DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE **RAPPORT 2024/5**

Whole-rock geochemistry on pegmatite occurrences in Greenland and their potential for critical raw materials – with a focus on lithium

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Introduction

Lithium, abbreviated as Li, is listed as one of the critical raw materials for the European Union (EU) in 2023 (European Commission 2023). Lithium is widely used in Li batteries for electric cars, mobile devices, and lithium minerals as a flux in glass and ceramics industry, where it lowers the melting point and viscosity of silica, and is applied as a flux additive for iron, steel, and aluminum production (USGS 2020b; 2022b). Lithium is therefore an important metal for the green energy transition. It is a highly reactive ion and is present in small amounts in crustal rocks (20 to 70 ppm by weight) and in seawater (0.14 to 0.25 ppm) (Dye, 2024). Higher concentrations of Li are found in granites and granitic pegmatites, often in one of the minerals: spodumene, petalite or lepidolite, however Li is also concentrated in brines and Salar deposits. The world's top five Li-producing countries are Australia, Chile, China, Bolivia, and Argentina, where the three countries Chile, Bolivia and Argentina are known as the Li Triangle, which are producing Li from Salar deposits (USGS 2020b; 2022b). The Greenbush mine in Australia is the largest hard-rock producing Li mine in the world, here Li is extracted from spodumene. China produces Li from brines and hard-rock mines (USGS 2024).

With the growing demand for Li, there is an interest in finding new sources. Greenland is underexplored for Li, and mineral exploration companies request Li data from Greenland. This report aims to describe the potential for discovering Li in Greenland. To do so, pegmatitic rocks from Greenland have been studied. Pegmatitic rock samples from Greenland were collected from the GEUS rock archive and analyzed for their whole rock major and trace element geochemistry. A total of 28 pegmatite samples were analyzed from different areas in Greenland (see Fig. 1).

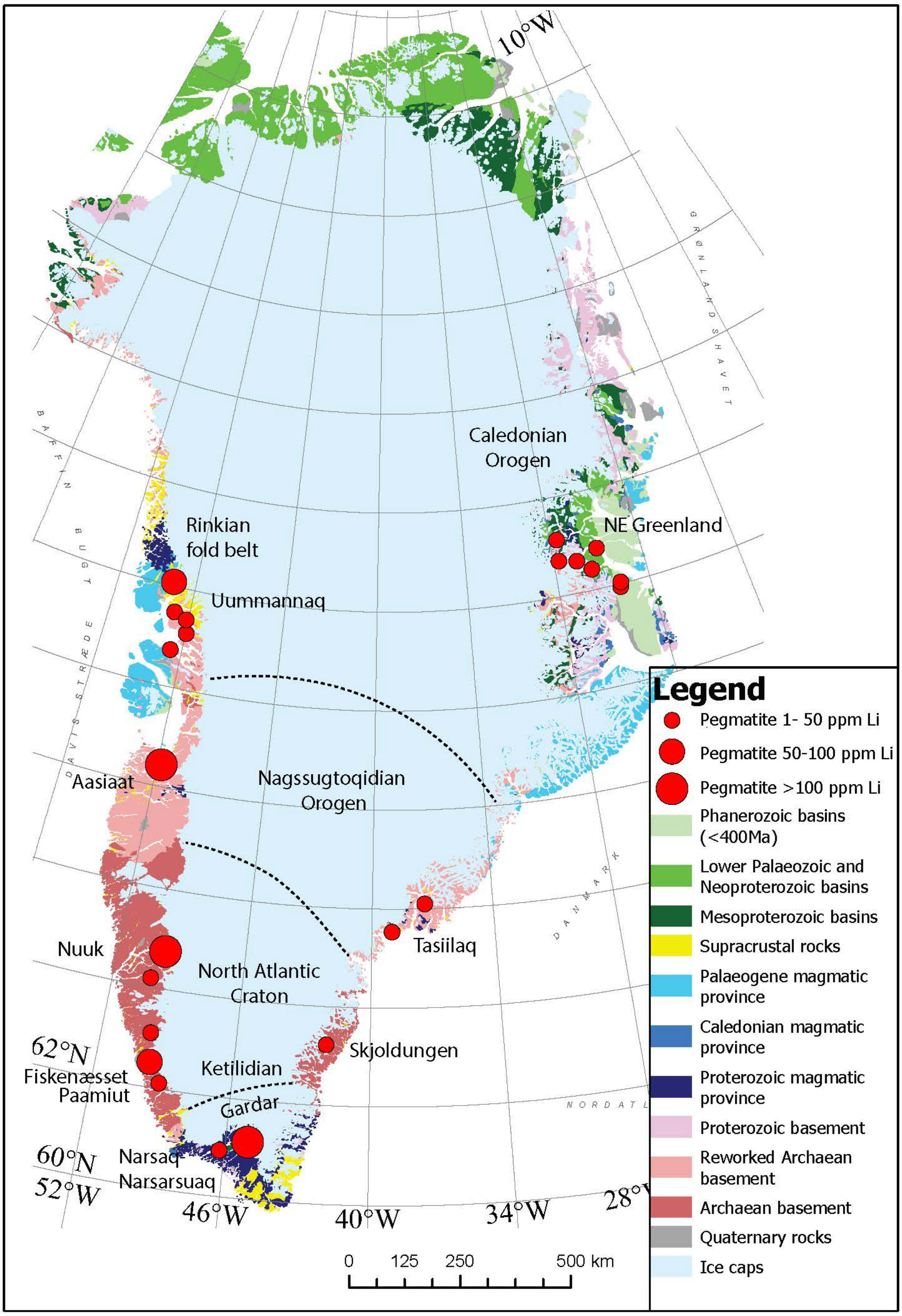

Figure 1: *Map of Greenland showing the locations for the pegmatite samples analyzed.*

Background on pegmatites

Pegmatites are defined as coarse grained crystalline igneous rocks with large interlocking crystals several centimeters in length intruded as sheets in the surrounding rocks. Pegmatites are commonly of minor size, from a few meters to tens of meters wide, compared to typical intrusive rocks, are rather inhomogeneous and often show zones with different mineral assemblages. Pegmatites often have a granitic composition however, other compositions are known, including gabbro or nepheline syenite. The term pegmatite is therefore only a textural description, while a prefix maybe be added to the description such as a granitic - or alkaline pegmatites.

Most granitic pegmatites consist of the mineral's quartz, feldspar, and micas, and are called simple pegmatites. More complex pegmatites can contain accessory minerals such as tourmaline, fluorite, lepidolite, spodumene, molybdenite, scheelite, beryl, uraninite and rare earth element-bearing minerals.

There is not one standardized scheme for the classification of granitic pegmatites (Simmons & Webber, 2008; Dill 2015). One of the approaches for the classifications for the granitic pegmatites are the geochemical-paragenetic subdivision, which is based on the geological environment as well as pressure and temperature conditions for the host rock and pegmatites (Černý et al. 2005; 2012). The second classification approach is the petrogenetic families which is based on granitic pegmatites derived from differentiation from magmatic intrusions. There are three families distinguished: LCT (Lithium, Cesium, and Tantalum) family, NYF (Niobium, Yttrium, and Fluorine) family, and the mixed LCT + NYF family.

Alkaline pegmatites are derived from alkaline magmatic rocks, where the melts are derived from the lithospheric mantle and typically associated with rifting of the continental crust. In this geotectonic setting the magmas are often silica-undersaturated and characterized by high concentrations of alkali metals and high field strength elements such as Y, Zr, Hf, Nb, Ta and Rare Earth Elements.

Sample selection

The GEUS database in the internal Greenland Portal ‘Sample archive’ indicated 996 samples collected with the text ‘pegm’ included in their sample description. Among those, 951 samples were rock samples collected by either GEUS or exploration companies. Only the GEUS and the Nordisk Mineselskab A/S samples were selected, resulted in a list of approximately 600 samples (Fig. 2). Running through the list indicated, some of the samples were other rock types but with pegmatite in the descriptions and a filtering of the samples resulted in approximately 400 pegmatite samples, most often sampled for radiometric dating purposes. The geographical distribution of the sampled pegmatites indicates where the geological field campaigns have been focused through time, and therein areas where pegmatites are more abundant. A total of 28 samples were selected from the archives and prepared, for bulk whole rock major and trace element geochemical analyses, From the following areas of interest (Fig. 1):

- Nuuk to Paamiut area (North Atlantic Craton, Archean rocks) (5 samples, Ivisaartoq, Ameralik, Fiskenæsset, Paamiut, Frederikshåb Isblink)
- Skjoldungen area (North Atlantic Craton, Archean rocks) (1 sample)
- Uummannaq area (Karrat Group, Paleoproterozoic rocks) (5 samples)
- Aasiaat area (West Nagssugtoqidian Orogen, Archean to Paleoproterozoic rocks) (3 samples, Lersletten)
- Tasiilaq area (East Nagssugtoqidian Orogen, Archean to Paleoproterozoic rocks) (2 samples)
- Narsaq - Narsarsuaq area in South Greenland (Gardar Province, Mesoproterozoic rocks) (6 samples, Tuttutooq, Motzfeldt Sø)
- Northeast Greenland (Neoproterozoic-Paleozoic rocks) (7 samples, Ella ø, Lyell Land, Gletscherland, Petermann Bjerg, Werner Bjerge)

Figure 2: *Samples registered in the GEUS archives from GEUS and Nordisk Mineselskab A/S with 'pegm' in the description, yellow = rock, blue = water, brown = surface, white = ice, grey = other countries.*

Analytical method

All samples were analyzed by the GEUS’ ICP-MS laboratory.

Major and trace element analytical procedure

For determining the Si content in the samples, the ’Borate-method’ was applied. 0.1 g of finely crushed sample was mixed with 0.9 of sodium tetraborate and fluxed for appr. 30 minutes in a Pt/Au crucible on a rotary table. The resulting glass pearl is treated with diluted nitric acid in a PP tube digestion vessel placed on a shake table and mixed until the glass pearl dissolved in acid. The sample was then diluted to 30 ml.

Before measurement the sample was diluted further 11 times. The international reference samples BHVO-2, BCR-2, OU-6, OShBo, and inhouse standard Disko-1, Gonv-1(GeoPT-45 standard), BVA-1 (GeoPT -49 standard) were prepared at the same method as the samples (Kystol & Larsen, 1999).

The samples were measured using a PerkinElmer AVIO-500 ICP-OES instrument. The set-up, data acquisition, calibration and calculations are done using the Syngistix software version 5.1. 0.0293. For the major elements, the elements determined are Al, Ca, Fe, K, Mg, Mn, Na, P, Si, and Ti.

The trace elements (Li, Sc, V, Cr, Co, Ni, Cu, Zn, Ga, Rb, Sr, Y, Zr, Nb, Mo, Cs, Ba, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Hf, Ta, Pb*, Th, U) were determined using a PerkinElmer NexION 1000 ICP-MS instrument. For these analyses, 0.1 g of finely crushed material was treated with hydrofluoric and nitric acid in a closed Savillex vessel (polytetrafluorethylene polymer) on a hotplate at 130° C. After 24 hrs. the samples were evaporated to dryness on the hotplate at 100° C. Nitric acid was added and the sample was evaporated to dryness again. This was repeated once more. Nitric acid, internal standard solution (Ge, Rh, Re) and water were added. The vessel is closed and placed on the hotplate at 130° C for 12 hours. The sample was diluted to 50 ml and, before measurement, the sample is diluted further 51 times.

For calibration of the instrument, certified solutions containing Rare Earth Elements and some additional elements were used. In addition to these, solutions of international reference materials, BHVO-2 and BCR-2 were included, and the reference material was prepared by the same method as the samples. As verification, an inhouse standard (Disko-1), one or two international reference samples and two blanks were prepared at the same time as the samples. The set-up, data acquisition, calibration and calculations are done using the NexION 1000 Syngistix™ software version 2.5.

Composition of the pegmatites

The whole rock geochemical data is presented in the total alkali-silica (TAS) diagram (Middlemost, 1994) (Fig. 3). Following the TAS classification of the pegmatite composition show that the Greenlandic pegmatites range between granites, syenite, foid-syenite, and foid-monzosyenite. A few samples plot at lower alkalis in the field for foidolite, gabbro, gabbro diorite and diorite.

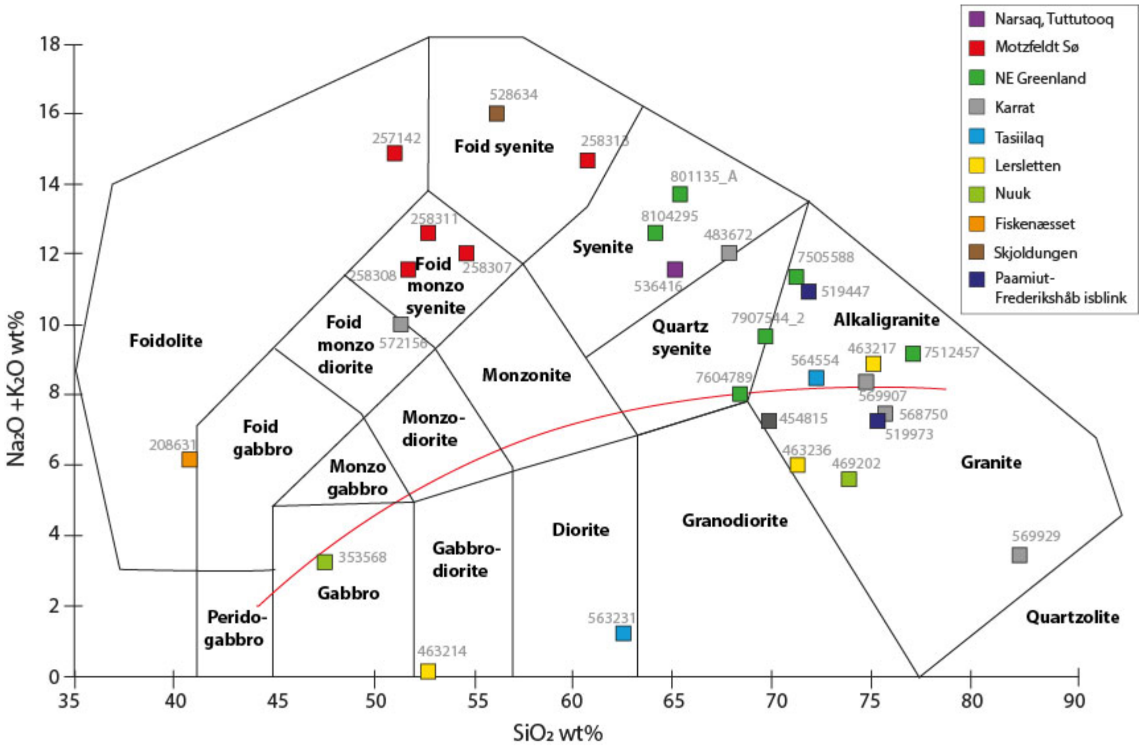

Figure 3: *The total alkali-silica (TAS) diagram after Middlemost (1994) for plutonic rocks.*

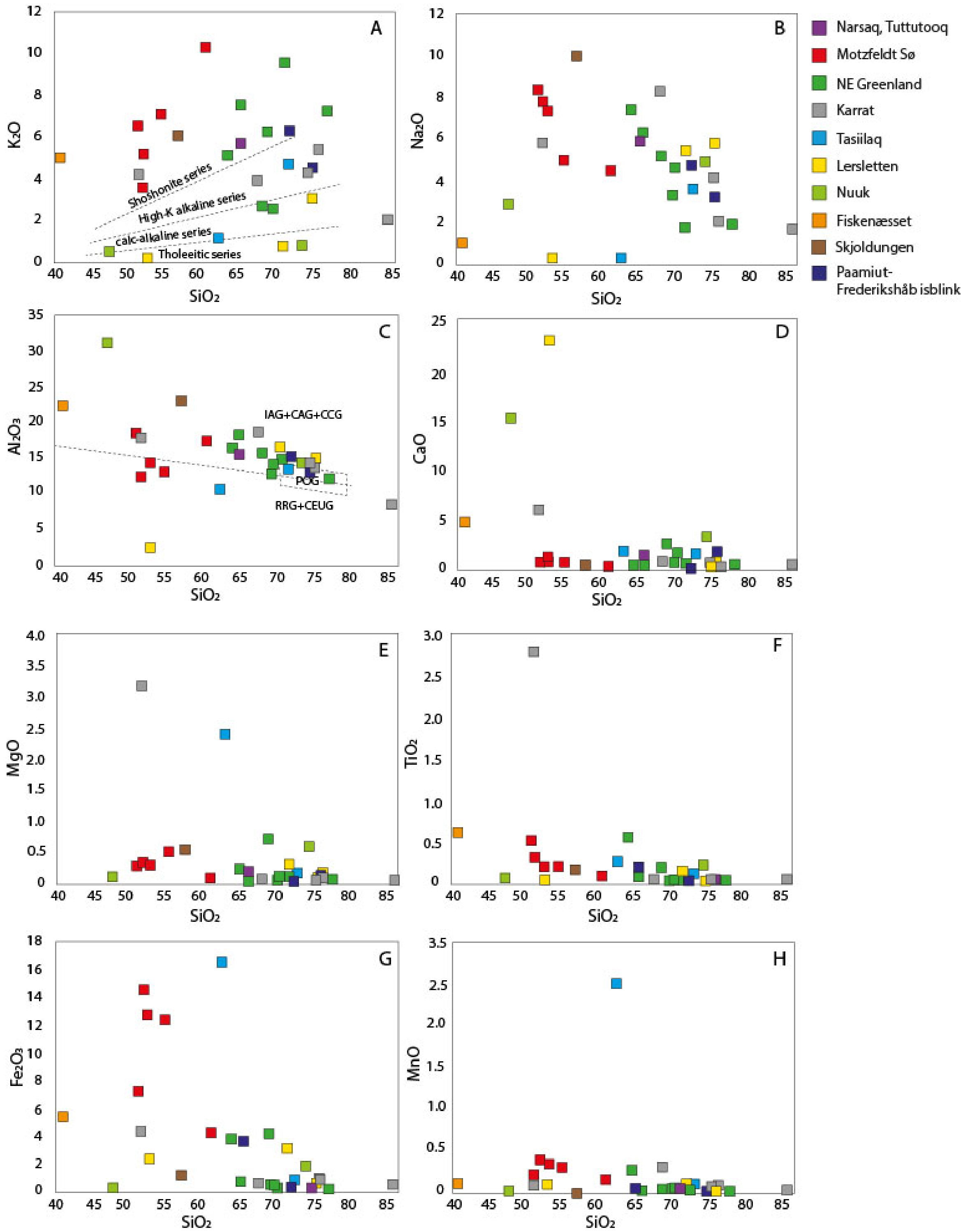

Figure 4: *Major element in the pegmatite in wt %. A) K_2O vs SiO_2, B) Na_2O vs SiO_2, C) Al_2O_3 vs SiO_2 with geotectonic discrimination scheme after Maniar & Piccoli (1989). IAG= island arc granitoids, CAG= continental arc granitoids, CCG= continental collision granitoids, RRG= rift-related granitoids, CEUG= continental epeirogenic uplift granitoids and POG= postorogenic granitoids. D) CaO vs SiO_2, E) MgO vs SiO_2, note Fiskesnæsset sample is not plotted for Mg (15.4%). F) TiO_2 vs SiO_2, G) Fe_2O_3 vs SiO_2, and H) MnO vs SiO_2.*

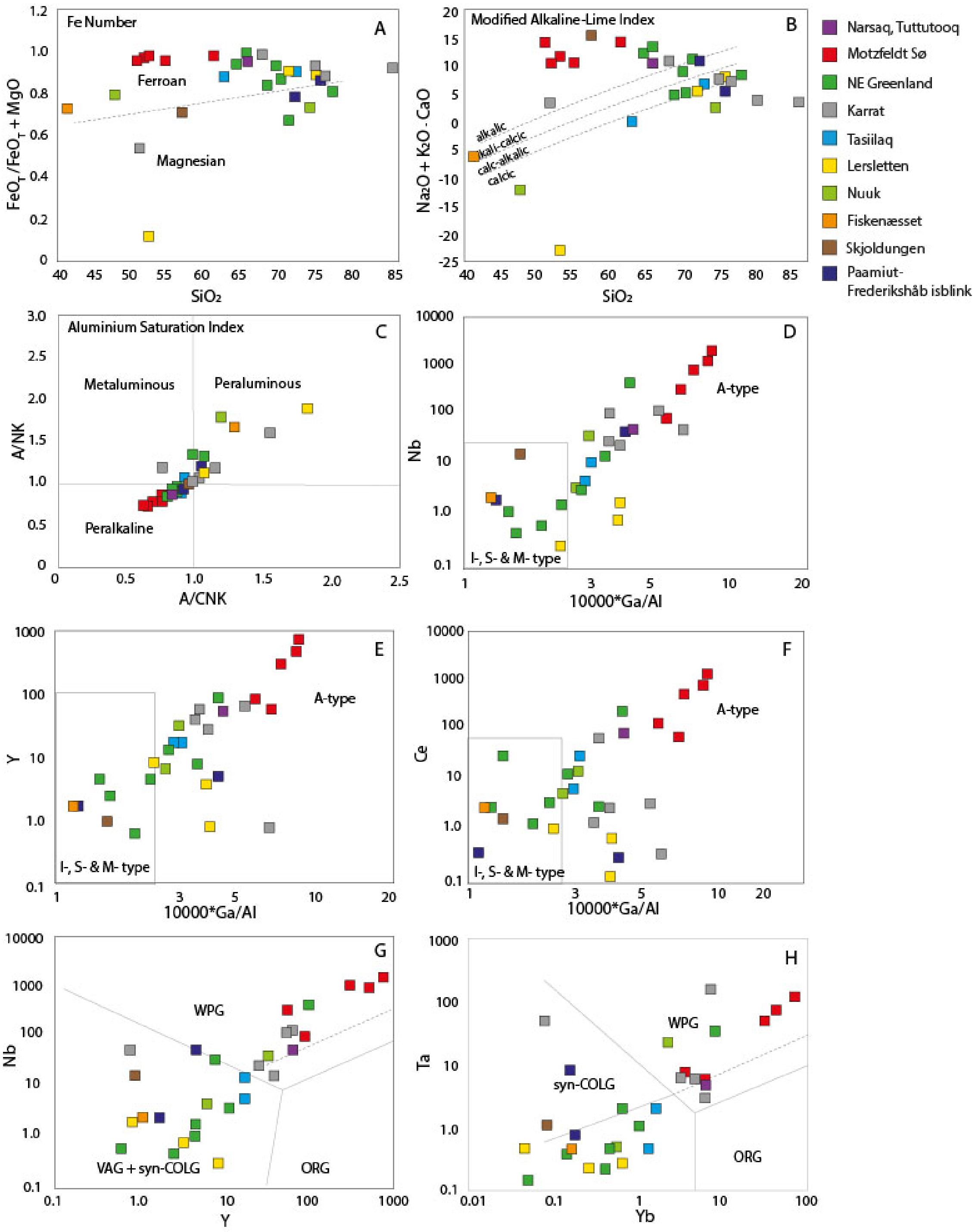

Figure 5: *Major and trace element diagrams. A) to C) are discrimination diagrams after Frost et al. (2001) with the parameters A) Fe-number, B) modified alkali-lime index (MALI) and C) Aluminum Saturation Index (ASI). From D) to F) are Whalen et al. (1987) diagrams showing the trace elements Y, Nb and Ce vs. 10000*Ga/Al, where the fields indicate the A-, I-, S - & M-type granitoids. G) to H) are geotectonic discrimination diagrams after Pearce (1984) plotting Yb vs. Nb and Y vs. Ta. WPG = within-plate granite, VAG = volcanic arc granite, syn-COLG = syn-collisional granite, ORG = ocean-ridge granite.*

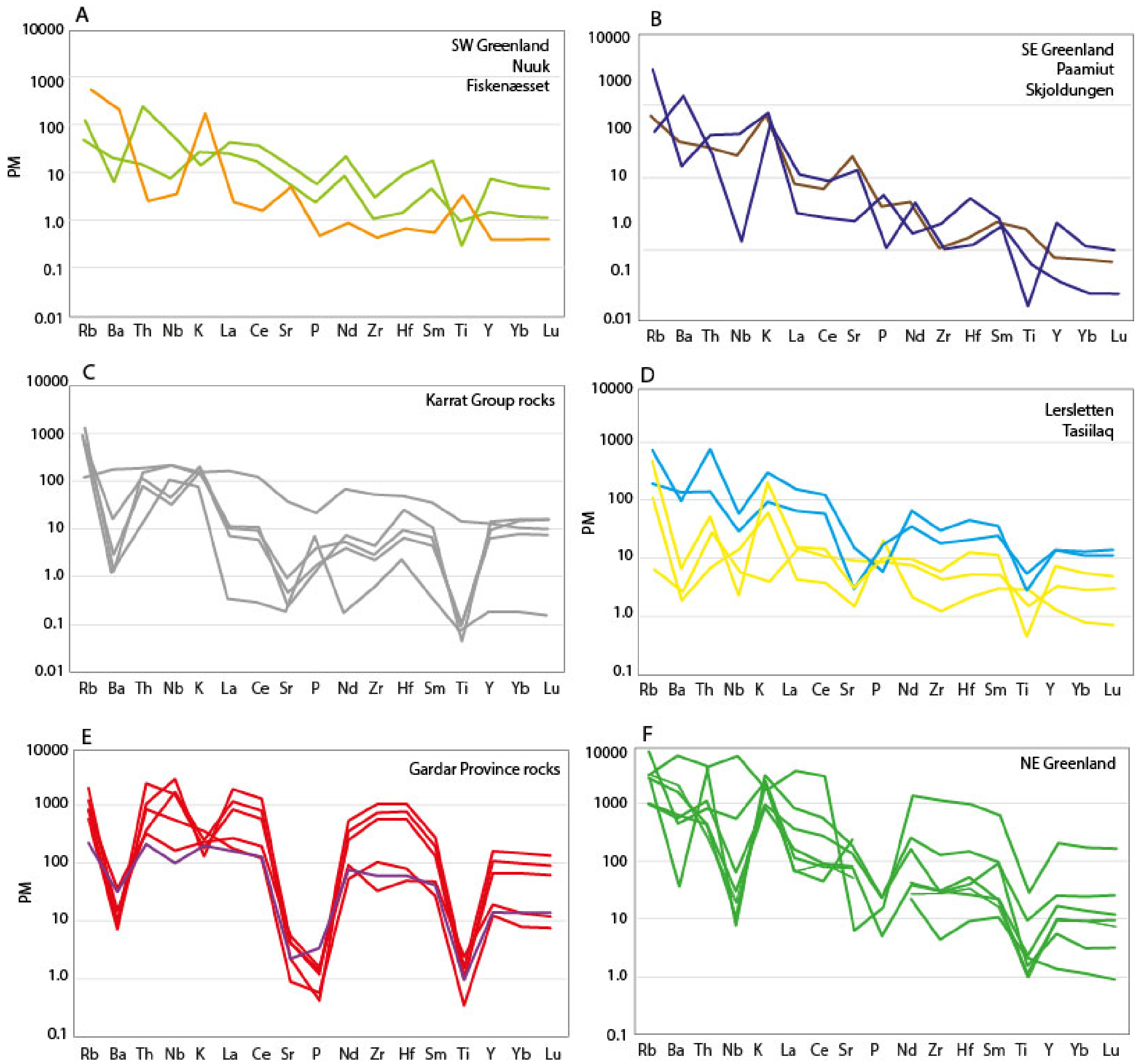

Figure 6: *Multi-element diagrams showing the A) pegmatites from SW Greenland from Nuuk to Fiskenæsset, B) pegmatites from Paamiut and Skjoldungen, C) pegmatites from the Karrat Group area, D) pegmatites from Lersletten, and Tasiilaq Nagssugtoqidian, E) Gardar Province rocks, and F) Pegmatites from NE Greenland. The data is normalised to primitive mantle values (McDonough & Sun 1995). The colours are the same as in Fig 5.*

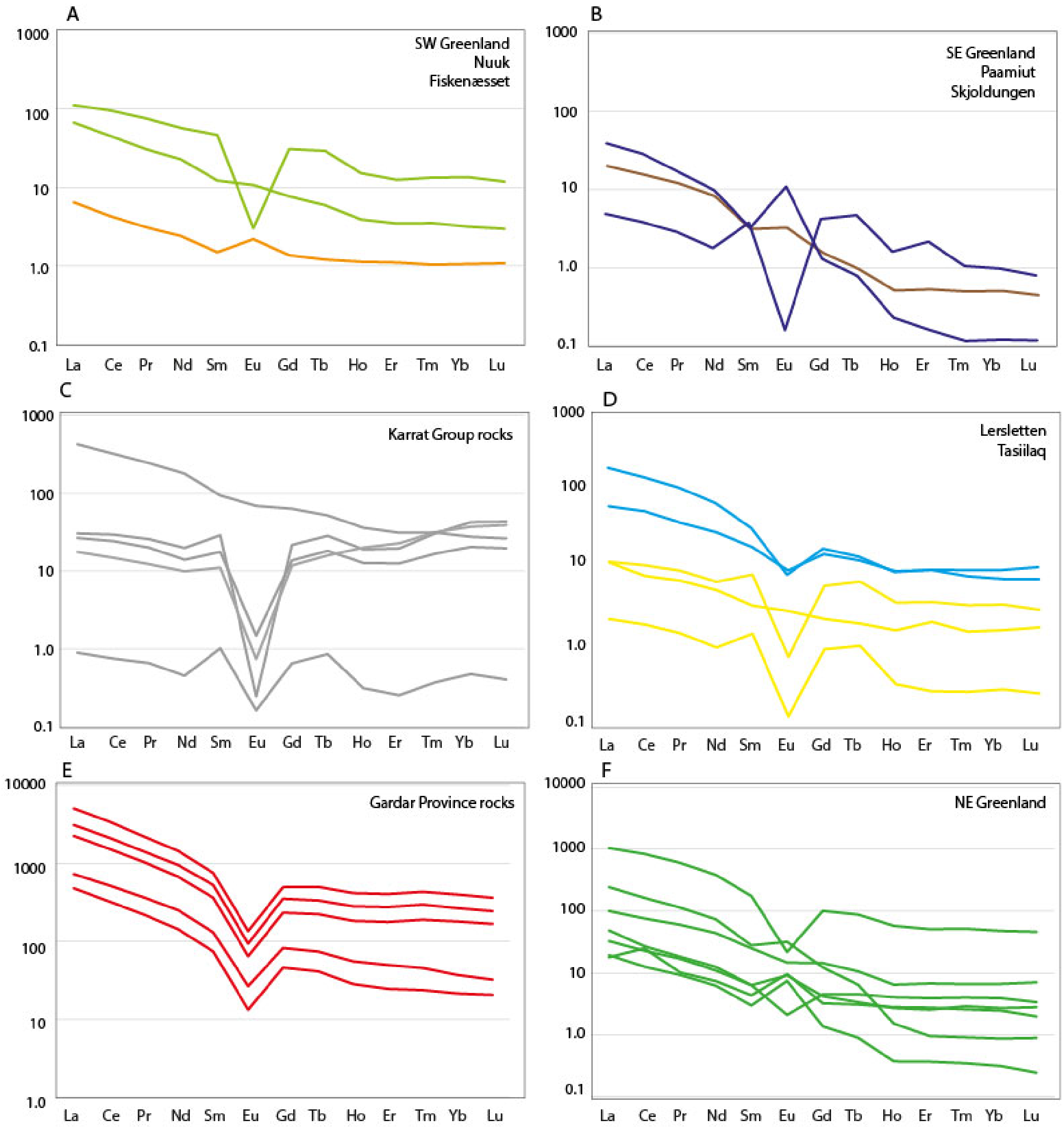

Figure 7: *Rare earth elements (REE) concentrations normalised to chondrite composition (McDonough & Sun 1995). A) pegmatites from SW Greenland from Nuuk to Fiskenæsset, B) pegmatites from Paamiut andSkjoldungen, C) pegmatites from the Karrat Group area, D) pegmatites from Lersletten, and Tasiilaq, E) Gardar Province rocks, and F) Pegmatites from NE Greenland. The colours are the same as in Fig 5.*

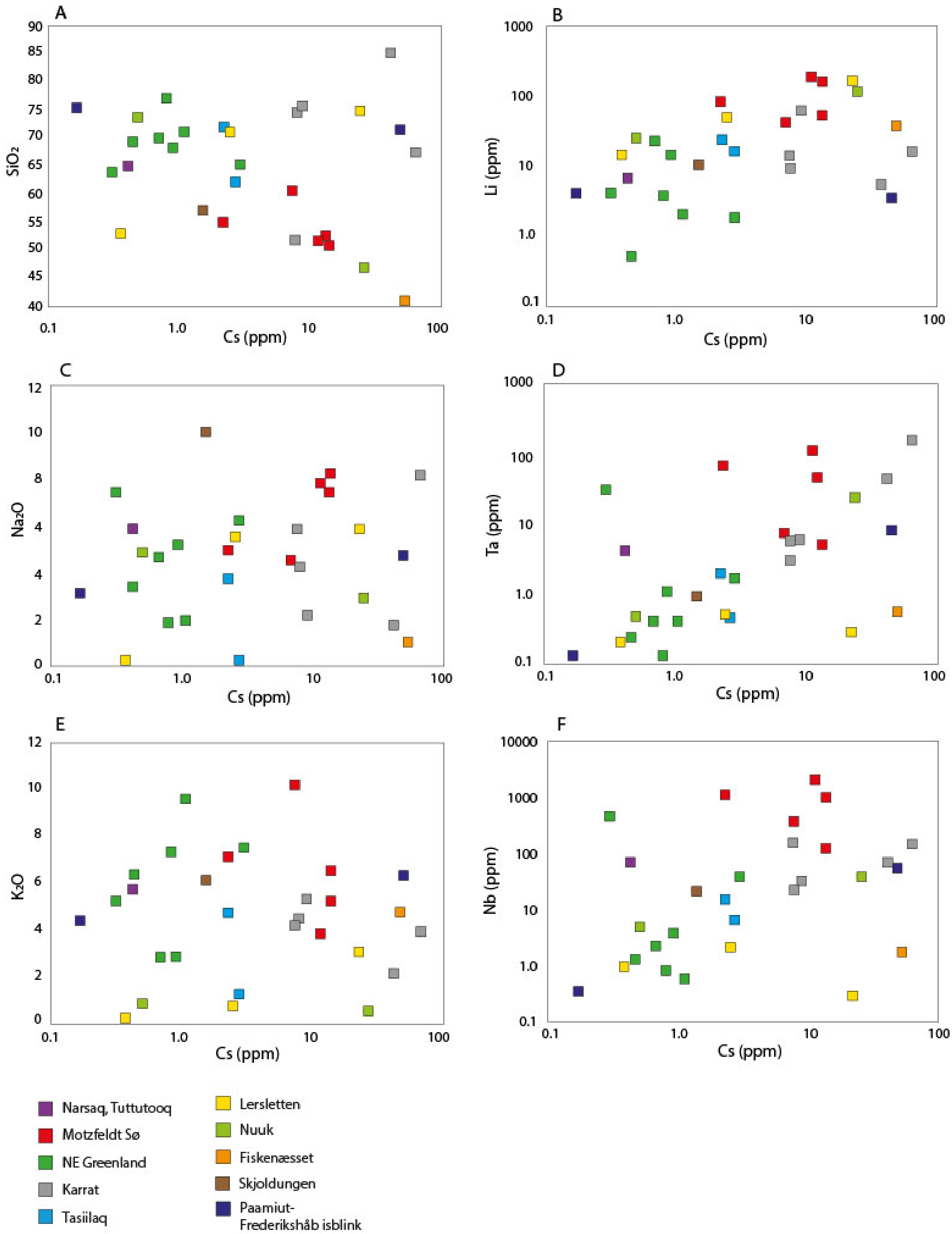

***Figure 8:** Major and trace element diagrams A) SiO_2 vs. Cs, B) Li vs. Cs, C) Na_2O vs. Cs, D) Ta vs. Cs, E) K_2O vs. Cs, F) Nb vs. Cs.*

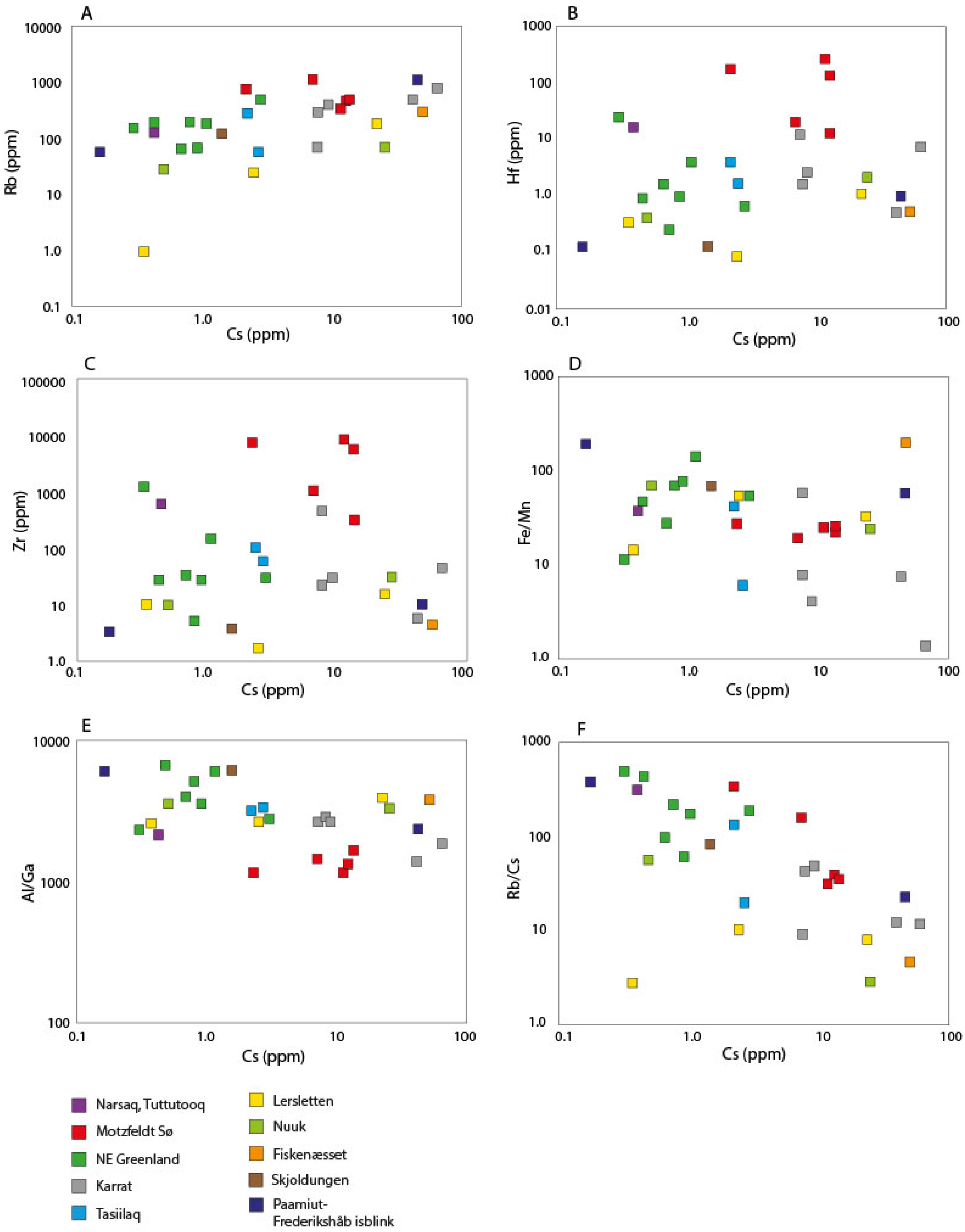

Figure 9: *Major and trace element diagrams A) Rb vs. Cs, B) Hf vs. Cs, C) Zr vs. Cs, D) Fe/Mn vs. Cs, E) Al/Ga vs. Cs, F) Rb/Cs vs. Cs. The colours for the samples are the same as in Fig 3.*

There is a positive correlation between the Li, Ta, Rb, Nb vs Cs (Fig. 8 and 9), which could indicate the elements Ta, Cs, Nb and Rb could be used as potential tracers for Li, when there is a lack of Li data available.

The bulk whole-rock geochemistry analyses are presented in Table 1, where the major elements are in wt% and trace elements are in ppm. Abbreviation: B.* = Bjerg(e), Frederikshåb Isb(blink), Peterman B(jerg),

Table 1. Whole rock data on major and trace element analyses.

GGU#	568750	569907	569929	572156	483672	463214	463217
Lat	72.116	71.185	71.517	70.699	71.383	68.429	68.419
Long	-53.510	-51.992	-52.972	-52.726	-52.075	-51.885	-51.857
Area	Karrat	Karrat	Karrat	Karrat	Karrat	Lersletten	Lersletten
Major (wt%)	GGU-XRF	GGU-XRF	GGU-XRF	GGU-XRF	GGU-XRF	GGU-XRF	GGU-XRF
SiO2	75.67	74.71	85.50	51.34	67.784	52.78	75.00
TiO2	0.02	0.02	0.01	2.81	0.009	0.06	0.01
Al2O3	13.31	14.04	8.61	17.78	18.845	2.15	14.47
Fe2O3	0.74	0.61	0.22	4.18	0.618	2.38	0.28
MnO	0.16	0.07	0.02	0.06	0.412	0.15	0.01
MgO	0.09	0.04	0.02	3.13	0.010	16.53	0.04
CaO	0.28	0.57	0.09	5.88	0.624	22.84	0.63
Na2O	2.06	4.12	1.61	5.80	8.116	0.07	5.78
K2O	5.39	4.29	2.02	4.24	3.880	0.03	3.04
P2O5	0.08	0.03	0.14	0.43	0.029	0.05	0.06
Sum	97.81	98.51	98.24	95.64	100.326	97.04	99.30
Trace (ppm)	GEUS-ICPMS	GEUS-ICPMS	GEUS-ICPMS	GEUS-ICPMS	GEUS-ICPMS	GEUS-ICPMS	GEUS-ICPMS
Li	60.9	8.9	5.3	12.5	15.88	14.4	161.1
Sc	2.60	8.36	4.90	12.19	11.09	2.09	0.82
V	1.55	0.45	0.52	209.81	0.46	83.13	0.30
Cr	18.44	1.18	0.83	39.03	0.06	14.76	1.40
Mn	1,205	537	179	495	3,043.99	1,135	58
Co	9.42	19.09	17.37	12.19	10.59	3.38	12.35
Ni	0.80	0.97	0.24	36.12	0.91	7.73	0.32
Cu	0.72	1.49	1.02	13.70	2.31	0.20	1.09
Zn	12	11	11	27	11.01	232	18
Ga	27.06	25.74	31.00	33.83	53.58	4.44	18.44
Rb	403	336	498	69	760.31	1	181
Sr	18	8	4	726	4.74	50	13
Y	26	37	1	54	60.47	3	8
Zr	29	22	6	529	45.94	11	15
Nb	28	19	64	134	134.95	0.9	0.3
Mo	1.2	0.1	0.0	0.5	0.24	0.3	0.0
Cs	8.9	7.8	41.9	7.6	65.05	0.4	22.7
Ba	102	18	7	1,100	8.52	4	11
La	6	4	0.2	101	7.24	2.9	3.0
Ce	15	9	0	197	18.07	5	7
Pr	1.86	1.14	0.06	22.60	2.39	0.67	0.91
Nd	6.41	4.54	0.21	81.55	9.06	2.47	3.22
Sm	2.61	1.64	0.15	13.89	4.28	0.51	1.29
Eu	0.08	0.04	0.01	3.88	0.01	0.16	0.04
Gd	2.73	2.35	0.13	12.58	4.31	0.46	1.25
Tb	0.66	0.57	0.03	1.87	1.03	0.07	0.26
Dy	4.11	4.64	0.15	10.11	6.38	0.43	1.43
Ho	0.70	1.09	0.02	1.97	1.04	0.09	0.21
Er	2.01	3.64	0.04	4.98	3.12	0.34	0.62
Tm	0.41	0.78	0.01	0.77	0.75	0.04	0.09
Yb	3.29	5.98	0.08	4.45	6.86	0.27	0.58
Lu	0.48	0.96	0.01	0.65	1.06	0.04	0.08
Hf	2.2	1.5	0.5	11.5	6.06	0.3	0.9
Ta	5.90	2.96	45.01	6.18	162.35	0.20	0.27
Pb	20.6	46.8	5.3	5.8	43.29	1.0	17.4
Th	8.6	5.6	0.8	14.1	11.70	0.8	1.6
U	3.10	3.10	2.68	3.94	12.33	0.36	3.85

GGU#	463236	353568	469202	508631	519447	519973	536416
Lat	68.425	64.729	64.170	63.104	62.080	62.556	60.908
Long	-51.852	-49.889	-50.289	-49.813	-49.186	-49.674	-46.183
Area	Lersletten	Ivisaartoq	Ameralik	Fiskenæs set	Paamiut	Frederik-shåb Isb.	Tut-tutooq;
Major (wt %)	GGU-XRF	GGU-XRF	GGU-XRF	GGU-XRF	GGU-XRF	GGU-XRF	GGU-XRF
SiO2	71.18	47.54	73.80	40.80	71.83	75.26	65.26
TiO2	0.10	0.06	0.19	0.67	0.00	0.03	0.19
Al2O3	16.44	31.05	14.19	22.71	15.14	13.42	15.40
Fe2O3	3.07	0.22	1.80	5.52	0.10	0.60	3.50
MnO	0.05	0.01	0.02	0.02	0.00	0.00	0.08
MgO	0.29	0.05	0.60	15.40	0.02	0.09	0.16
CaO	0.36	15.07	2.87	4.75	0.21	1.37	1.03
Na2O	5.44	2.84	4.81	1.09	4.71	3.04	5.85
K2O	0.60	0.39	0.76	5.11	6.29	4.36	5.66
P2O5	0.11	0.11	0.05	0.01	0.08	0.01	0.07
Sum	97.63	97.33	99.09	96.08	98.38	98.18	97.20
Trace (ppm)	GEUS-ICPMS	GEUS-ICPMS	GEUS-ICPMS	GEUS-ICPMS	GEUS-ICPMS	GEUS-ICPMS	GEUS-ICPMS
Li	47.6	125.4	24.0	67.9	3.4	3.6	7.3
Sc	7.26	10.96	3.62	14.39	0.89	0.40	4.42
V	1.05	1.06	17.85	140.19	0.53	4.17	1.66
Cr	7.85	1.25	4.14	702.40	1.32	1.48	1.12
Mn	387	64	173	163	11	20	604
Co	8.58	7.99	13.40	37.87	17.98	22.23	21.44
Ni	21.03	5.73	5.96	126.77	0.52	0.82	0.67
Cu	1.51	14.14	3.38	1.45	2.41	7.31	3.35
Zn	172	12	24	86	5	b.d.	108
Ga	34.34	49.61	19.91	15.78	33.85	12.11	35.94
Rb	26	72	28	343	1,093	61	131
Sr	4	282	124	99	22	318	44
Y	1	31	6	2	4	0	60
Zr	2	30	11	4	10	4	620
Nb	2.4	39	4.8	2.3	52	0.3	65
Mo	0.1	6.6	0.1	0.0	0.0	0.0	1.5
Cs	2.5	25.7	0.5	84.3	47.5	0.2	0.4
Ba	2	40	132	1,396	107	3,857	206
La	0.5	27	16	2	1.1	8	102
Ce	1	59	28	3	2	16	211
Pr	0.14	7	2.87	0.29	0.25	1.44	25.87
Nd	0.44	26	10.34	1.09	0.76	4.14	93.49
Sm	0.21	6.91	1.81	0.22	0.52	0.44	16.49
Eu	0.01	0.17	0.61	0.12	0.01	0.56	1.20
Gd	0.18	6.15	1.53	0.27	0.77	0.24	13.64
Tb	0.04	1.06	0.21	0.04	0.16	0.03	2.03
Dy	0.15	5.36	1.08	0.28	0.69	0.06	10.74
Ho	0.02	0.83	0.21	0.06	0.08	0.01	2.12
Er	0.04	2.00	0.55	0.18	0.32	0.02	5.90
Tm	0.01	0.33	0.09	0.03	0.02	0.00	0.96
Yb	0.04	2.17	0.51	0.17	0.15	0.02	6.01
Lu	0.01	0.29	0.07	0.03	0.02	0.00	0.92
Hf	0.1	2.2	0.3	0.2	0.8	0.1	14.8
Ta	0.48	23.38	0.48	0.76	7.89	0.13	4.10
Pb	3.9	25.2	12.3	2.3	11.8	10.1	45.4
Th	0.1	18.5	1.2	0.2	5.9	2.7	16.5
U	2.80	2.42	0.14	0.03	4.80	0.03	5.27

GGU#	257142	258307	258308	258311	258313	528634	563231
Lat	61.142	61.217	61.215	61.215	61.216	63.245	66.117
Long	-45.236	-45.005	-45.003	-45.005	-44.998	-41.997	-37.438
Area	Motztfeldt Sø	Motztfeldt Sø	Motztfeldt Sø	Motztfeldt Sø	Motztfeldt Sø	Skjoldung en	Tasiilaq
Major (wt%)	GGU-XRF	GGU-XRF	GGU-XRF	GGU-XRF	GGU-XRF	GGU-XRF	GGU-XRF
SiO2	50.97	54.66	51.72	52.61	60.66	56.86	62.50
TiO2	0.48	0.19	0.30	0.21	0.07	0.16	0.25
Al2O3	18.45	13.17	12.56	14.26	17.33	22.93	10.57
Fe2O3	7.00	12.39	14.31	12.73	4.24	1.39	16.66
MnO	0.27	0.40	0.51	0.45	0.19	0.02	2.54
MgO	0.31	0.50	0.38	0.24	0.09	0.53	2.37
CaO	0.73	0.64	1.16	0.66	0.12	0.37	1.55
Na2O	8.33	4.87	7.77	7.40	4.46	9.96	0.10
K2O	6.52	7.10	3.72	5.18	10.15	6.09	1.13
P2O5	0.03	0.01	0.02	0.03	0.01	0.05	0.10
Sum	93.10	93.93	92.46	93.75	97.33	98.37	97.75
Trace (ppm)	GEUS-ICPMS	GEUS-ICPMS	GEUS-ICPMS	GEUS-ICPMS	GEUS-ICPMS	GEUS-ICPMS	GEUS-ICPMS
Li	57.6	81.4	167.0	158.2	45.6	9.6	16.0
Sc	1.68	4.40	7.50	3.66	0.90	0.26	7.50
V	0.93	0.07	0.07	0.04	0.03	6.85	55.43
Cr	0.53	0.85	0.16	0.82	1.16	1.31	116.97
Mn	2,036	3,205	3,976	3,574	1,473	128	19,068
Co	2.49	9.28	9.03	10.66	22.43	10.90	10.97
Ni	28.73	0.23	0.79	0.23	8.55	1.82	34.72
Cu	3.03	2.28	2.60	4.13	2.98	2.75	16.25
Zn	181	731	784	654	464	26	69
Ga	57.51	58.44	57.59	56.18	62.70	19.63	16.26
Rb	472	719	343	500	1,167	122	57
Sr	108	44	84	81	18	563	11
Y	81	458	676	283	52	1	16
Zr	341	7,611	10,799	5,916	1,075	3	55
Nb	107	1,073	1,805	985	354	19	6
Mo	3.6	4.2	0.8	1.9	0.5	0.1	2.7
Cs	13.7	2.2	11.3	13.0	7.1	1.5	2.7
Ba	235	97	47	57	64	376	414
La	172	734	1,194	532	113	5	17
Ce	320	1,311	2,116	946	200	10	37
Pr	34	132	205	96	20	1.11	4.01
Nd	114	433	656	305	65	3.77	14.90
Sm	19.18	77.76	111.07	53.54	10.91	0.46	3.10
Eu	1.50	5.26	7.64	3.63	0.75	0.18	0.59
Gd	16.32	69.79	98.30	46.31	9.13	0.31	3.40
Tb	2.66	12.01	17.98	8.06	1.49	0.03	0.51
Dy	15.01	74.43	106.72	47.77	8.16	0.15	2.70
Ho	3.01	15.36	22.66	9.98	1.55	0.03	0.56
Er	7.93	43.83	64.51	28.23	3.94	0.08	1.70
Tm	1.13	7.28	10.62	4.67	0.58	0.01	0.22
Yb	5.95	42.84	64.02	28.80	3.44	0.08	1.31
Lu	0.79	5.99	8.89	4.10	0.51	0.01	0.20
Hf	12.1	188.4	257.7	140.2	19.6	0.1	1.5
Ta	5.09	66.64	109.20	44.72	6.57	0.95	0.46
Pb	45.6	399.5	85.2	113.5	49.7	11.4	2.4
Th	25.3	28.9	82.1	184.7	65.9	3.5	5.1
U	2.48	20.77	28.32	31.13	29.71	0.75	0.99

GGU#	564554	454815	7505588	7512457	7604789	8104295	7907544
Lat	65.533	72.783	72.464	72.698	73.112	71.981	72.679
Long	-39.015	-24.887	-25.661	-26.368	-27.570	-23.933	-27.503
Area	Tasiilaq	Ella ø	Lyell Land	Gletsch-erland	Peter-mann B.	Werner Bjerge	Gletsch-erland
Major (wt%)	GGU-XRF	GGU-XRF	GGU-XRF	GGU-XRF	GGU-XRF	GGU-XRF	GGU-XRF
SiO2	72.28	69.87	71.18	77.20	68.37	64.11	69.54
TiO2	0.11	0.02	0.03	0.04	0.19	0.58	0.02
Al2O3	13.38	13.96	14.66	12.03	15.38	16.22	13.10
Fe2O3	1.07	0.43	0.23	0.31	4.17	3.78	0.26
MnO	0.02	0.01	0.00	0.00	0.05	0.30	0.00
MgO	0.11	0.06	0.11	0.07	0.70	0.22	0.02
CaO	1.21	1.91	0.33	0.42	2.81	0.42	0.43
Na2O	3.73	4.60	1.88	1.88	5.15	7.42	3.43
K2O	4.70	2.69	9.55	7.30	2.82	5.11	6.25
P2O5	0.03	0.00	0.05	-0.01	0.05	0.03	-0.01
Sum	96.63	93.56	98.03	99.25	99.68	98.19	93.05
Trace (ppm)	GEUS-ICPMS	GEUS-ICPMS	GEUS-ICPMS	GEUS-ICPMS	GEUS-ICPMS	GEUS-ICPMS	GEUS-ICPMS
Li	23.3	20.2	2.0	3.3	12.8	4.5	0.5
Sc	2.71	1.51	0.53	0.57	5.19	3.03	0.43
V	3.38	1.22	1.82	1.17	31.48	11.72	1.58
Cr	2.11	1.16	1.43	0.92	15.62	1.35	1.17
Mn	171	101	11	29	362	2,290	37
Co	24.52	12.06	17.55	22.67	22.02	10.17	33.69
Ni	5.44	0.63	0.95	0.63	9.02	0.32	0.52
Cu	99.59	1.05	0.35	1.79	533.41	2.30	1.46
Zn	17	7	b.d.	2	34	209	1
Ga	21.79	17.53	12.75	12.93	22.52	36.62	10.33
Rb	291	67	198	174	60	155	195
Sr	86	176	383	491	268	12	102
Y	16	4	2	1	11	90	4
Zr	103	35	142	5	30	1,213	29
Nb	15	2	1	1	4	456	1
Mo	2.7	0.0	0.6	0.0	0.7	3.7	0.3
Cs	2.3	0.7	1.1	0.8	0.9	0.3	0.4
Ba	271	462	4,785	1,094	371	24	1,403
La	47	12	58	5	24	247	4
Ce	92	17	100	8	46	511	15
Pr	10.22	1.70	10.53	0.86	5.57	55.55	0.94
Nd	32.15	5.74	33.56	2.86	20.09	175.35	3.37
Sm	4.96	0.94	4.15	0.44	3.72	25.84	0.64
Eu	0.47	0.51	1.79	0.42	0.83	1.23	0.54
Gd	3.62	0.84	2.45	0.27	2.86	20.06	0.64
Tb	0.52	0.12	0.23	0.03	0.38	3.16	0.11
Dy	2.54	0.71	0.56	0.12	1.88	16.37	0.69
Ho	0.50	0.15	0.08	0.02	0.35	3.14	0.15
Er	1.56	0.41	0.15	0.06	1.08	8.13	0.44
Tm	0.24	0.07	0.02	0.01	0.16	1.28	0.06
Yb	1.56	0.44	0.14	0.05	1.07	7.70	0.40
Lu	0.26	0.07	0.02	0.01	0.17	1.14	0.05
Hf	4.0	1.4	3.9	0.2	1.0	24.7	0.8
Ta	1.73	0.41	0.39	0.13	1.00	29.46	0.23
Pb	36.6	22.4	60.6	30.5	14.5	26.5	20.0
Th	39.8	3.8	38.2	3.7	8.9	35.7	2.1
U	9.63	0.54	1.32	0.13	3.32	8.88	0.31

GGU#	8011135_A
Lat	71.962
Long	-24.179
Area	Werner B.*
Major (wt%)	GGU-XRF
SiO2	65.33
TiO2	0.05
Al2O3	18.27
Fe2O3	0.71
MnO	0.01
MgO	0.01
CaO	0.05
Na2O	6.16
K2O	7.46
P2O5	0.01
Sum	98.07
Trace (ppm)	GEUS-ICPMS
Li	1.8
Sc	0.13
V	2.90
Cr	221.21
Mn	88
Co	4.54
Ni	43.93
Cu	7.83
Zn	15
Ga	34.58
Rb	513
Sr	158
Y	7
Zr	33
Nb	38
Mo	18.5
Cs	2.9
Ba	313
La	8
Ce	14
Pr	1.57
Nd	5.01
Sm	0.94
Eu	0.12
Gd	0.90
Tb	0.16
Dy	1.00
Ho	0.22
Er	0.63
Tm	0.10
Yb	0.63
Lu	0.08
Hf	0.7
Ta	1.76
Pb	14.1
Th	6.9
U	0.89

The pegmatite areas and their characteristics

The different areas in Greenland are presented in a chronological order from oldest to youngest (North Atlantic Craton, Rinkian, Nagssugtoqidian Orogen, Ketilidian Orogen, the Gardar Province, Caledonian Orogen) (Fig. 1).

Nuuk area, North Atlantic Craton, Southwest Greenland

Archean North Atlantic Craton (NAC) in the Nuuk area represents the oldest part of Greenland, where rocks were formed up to 3800 Ma ago (Nutman et al. 1996) (Fig. 10). The region consists of several smaller continental blocks that amalgamated in thermal episodes between 2750-2600 (Hollis et al. 2006), which was followed by the intrusion of the Qórqut granite complex 2550 Ma (Nutman et al. 2011; Næraa et al. 2014). There are abundant and voluminous pegmatites in the Nuuk area that are related to the amalgamation periods as well as to the formation of the Qórgut granite complex (Steenfelt et al. 2007).
The pegmatite sample from Ivisaartoq (353568) classifies as a gabbro in the TAS diagram (Fig. 3), and has enrichment of Al_2O_3 (31%), CaO (15%) (Fig. 4), and elevated Li (125 ppm), Sr, Ta, Pb, Th, Ga and REEs (Fig. 5-7). The pegmatite plot in the ferroan field in the Frost (2001) diagram (Fig. 5.A) and in the calcic field in the MALI index (Fig. 5.B) and is peraluminous. There are no age constraints on the pegmatite, but it likely has an Archean age. For the REEs the pegmatite has a negative Eu anomaly indicating plagioclase fractionation.
The pegmatite sample from Ameralik (469202) classifies as a granitic pegmatite in the TAS diagram (Fig. 3) and is peraluminous, and in the Pearce (1984) diagram the pegmatite plot in the field for volcanic arc granites or syn-collisional granites (Fig.5). The Li content in the pegmatite is only 24 ppm but is enriched in incompatible elements compared to the primitive mantle, especially the lighter ones (Fig. 6), but is otherwise quite barren and likely represents local melting of metavolcanic and metasedimentary rocks and related to the oldest pegmatites in the area.

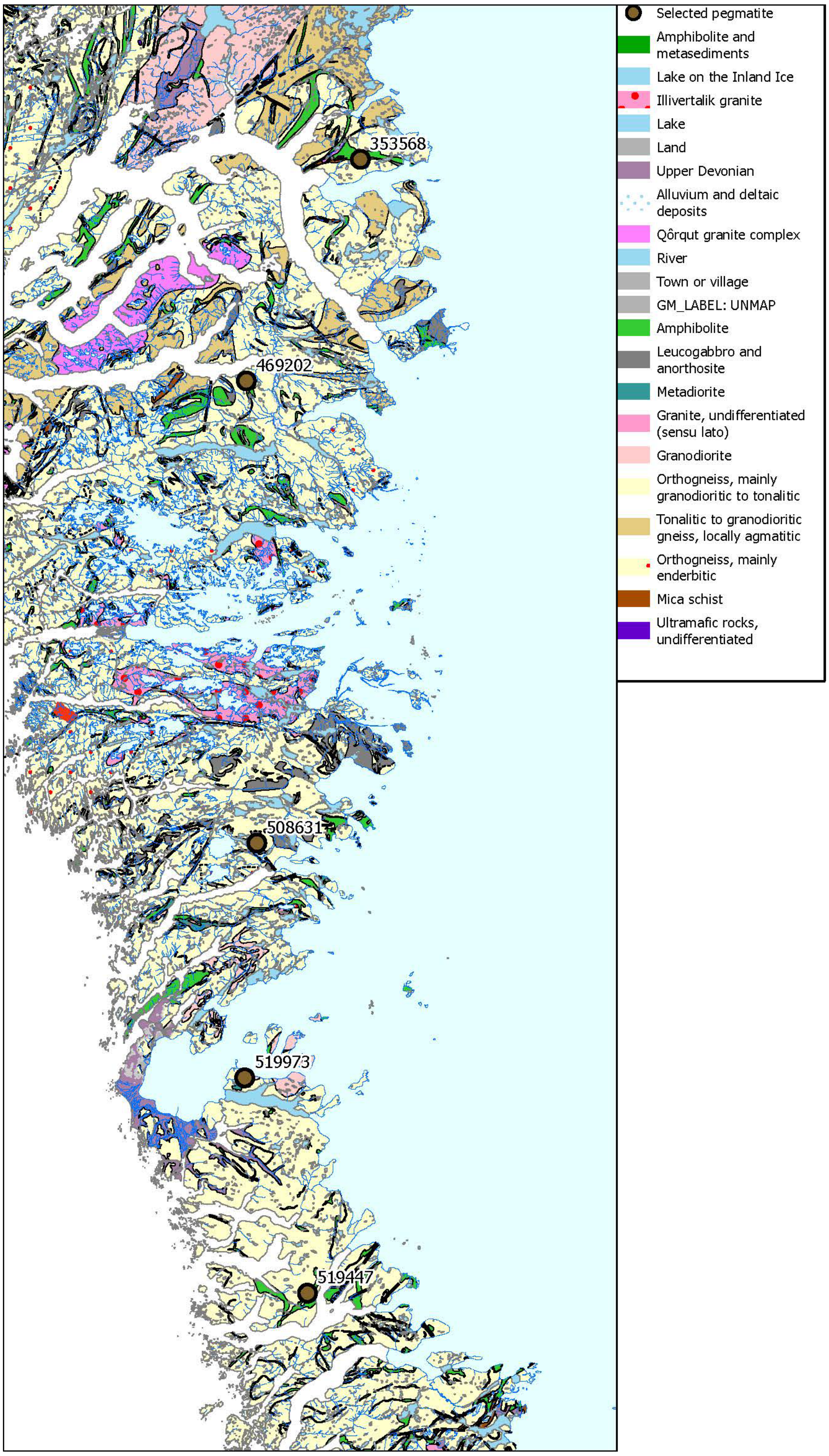

Figure 10: *Map showing the North Atlantic Craton (Archean block) from Nuuk to Paamiut area with the location of five pegmatite samples.*

Fiskenæsset - Paamiut area, North Atlantic Craton, Southwest Greenland

The region between Fiskenæsset and Paamiut is part of NAC (Fig. 10), and Mesoarchaean tonalite-trondhjemite-granodiorite (TTG) orthogneisses make up about 80% of the NAC in West Greenland (Garde et al. 2020). In the Fiskenæsset area, the ca. 2950 Ma Fiskenæsset complex is world famous, which includes a ca. 550m thick series of ultramafic complexes with intrusive sheets of anorthosite, leucogabbro, gabbro, and ultramafic rocks (Myers, 1985; Windley et al., 1973; Keulen et al. 2014).

The pegmatite (508631) from Fiskenæsset yields a foidolitic composition in the TAS diagram, and has a low Si concentration, and high Al, Mg, Fe, Ca, K, Cr, and elevated levels of Ni, Zn, Rb, Cs, Co, and Ba. Both the pegmatites from Paamiut and Fiskenæsset region plot as volcanic arc granite or syn-collisional granite in the Pearce (1984) diagram (Fig. 5). They display a positive Eu anomaly. The three pegmatites from Paamiut to Fiskenæsset have enrichment in the lightest incompatible elements Rb to La (Fig. 7). The Li content is 68 ppm for this pegmatite.

The pegmatites from Paamiut area (sample 519447 and 519973) plot in the granite and sub-alkaline field in the TAS diagram (Fig. 3) and as volcanic arc granite or syn-collisional granites in the Pearce diagram (Fig. 5). The pegmatite sample 519447 shows elevated K, Rb, Cs, Ba, Pb, Th, U and enrichment in the lighter REEs (La to Nd) compared to chondrite. There is a negative Eu anomaly for the REEs, indicating plagioclase fractionation (Fig. 7). Pegmatite sample 519973 yields an enrichment in Ba and Sr, but otherwise the pegmatites are barren. The Li content is 3 ppm for this pegmatite sample. In the 1970s spodumene has been reported from the Paamiut area at Snefjeld where the Li content was 1.23% (Geisler, 1972).

Skjoldungen alkaline province, North Atlantic Craton, South-east Greenland

The Skjoldungen Alkaline Province is part of the North Atlantic Craton (NAC) of Greenland, and the area contains rare occurrences of Archaean alkaline rocks with multiple c. 2750 Ma to 2690 Ma old mildly alkaline intrusions of mafic-ultra-mafic, intermediate and evolved compositions, as well as the late stage of strongly alkaline 2680-2650 Ma nephelinitic-carbonatitic Singertât Complex (Nielsen and Rosing, 1990; Kolb et al. 2013; Kokfelt et al. 2016) (Fig. 11).

The pegmatite sample from Skjoldungen (528634) classifies as foid syenite in the TAS diagram (Fig. 3), and has enrichment of Al_2O_3 (22.9%), Na_2O (9.96%), K_2O (6,1%) (Fig. 4), and elevated Sr, and Ba and REE. The pegmatite also plots as a peralkaline rock and lies within the alkaline field in the MALI index diagram and classifies here as volcanic arc granite or syn-collisional granite (Fig. 6). The pegmatite is enriched in the lighter incompatible elements (Rb to Nd) (Fig. 7B) and lighter REEs La to Eu (Fig.8). The lithium content is 10 ppm for the sample.

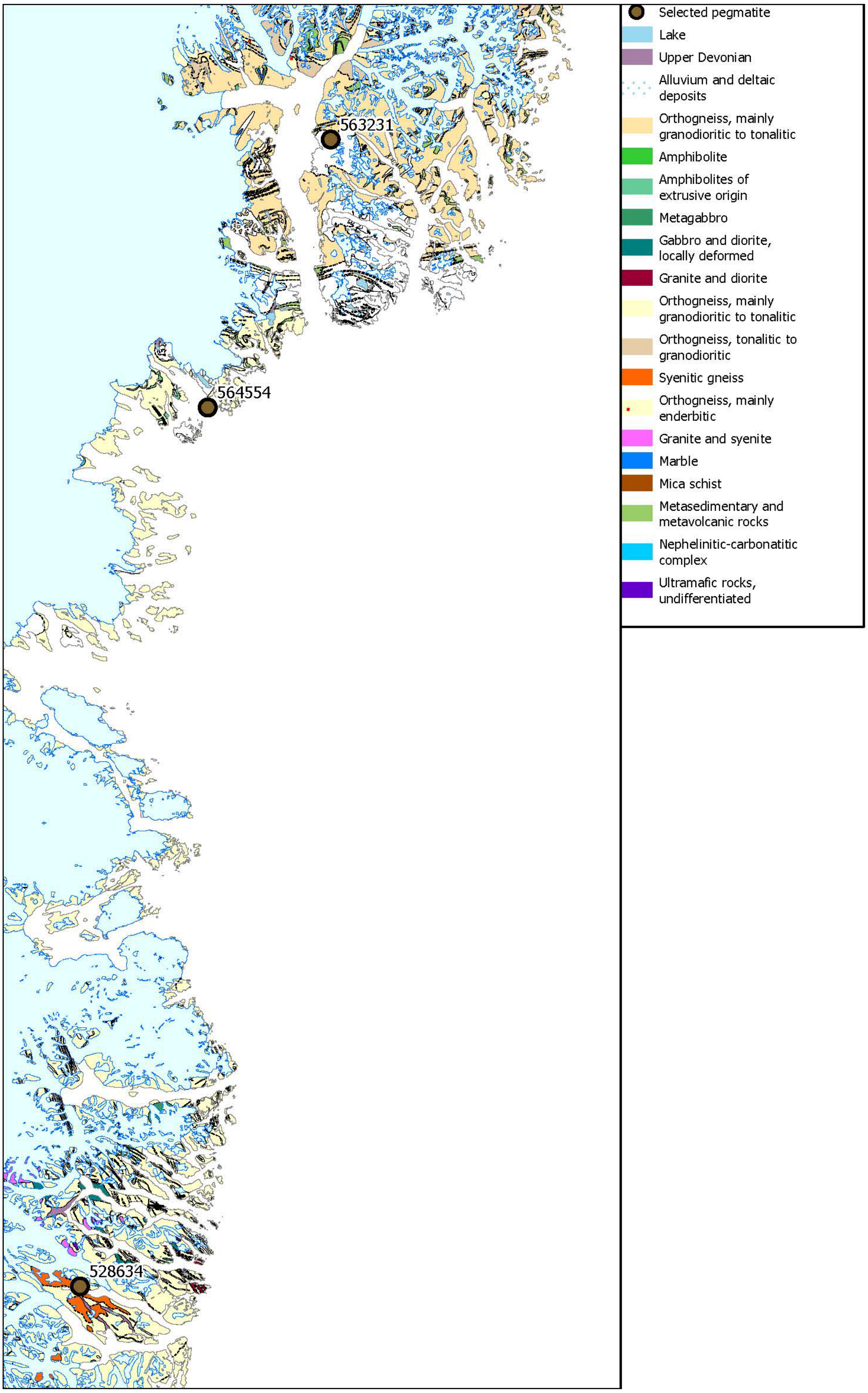

***Figure** 11: Map showing the Tasiilaq area and the pegmatite sample locations. The area is part of the Nagssugtoqidian Orogen.*

Uummannaq area, Rinkian fold belt and Karrat Group, Northwest Greenland

The Uummannaq area in Northwest Greenland consists of Archean basement rocks overlain by the metasedimentary and metavolcanic rock series of the Karrat Group. The Karrat Group is cut by abundant pegmatites of granitic to migmatitic origin (Crocott & Pulvertaft, 1990; Steenfelt et al. 2016; Rosa et al. 2023) (Fig. 12). The pegmatites in the area could be related to the 1860 Ma Prøven granite in the Upernavik area, which is a hypersthene-bearing igneous complex with various granitic units (Kalsbeek, 1981; Thomassen et al. 1998) of both porphyritic feldspar granitic sheets and leucogranites as sheets and veins (Thomassen et al. 1999; Kokfelt et al. 2024).

The pegmatite samples intruding into the Karrat Group in (483672, 568750, 569907, 569929, 572156) plot as granitic pegmatites, foid monzosyenite, and one as a quartzolite. The four samples plot in the field for within-plate granites in the Pearce (1984) diagram (Fig. 5), which are interpreted as intrusion formed in continental rift zones or ocean island settings. The quartzolite is quite barren, but the granitic pegmatites have elevated values for Mn, Rb, Ta and REEs. The foid monzosyenite pegmatite shows enrichment in V, Mn, Sr, Zr, Nb, Ba and REEs. The Li content is between 5-61 ppm for the pegmatites, and the pegmatites with the highest content plot as a granite in the TAS diagram.

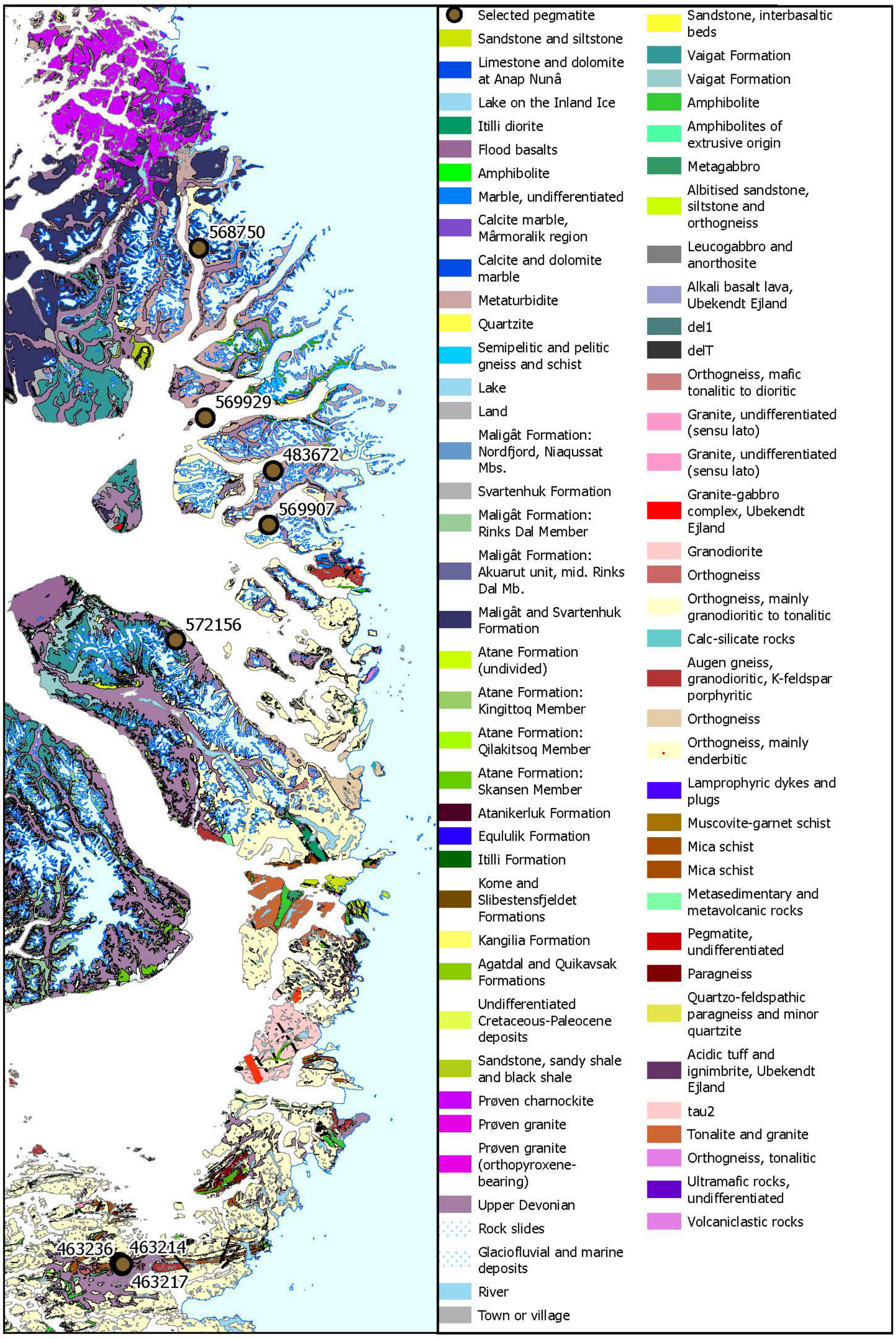

Figure 12: *Map showing the area between Sisimiut to the Uummannaq area in West Greenland, where the samples around Lersletten are in the northern part of the Nagssugtoqidian Orogen of West Greenland, and the samples in the Uummannaq area are part of the Karrat Group rocks.*

Aasiaat area, Nagssugtoqidian Orogen, West Greenland

The Nagssugtoqidian Orogen is a wide continental collisional zone going across Greenland from West (Kangerlussuaq to Aasiaat area) to Tasiilaq area in South-East Greenland (Hollis et al. 2006; Nutman et al. 2008; Kolb 2014; Kolb et al. 2016). Continent collision occurred around 1870 Ma, between the Rae craton and North Atlantic Craton (Nutman et al. 2008) (Fig 12). Here we discuss the western side of the orogen, the eastern side will be discussed further below.

Pegmatites from Lersletten/Naternaq (sample 463217, 463236, 469202) show a granitic, alkali granitic and a gabbro-dioritic composition in the TAS diagram (Fig 3). The gabbro-diorite, which have high Mg, Fe, Ca and Mn contents, and elevated Zn, but a low Li content of 14 ppm. The alkali granitic pegmatite (463217) has Li content of 161 ppm and Cs compared to the other granitic pegmatite, with a Li content of 48 ppm. In the Pearce (1984) diagram (Fig. 5) the pegmatites all plot as volcanic arc granites or syn-collisional granites.

Tasiilaq area, Nagssugtoqidian Orogen, Southeast Greenland

The Nagssugtoqidian Orogen is a wide continental collisional zone going across Greenland from west (Kangerlussuaq to Aasiaat area) to Tasiilaq area in Southeast Greenland (Hollis et al. 2006; Nutman et al. 2008; Kolb 2014; Kolb et al. 2016). Continent collision occurred around 1870 Ma, between the Rae craton and North Atlantic Craton (Nutman et al. 2008) (Fig 11 and 12). Here we discuss the southeastern side of the orogen.

The pegmatites in the Tasiilaq area in Southeast Greenland (sample 563231, 564554) show an alkali granitic and dioritic composition in the TAS diagram. The alkali granitic pegmatite (564554) has elevated Cu, Rb, Ba and REE concentrations. The dioritic pegmatite shows the highest Mn content of all studied pegmatite samples (2.5 wt%) and yields elevated Cr, Ba, and REEs as well (Fig. 7). The lithium contents are 16 and 23 ppm for the two samples.

Narsaq - Narsarsuaq area, Ketilidian Orogen and Gardar province, South Greenland

The 1850-1720 Ma Paleoproterozoic Ketilidian Orogen was a mountain-building event that affected South Greenland, where new juvenile crust formed (Garde et al. 2002) during fore-arc accretion and oblique convergence. The area is divided into the foreland with the Border Zone in the North bordering the Archean craton, the Julianehåb Batholith in the central part and the Psammite and Pelite zones towards the southern tip of Greenland (Garde et al. 2002). Granitic igneous rocks and rapakivi granites intruded into the area during the late phases of the Ketilidian Orogeny. Subsequently, this area was affected by continental rifting and sedimentation during the Mesoproterozoic (c.1320–1120 Ma old), forming the Gardar Province, and a suite of intrusive and extrusive igneous rocks of alkaline-peralkaline composition intruded the Ketilidian rocks (Sørensen, 2001; Paslick et al. 1993). The magmatic intrusions in the area include multiple dykes, the Nunarssuit alkaline complex, Igaliko alkaline complex, Motzfeldt Sø Centre, Grønnedal-Ika complex and Ilimaussaq intrusive complex (Upton et al. 1996) (Fig. 13).
The samples from Motzfeldt Sø Centre show a composition ranging between foidolite, foid syenite to foid monzosyenite in the TAS diagram (Fig. 3). The pegmatites are peralkaline, have the highest Mali index and Fe-numbers of all studied samples. The pegmatites are enriched in Mn, Hf, Ta, Zn, Ga, Rb, Y, Zr, Nb, Yb, REEs and are elevated in Li (45-167 ppm), Cs and Ga (Fig 6 to 7). The pegmatite from Tuttutooq plots as a syenite in the TAS diagram, it has enrichment in Mn, Zn, Zr, Pb, Th and REEs. All the pegmatites from the Gardar Province analyzed here, plot as within-plate granites. The pegmatites from the Gardar Province have the highest Nb, Y, Ce, Y, Nb, Ta, Hf, Zr, REEs, Li contents of all the pegmatites analyzed from Greenland in this project (Fig. 6, 7, 8, 13).

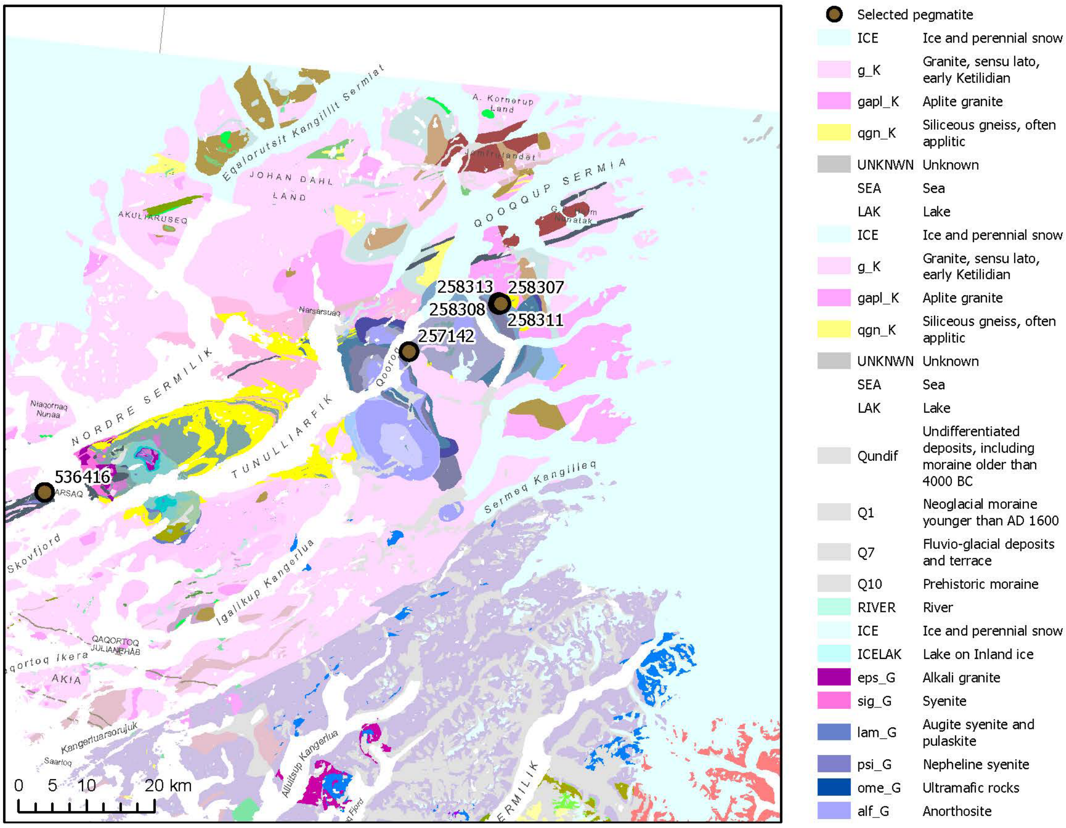

Figure 13: *Geological map showing South Greenland focused around the Gardar Province rocks.*

Northeast Greenland, the Caledonian Orogen

The Caledonian Orogen stretches along the entire central eastern and northeastern coast of Greenland. The studied samples are all derived from the Alpefjord area, in the southern part of the orogen. In the area two major orogenic events took place, one in the Neoprotorozoic, called Grenvillian event, followed by the Silurian-Carbonian Caledonian orogeny. Both orogenic events generated granitic and more mafic intrusions. Archaean and Palaeoproterozoic orthogneisses and Mesoproterozoic metasedimentary rocks were overlain by a thick package of Neoprotorozoic Eleonore Bay Supergroup and Palaeozoic sediments. During the Caledonian orogen, significant migmatisation occurred in the Mesoproterozoic metasediments. The Devonian to Silurian age (435-425 Ma) magmatic rocks in the area include monzonites, diorites, granodiorites with minor amounts of granite (Sønderholm & Tirsgaard, 1993; Thrane et al. 2021; Kokfelt et al. 2023).

The pegmatites from NE Greenland were collected by Nordisk Mineselskab A/S in the period between 1960s-1980s at the localities: Ella Ø, Lyell Land, Gletscherland, Petermann Bjerg and Werner Bjerge. The samples are 7505588, 7512457, 7604789, 8104295, 7907544_2, 8011135_A, and plot as granites, alkali granites and syenites in the TAS diagram, above the line separating alkaline rocks from the sub-alkaline. The syenitic pegmatite sample from Werner Bjerge (8104295) has enrichments in Mn, Zn, Y, Zr, Nb, Pb, Th, Ta and REEs. The syenitic pegmatite sample from Petermann Bjerg (7604789) shows elevated Cu, Sr, Pb, Th and REEs. The lithium contents are low and between 1-20 ppm for the samples from NE Greenland (Fig. 14).

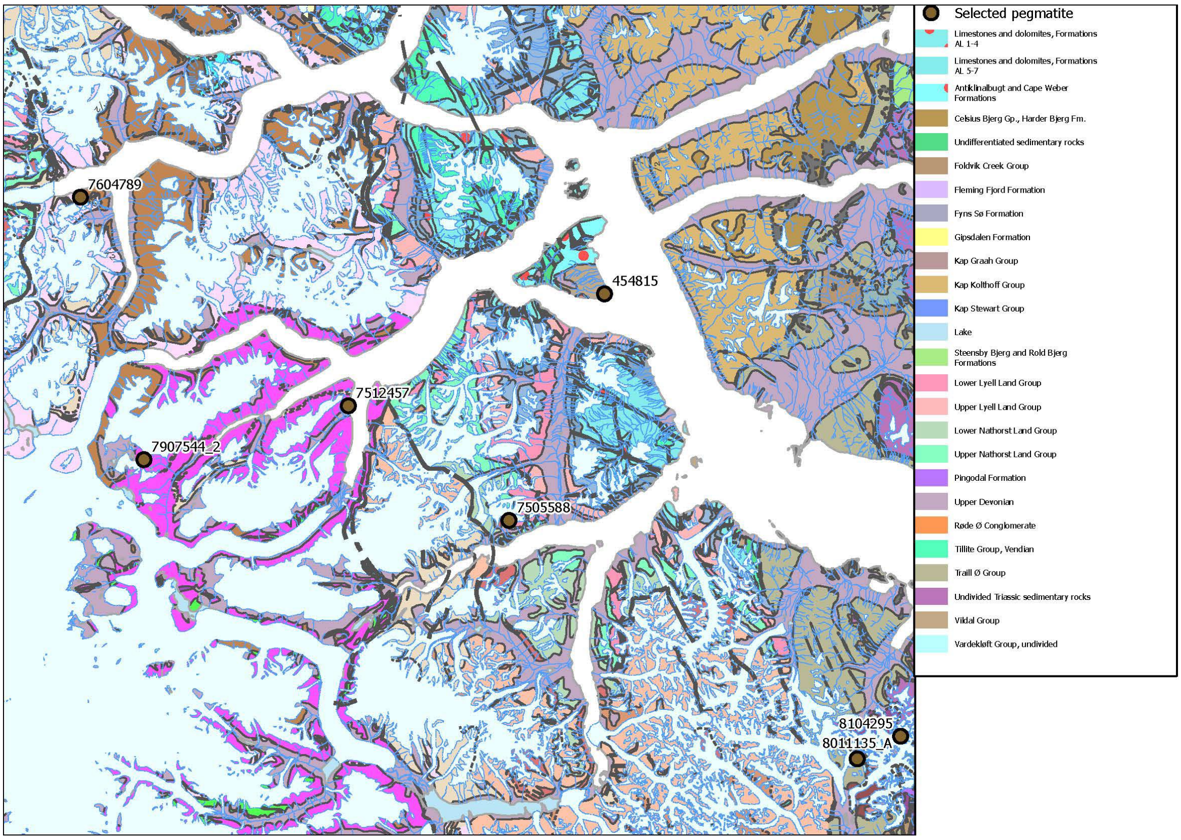

Figure 14: *Geological map showing the area in Northeast Greenland between Gletscherland and north Stauning Alper.*

Lithium in pegmatites from Greenland

South Greenland

The c. 1300-1140 Ma Gardar period involved alkaline magmatism which resulted in several large magmatic intrusions in South Greenland. The lithium content have been measured from different rock types in the Ilimausaq Intrusive complex, where the Li content range between 16 to 2147 ppm;16-80 ppm in augite syenite, 182 ppm in quartz syenite, 156 ppm in alkali granite, 91 ppm in pulaskite, 132 ppm in foyaite, 161 ppm in sodalite foyaite (Bailey et al. 2001), 1421 to 1944 ppm in naujakasite lujavrite and 1914 to 2147 ppm in arfvedsonite lujavrite (Kunzendorf et al. 1982). Kunzendorf et al. (1982) estimated 235,000 t of Li from arfvedsonite lujavrite from the Ilimaussaq Intrusive Complex. The estimate was based on 600 samples from 7 drill cores, with Li grade of 0.19 % Li. Estimates on other elements Be is 7300 t, Zn 225,000 t, Nb 51,000 t and Zr 398,000 t, REE 1,130,000 t, and Y 105,000 t in the Kvanefjeld area. There are several mica minerals registered from the Ilimaussaq Intrusive Complex with Li in their chemical formula, such as polylithionite ($KLi_2AlSi_4O_{10}(F,OH)_2$)), lepidolite, or ephesite ($NaLiAl_2(Si_2,Al_2)O_{10}(OH)_2$), and other minerals include djerfisherite ($K_6(Na,Li)(Fe, Cu, Ni)_{24}S_{25}Cl$), neptunite $KNa_2Li(Fe^{2+}, Mn^{2+})_2Ti_2Si_8O_{24}$(Bøggild, 1953; Kunzendorph et al. 1982; Petersen, 2001). the Li content in polylithionite is 8.24 % (Bøggild, 1953).

At the former Ivittuut cryolite mine, some of the minerals also have enrichment in Li. The mineral cryolithionite ($Na_3Li_3Al_2F_{12}$) from the Ivittuut cryolite deposit has a Li content of 5.6 % (Bøggild, 1953; Pauly, 1986), and zinnwaldite 1.67%, biotite from a pegmatite 0.58% (Pauly, 1986). The company Eclipse Metals Ltd.is exploring the deposit where their 2022 grab sampling campaign indicated grades up to 430 ppm Li. The company is also testing the REE potential from the nearby Grønnedal-Ika deposit.

For this study only few pegmatite samples, from the Motzfelt Sø Centre and one from Tuttutooq near Narsaq were analyzed and ranges from foid monzosyenite, foidolite, syenite, and foid syenite. The pegmatites from Motzfelt Sø centre the Li

content varied between 45-167 ppm. The analyzed samples from Motzfelt Sø centre and Tuttutooq (this study) are within the same range as the quartz syenite, alkali granite, foyaite and sodalite foyaite from the Ilimaussaq intrusion.
In 2023 the 1st prize winner of the Greenland national mineral hunt 'Ujarassiorit' won for a rock with a combination of enrichment in Mn, Li, Be, Ca, Ce, Ga, Y, Nb, Sr, Zn, REE from the locality Qaqortukuluup Tasiusaata Qinnguata kuua, between Narsaq and Qaqortoq, there the Lithium content was 67 ppm. During the Summer of 2024 the Government of Greenland, GEUS and US Department of State had a lithium project involved sampling pegmatites in South Greenland.
The new data from the 28 pegmatite samples (this study) confirms the Gardar Province in South Greenland is one of the interesting areas in Greenland to do further Li exploration and critical raw materials such as Sr, Ta, Nb, Ga, Ce and REEs.

Northeast Greenland

The area in Northeast Greenland also contains a potential for lithium. The pegmatites analyzed in this study has no enrichment in Li, but some of the other CRM such as Cu, Co, Sr and REEs are slightly enriched. Rosa et al. (2023) propose that hydrothermal veins can have potential for Li as well as Sn, W, Bi and Mo. The former exploration company Avannaa Resources Limited explored for CRM in the area around Jameson Land, Wegener Bjerge and Liverpool Land around 2008-2013, where the highest content Li was around 100 ppm in Morænedal (Rose, 2010; Haugaard, 2011; Thomassen, 2012; Rehnstrøm, 2012; Rink, 2012; Thomassen, 2012; Thomassen, & Rink, 2013). Hallenstein & Pedersen (1982; 1983) report enhanced Li values in greisen samples associated with Caledonian granites, where lithium is contained in lepidolite (Keulen et al. 2023).

Southern West Greenland

The pegmatite from Fiskenæsset, Ivisaartoq, Karrat and Lersletten also contains enrichments of lithium, and range between 61-161 ppm. There is reported spodumene from Snefjeld in the Paamiut area in the 1970s (Geisler, 1972), which indicate the North Atlantic Craton could contain complex pegmatites with spodumene. In 2024 the company Brunswick Exploration Inc. confirmed new spodumene finding in the Nuuk area at Ivisaartoq. The company announced applications for new licenses within the Nuuk area, and further north in the Uummannaq and Disko Bay area. The company is the first to actively explore for lithium in Greenland.

Conclusions

There is potential to find lithium within pegmatites with alkaline compositions in Greenland, where the lithium can be found in various micas and amphiboles and rarer minerals. The alkaline rocks can carry other critical raw materials such as REEs, Nb, Y, Ta and other. The results from this study suggest further exploration for Li on all the Gardar province intrusions. Since the GEUS archive is missing representative samples from Kvanefjeld/Kuannersuit, and some of the magmatic intrusions from the Gardar Province, fieldwork to the area and collection of samples from the various magmatic intrusions are proposed. The Gardar Province area is also proposed by Rosa et al. (2023) for further studies for CRM.
The lithium in complex pegmatites in granitic pegmatites could be in spodumene, or micas. There is a potential for lithium in the pegmatites from the North Atlantic Craton, the Nagssugtoqidian Orogen and the Rinkian fold belt and the Karrat Group.

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