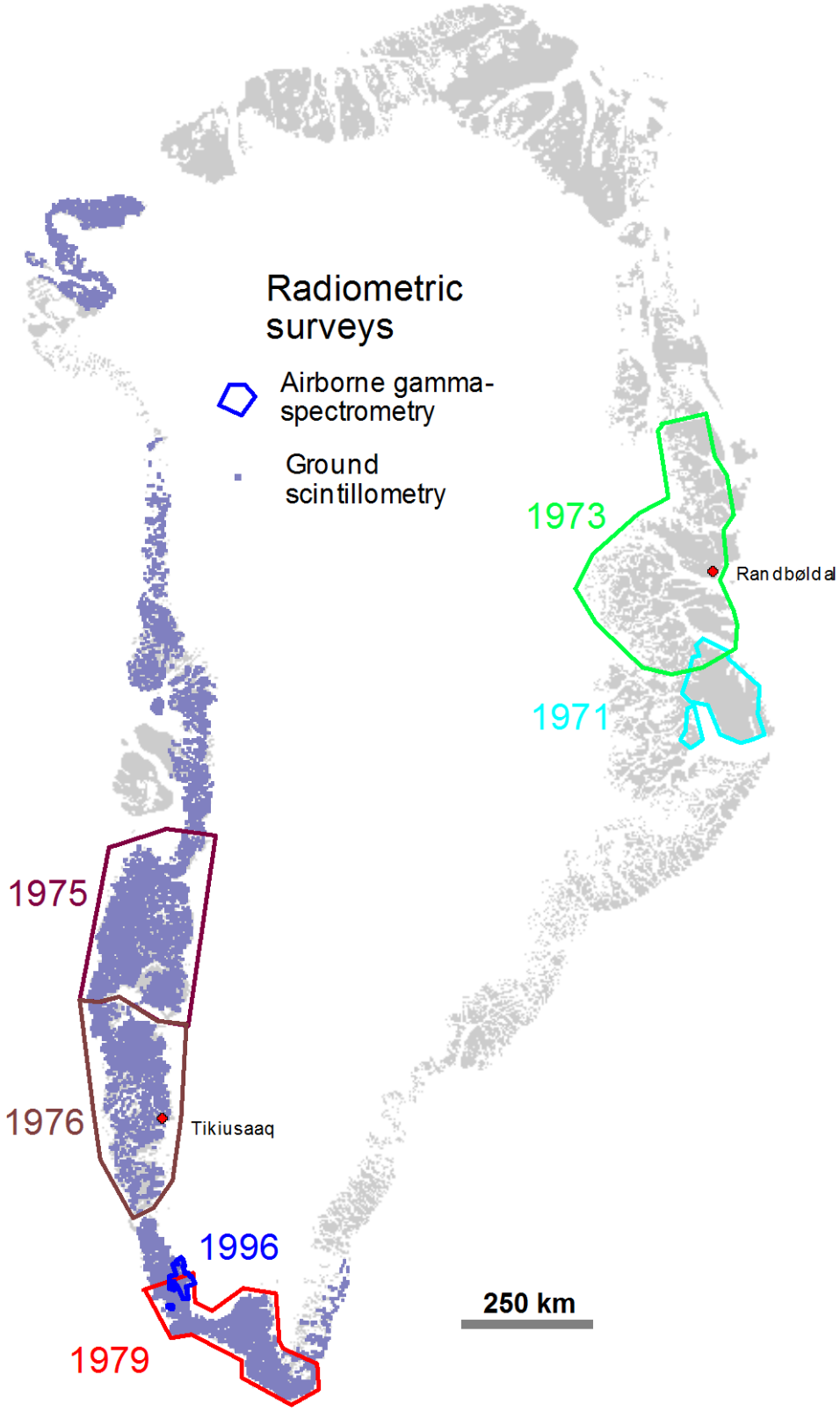

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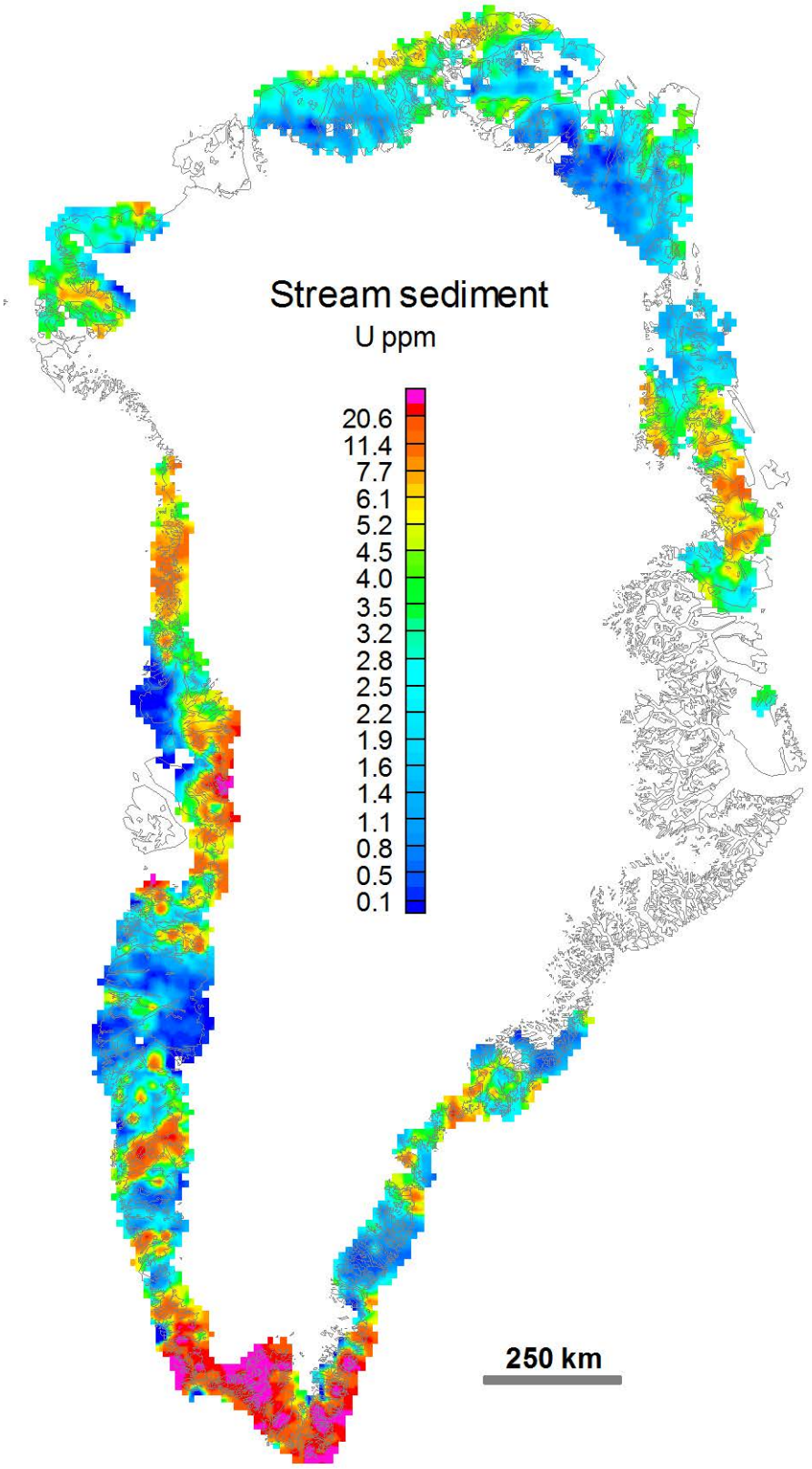

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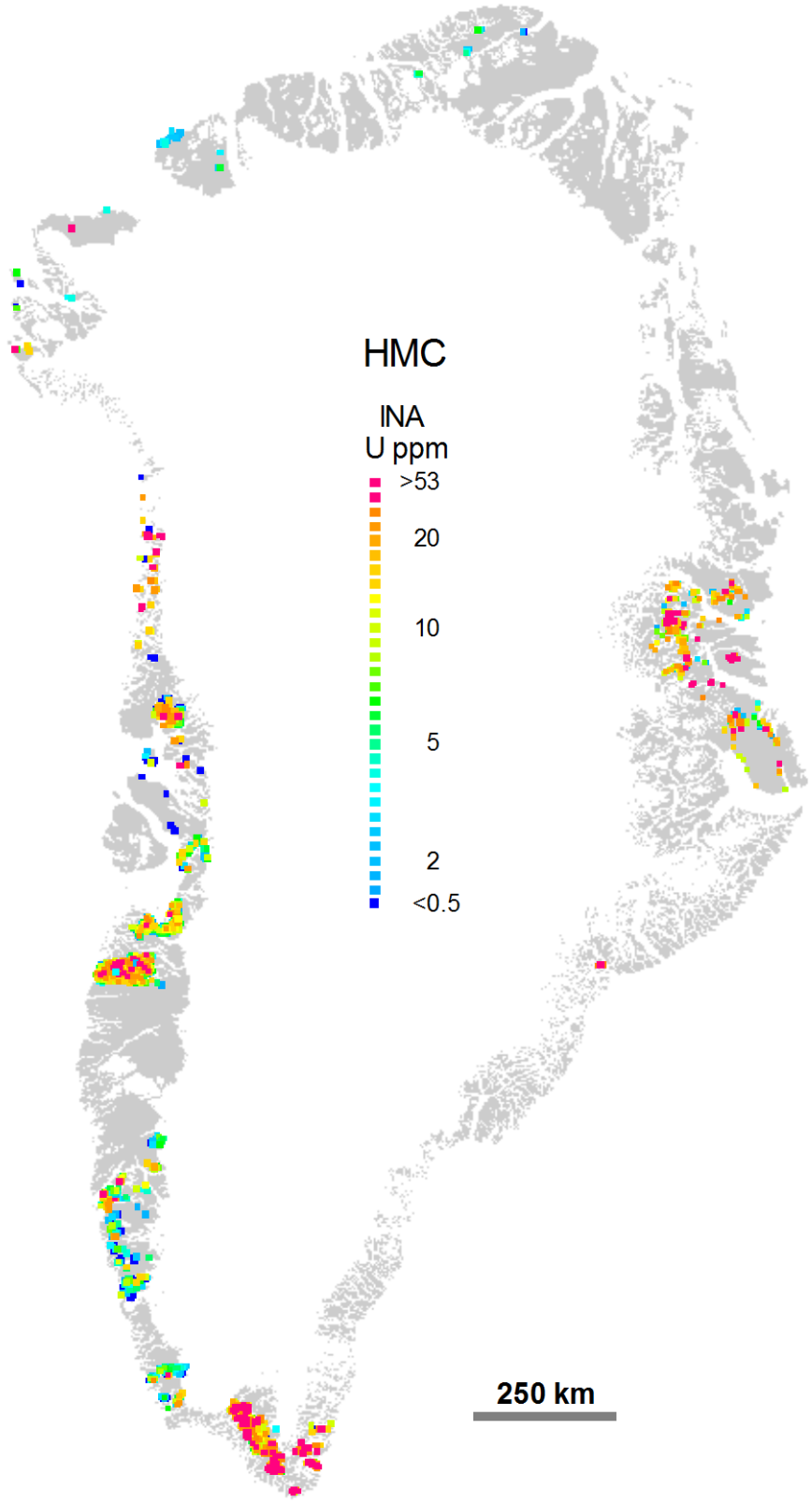
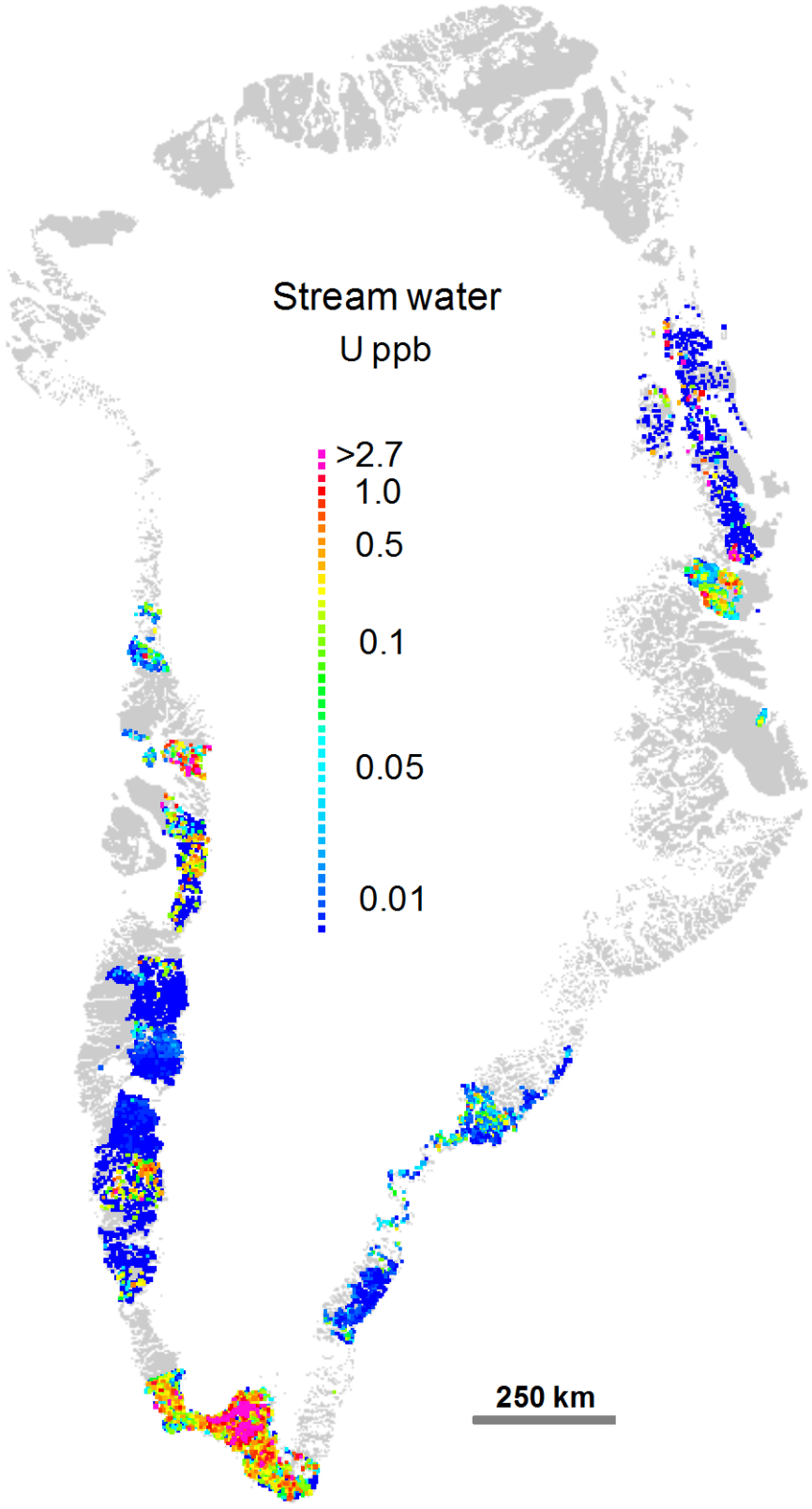


Map 9. *Colour-scaled symbol plot of U concentrations of heavy mineral concentrates of stream sediment collected by GEUS and companies, see Map 4, and analysed by instrumental neutron activation method (INA).*



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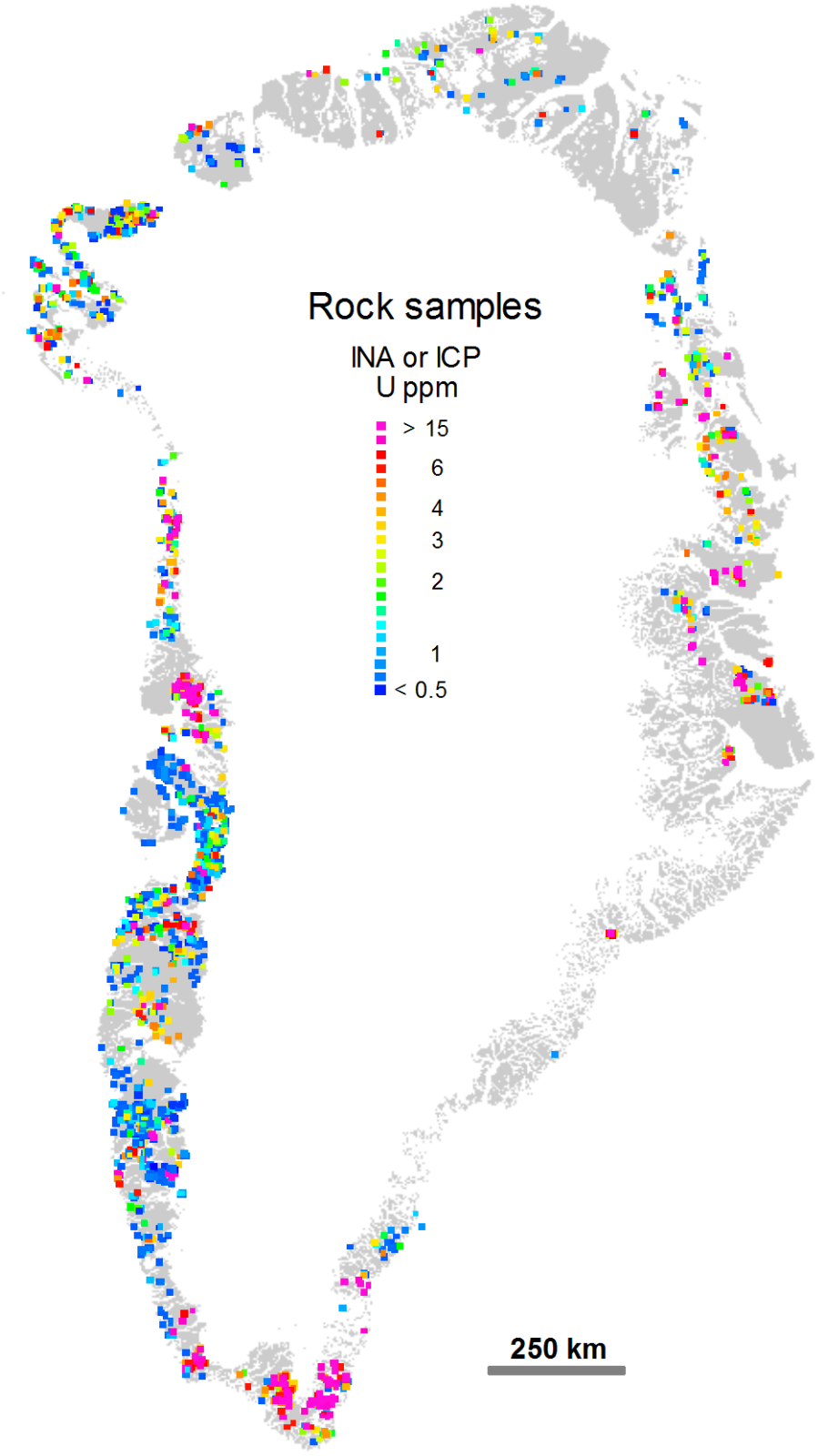
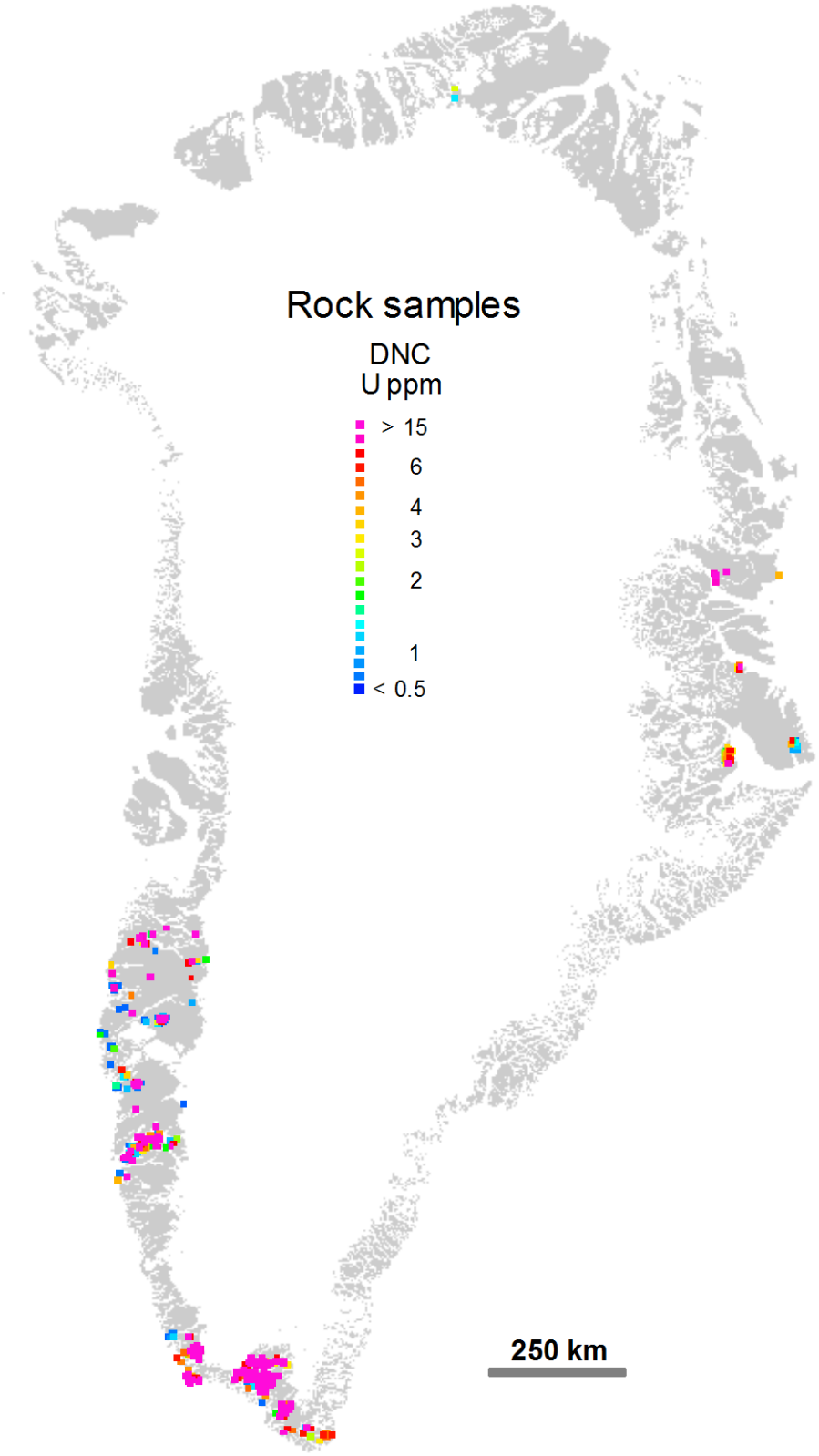


Map 11. *Colour-scaled symbol plot of U concentrations of rock samples collected for mineral exploration and geological research and analysed by instrumental neutron activation (INA) or inductively coupled plasma spectrometry (ICP).*



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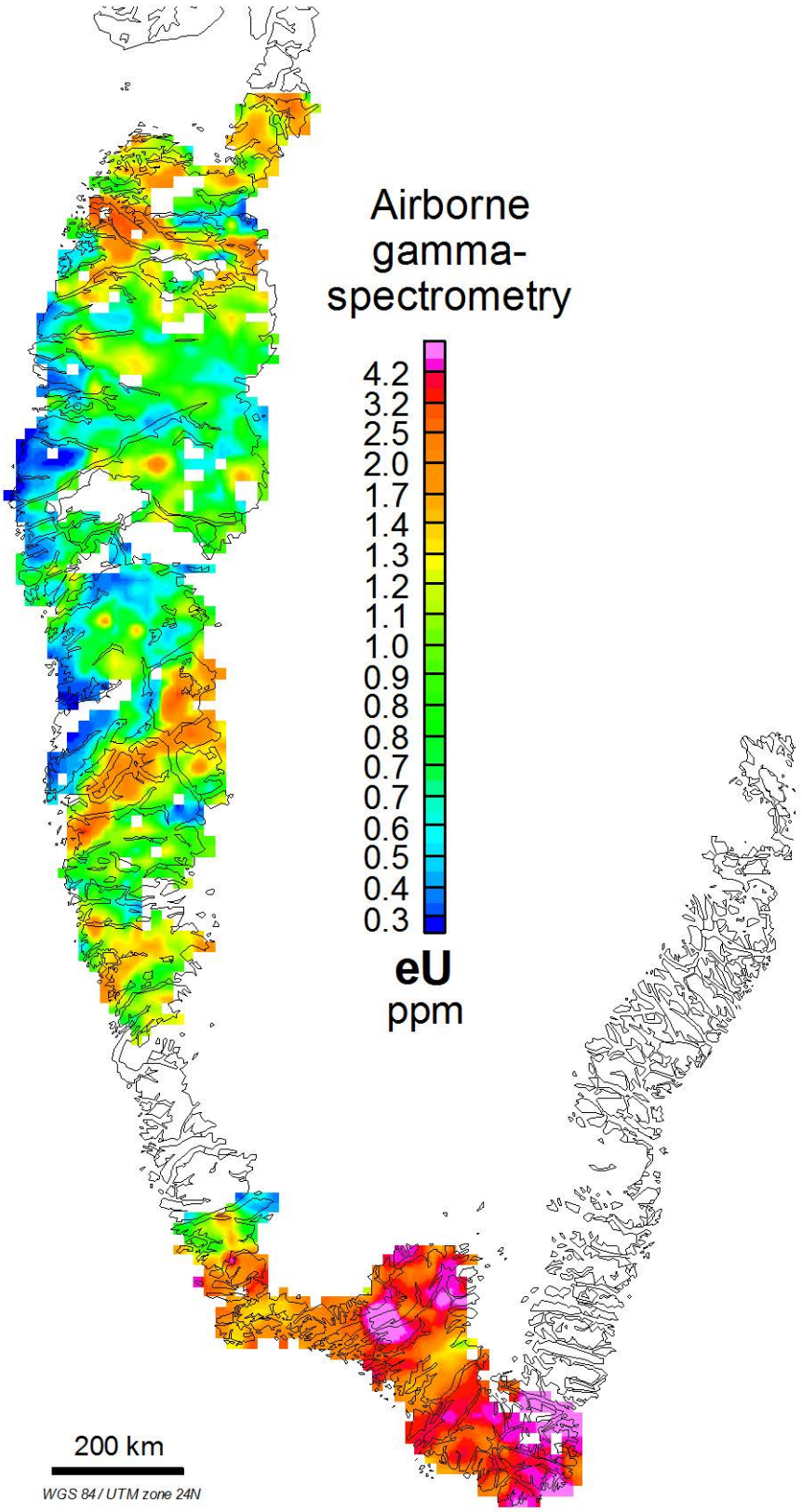

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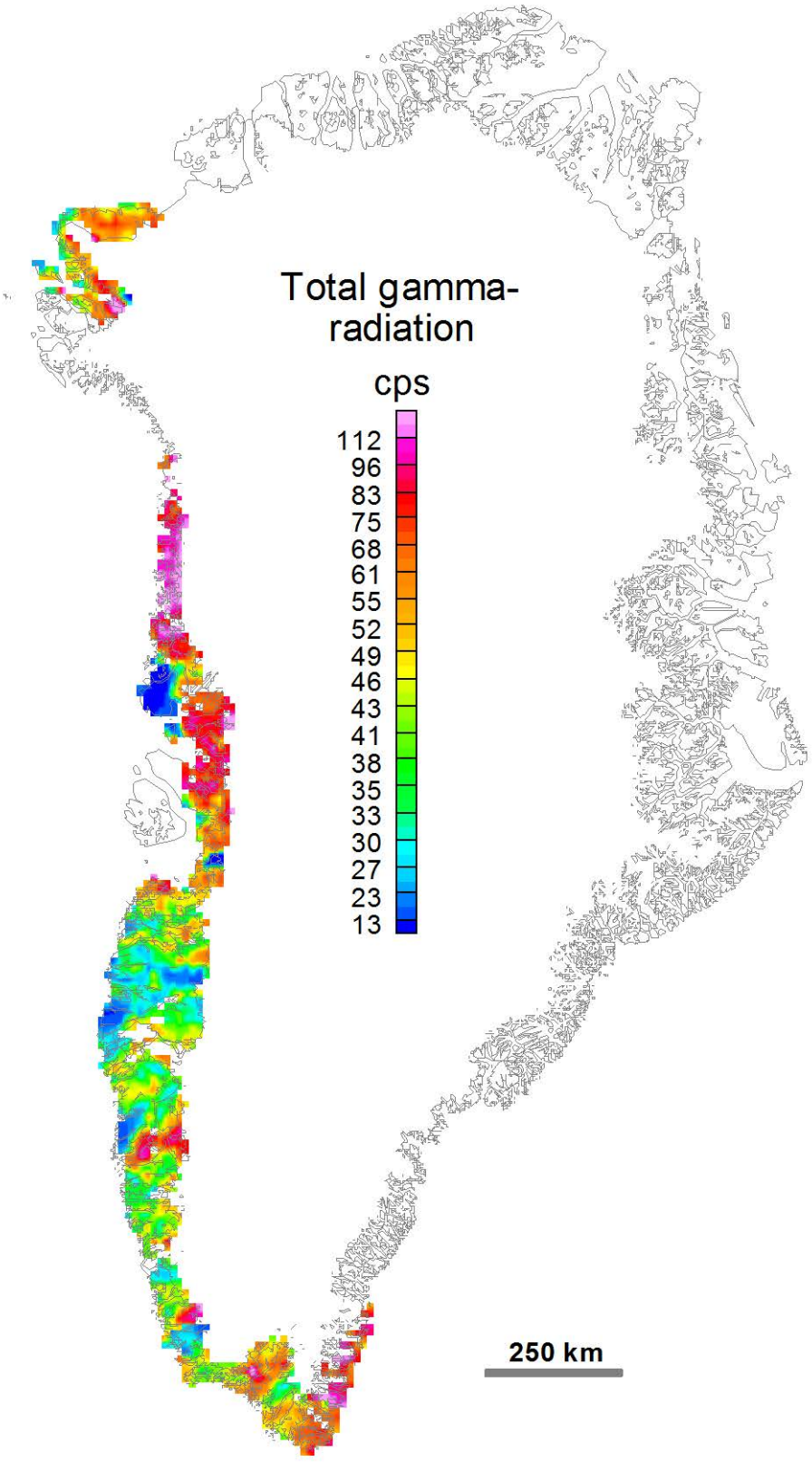

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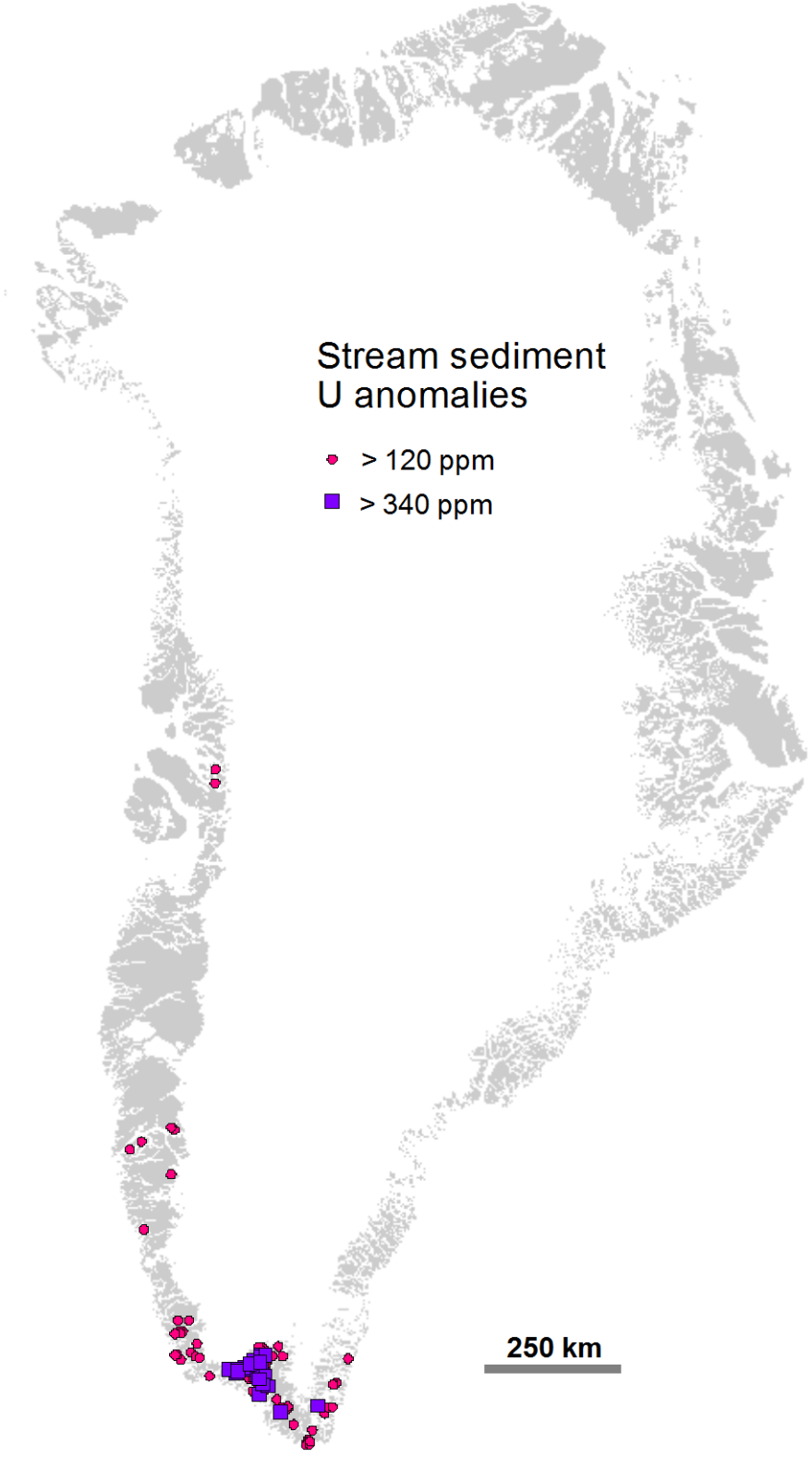

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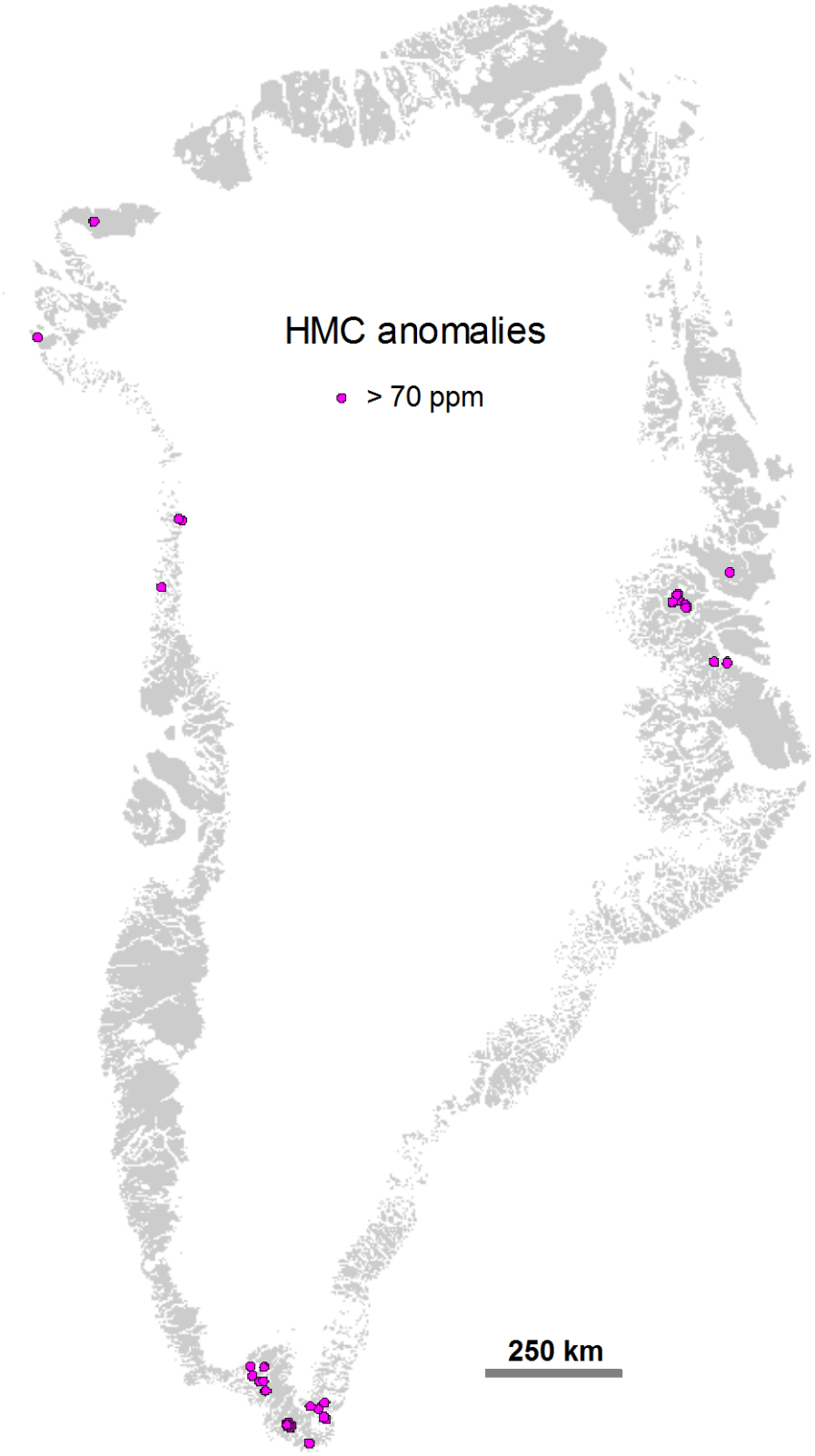

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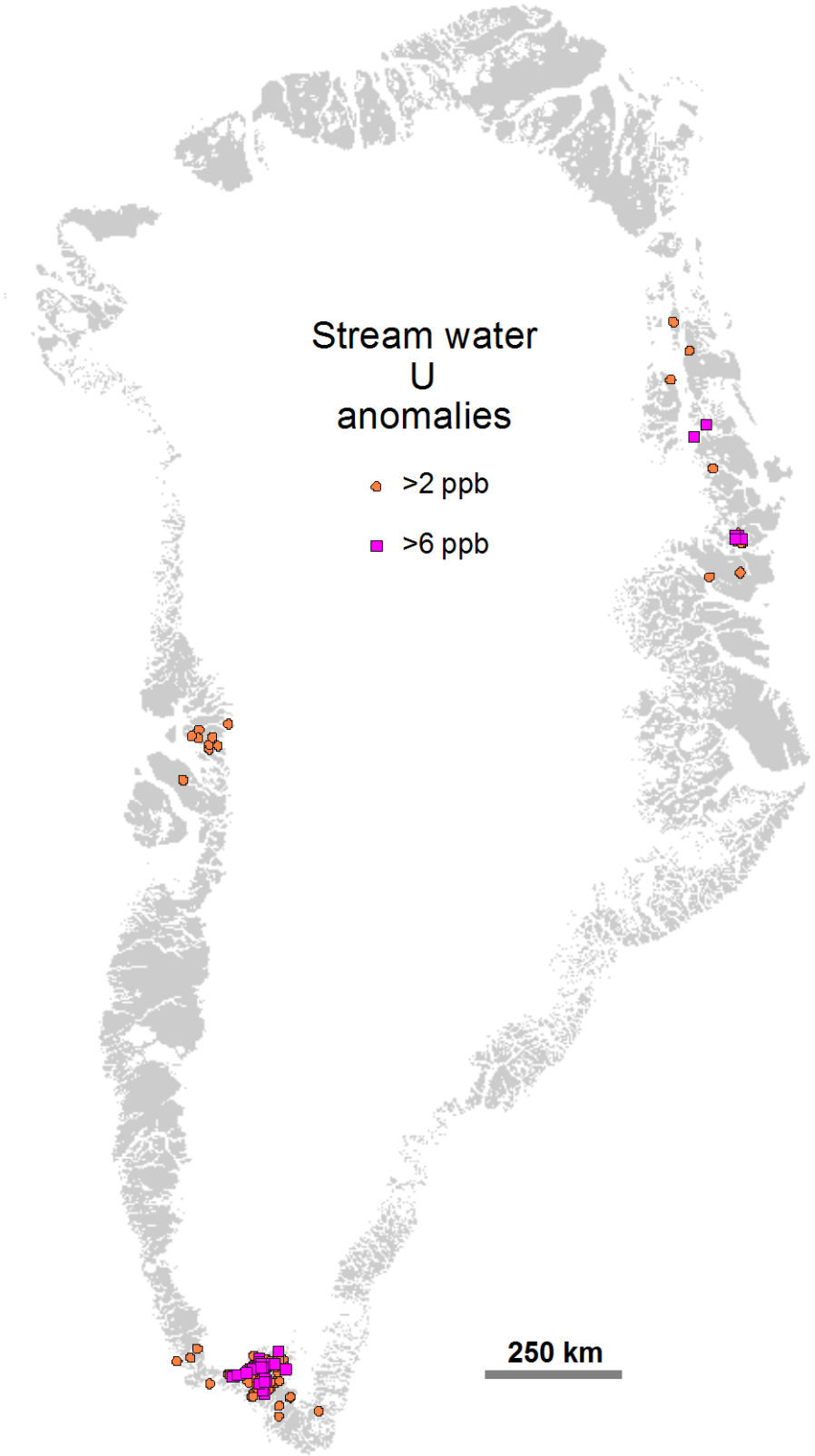
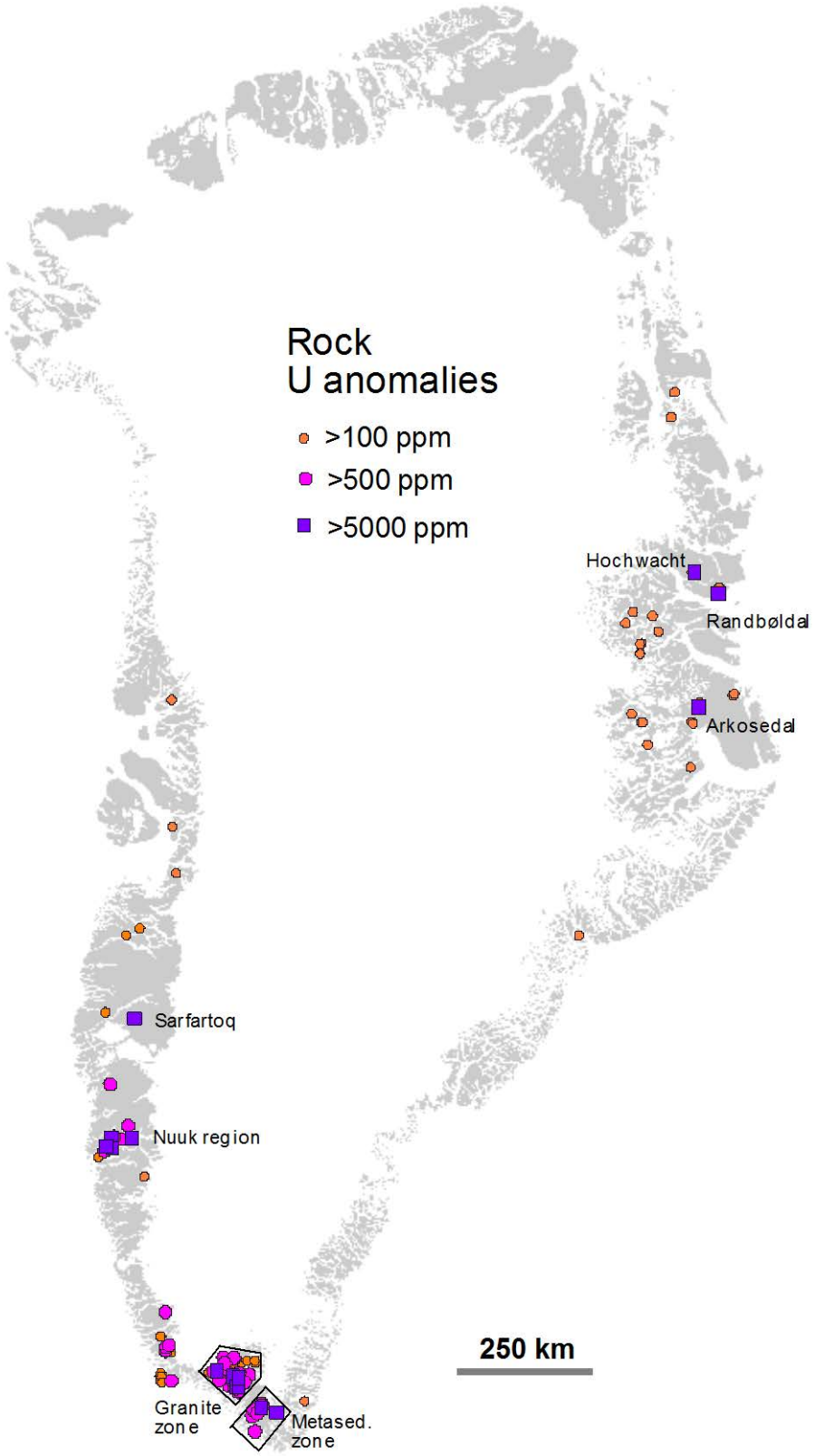
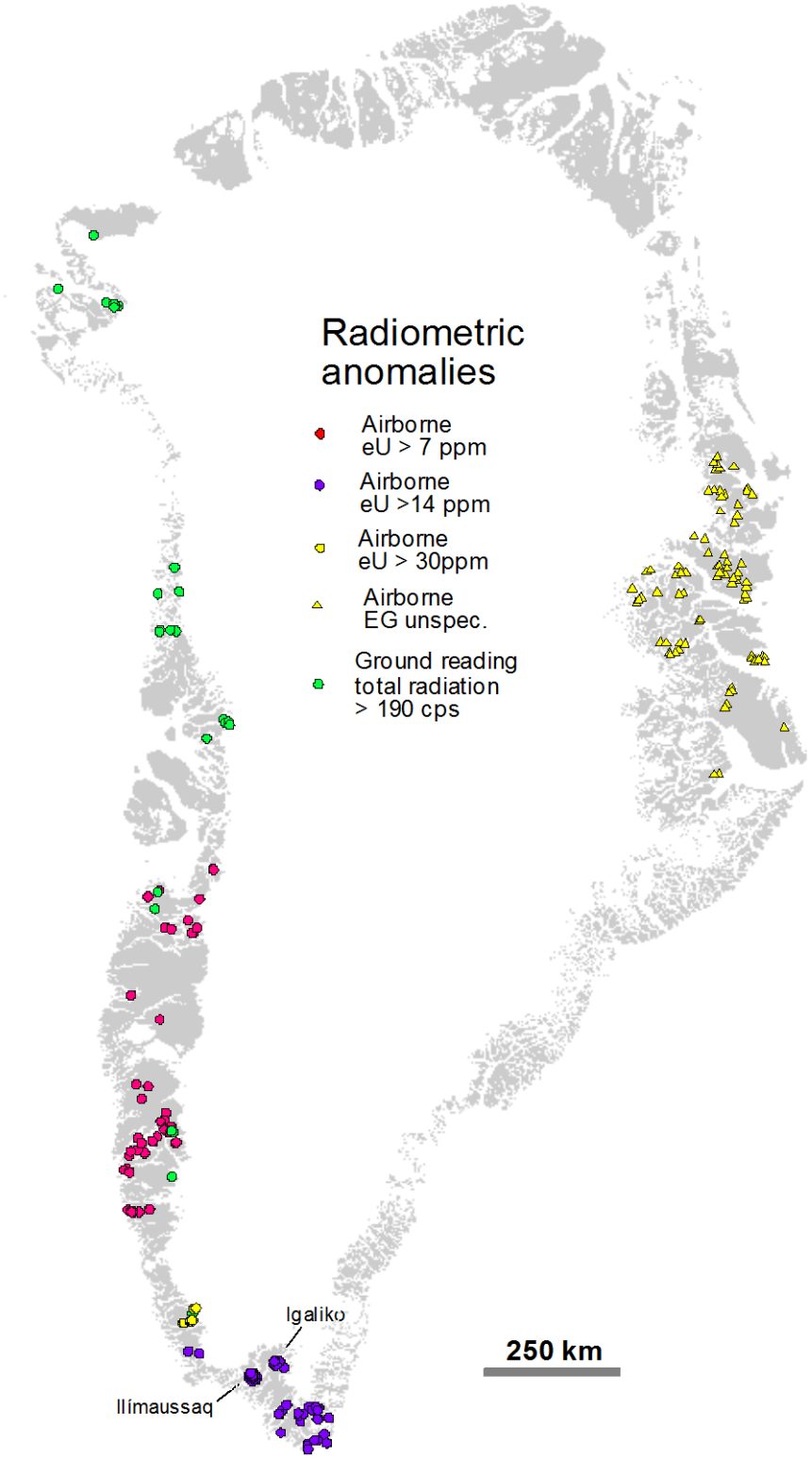


Map 17. *High concentrations of U recorded in stream water samples, maximum is 82 ppb.*



Map 18. *High concentrations of U recorded in rock samples collected mainly for uranium exploration, but also for base metals or gold. Maximum is 38800 ppm. Known U occurrences with names.*



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