

Petrography, geochemistry and geochronology of the Putoq Intrusion (SW Greenland) indicate affinity to the Julianehåb Igneous Complex

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The Putoq Intrusion is a small (8×4 km) body of distinctive rocks that intruded Julianehåb Igneous Complex granitoids close to Qaqortoq in SW Greenland. It comprises an outer hornblende monzonite surrounding an inner hornblende syenite. Evidence for mingling with mafic magmas is present in both the monzonite and syenite. The rocks are metaluminous and quartz-bearing. Zircon U-Pb dating of two samples yields an age of c. 1.81 Ga, indicating a link to c. 1.81–1.79 Ga rocks of the younger portion of the Julianehåb Igneous Complex, and that the Putoq Intrusion is unrelated to the c. 1.1 Ga Gardar Province intrusions to the north. The Putoq Intrusion is similar to the Julianehåb Igneous Complex in that it has trace element patterns typical of crustal rocks linked to subduction, and initial $^{87}\text{Sr}/^{86}\text{Sr}$ and ϵNd values of 0.7027 to 0.7044 and +0.6 to –1.4, respectively. The higher K_2O contents, more alkalic and ferroan compositions of the Putoq Intrusion are similar to contemporaneous granitoids of the Adlavik Domain in the Makkovik Province of Labrador, Canada. However, the Adlavik rocks are distinguished from the Putoq Intrusion by higher concentrations of high field strength elements. The Putoq Intrusion is therefore considered to represent an alkalic component of the Julianehåb Igneous Complex, potentially formed by fractionation of mafic magmas derived from melting of an enriched lithospheric mantle source.

Keywords: SW Greenland, Syenite, Geochronology, Geochemistry, Julianehåb Igneous Complex, Ketilidian Orogen

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This study presents petrographic, geochemical, isotopic and geochronological observations on an intrusion in an area named Putoq near Qaqortoq in SW Greenland, which we refer to as the Putoq Intrusion. This pluton has not previously been studied in detail and is of particular interest because it is lithologically distinct from, and intrusive into, the subduction-related I-type granitoids of the Julianehåb Igneous Complex (JIC) that dominate the area. Furthermore, it is located c. 12 km south of the syenites of the 1.1 Ga Ilímaussaq Intrusion of the alkaline Gardar Province. Thus, the age and affinity of the Putoq Intrusion are unclear. The aim of this study is to characterize

this unique intrusion and to assess its relationship to the JIC, Gardar Province and other rocks in SW Greenland.

Geological background

The geology of Southwest Greenland is dominated by the Ketilidian Orogen (c. 1.86–1.75 Ga) and the Gardar Province (c. 1.33–1.14 Ga; Fig. 1a). The Ketilidian Orogen is interpreted as a major continental arc that records an episode of Paleoproterozoic juvenile continental crustal growth (Garde *et al.* 2002). It

is divided into the Northern, Central and Southern Domains (Steenfelt *et al.* 2016). The Northern Domain is dominated by Archean gneisses of the North Atlantic Craton and is interpreted as the foreland region of the convergent margin, and the Central Domain consists predominantly of granitic rocks of the JIC and represents the continental arc (Garde *et al.* 2002). The Southern Domain is dominated by amphibolite to granulite facies gneisses and migmatites with protoliths interpreted to be metasediments from the forearc region (Garde *et al.* 2002). The JIC is correlated to the Makkovik Province in Canada, and further afield is linked to a major Paleoproterozoic crustal growth event along the margin of the supercontinent Columbia (Johansson *et al.* 2022). Geochronological data indicate that the JIC grew in two pulses at c. 1.85 and 1.80 Ga (Vestergaard *et al.* 2024). In SW Greenland, the central portion of the JIC is volumetrically dominated by the Younger Julianehåb Igneous Suite (1.8 Ga), with Older Julianehåb Igneous Suite rocks

(1.85 Ga) restricted to the northern and southern boundaries (Vestergaard *et al.* 2024). The Younger Julianehåb Igneous Suite grew rapidly during a possible magmatic flare-up in response to slab roll-back (Vestergaard *et al.* 2024). Field evidence for contemporaneous mafic and felsic magmatism is common (Vestergaard *et al.* 2025).

The Mesoproterozoic Gardar Province is part of a continental rift system that formed during the break-up of Columbia and that stretched from present day Finland to Canada (Upton *et al.* 2003; Ernst *et al.* 2008). In South Greenland, magmatism occurred in two pulses at 1.33–1.26 Ga and 1.18–1.14 Ga, producing magmatic rocks ranging from mafic dike swarms to kilometre-scale intrusive complexes (Upton *et al.* 2003). The intrusive complexes are typically alkaline and range in composition from mafic to felsic and include both silica undersaturated and saturated compositions including quartz syenite and nepheline syenites, as well as highly differentiated agpaitic

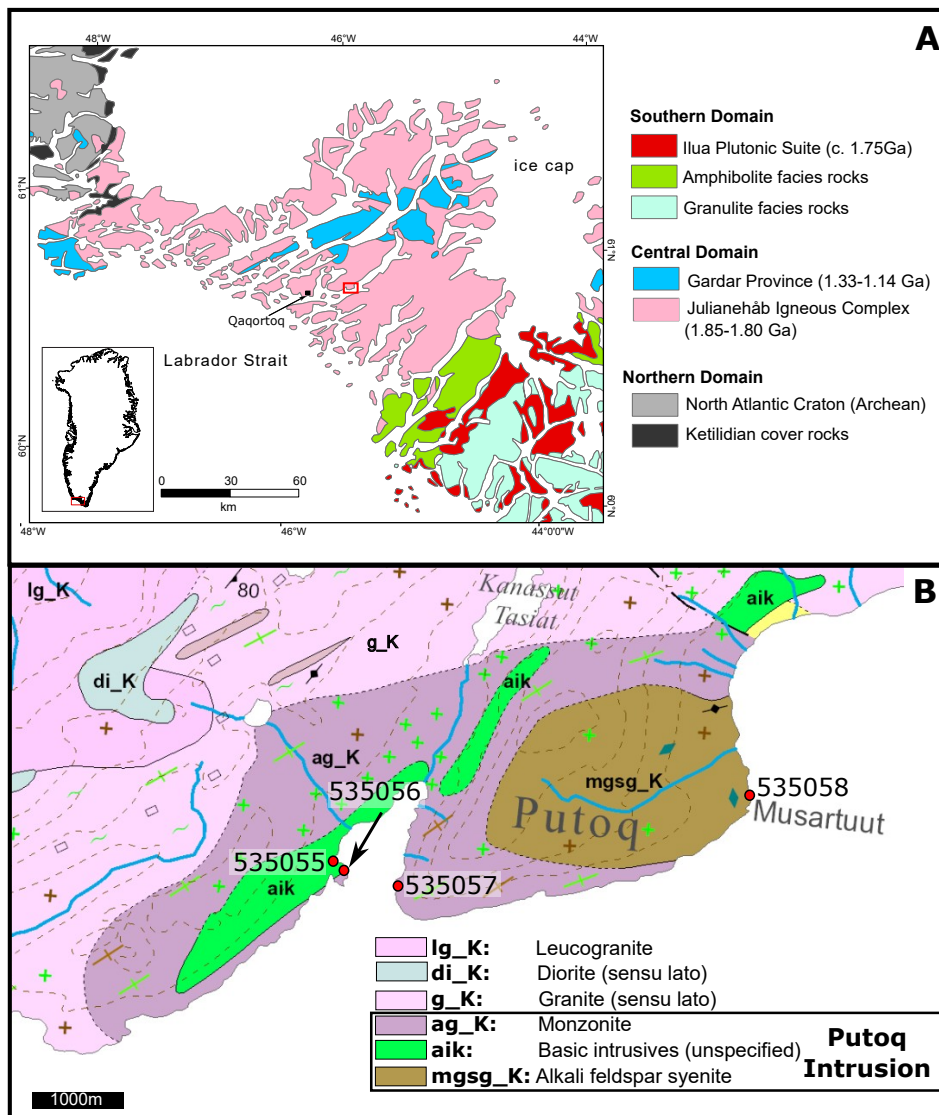


Fig. 1. A: Overview of geology of the Ketilidian Orogen in SW Greenland in the region near Qaqortoq (modified from Vestergaard *et al.* 2025). The red square shows location of study area shown in B. **B:** geology of the region around Putoq modified from Kokfelt *et al.* (2019; after Al-laart 1972) with sample locations. Note that the lithology ag_K is labeled as albitised rocks in Kokfelt *et al.* (2019) due to a transcription error as both the monzonite and albitised rocks are mapped with the same background colour and symbol (sg) in Al-laart (1972).

syenites (Upton & Emeleus 1987; Upton *et al.* 2003). These rocks host the largest rare earth element (REE) and high field strength element (HFSE) resource in Europe (e.g. Borst *et al.* 2016; Rooks *et al.* 2026).

The Putoq Intrusion is a c. 3 × 2 km oval intrusion located c. 17 km east of Qaqortoq on the northern shores of Igaliko Fjord in the JIC (Fig. 1a). Allaart (1972, 1973a) describes the rocks as an early, medium to coarse grained monzonite (aG_K on Fig. 1b) showing gradational contact with surrounding granites (g_K). The monzonite surrounds a younger body of leucocratic syenite which includes many dioritic xenoliths (mgsg_K on Fig. 1b). The mafic rocks (aik on Fig. 1b) are interpreted as basic intrusive rocks of unknown age and are described in the map text as late-orogenic dikes forming generally sub-horizontal net-veined complexes (Allaart 1973a).

Fieldwork was carried out in August 2020 as part of a larger field campaign to geochemically and geochronologically characterize the western parts of the JIC and Southern Domain (Fig. 1a; Vestergaard 2023; Vestergaard *et al.* 2024, 2025). Four samples (535055, -056, -057 and -058) were collected from the Putoq In-

trusion, which we will further analyse here (Fig. 1b). Characterizing geological field relationships was not a focus of the 2020 campaign, and our sampling was based on pre-existing maps (Allaart 1972; Kokfelt *et al.* 2019). We note that a smaller body of syenite is mapped c. 20 km to the north, east of the southern portion of the Ilímaussaq Intrusion (Allaart 1972), as well as several isolated bodies in Johan Dahl Land north of Narssarssuaq (Allaart 1973b); however, these bodies were not investigated in the present study.

Methods

Mineral chemistry data were obtained using a JEOL JXA-8200 electron microprobe (EMP) at the Department of Geosciences and Natural Resource Management, University of Copenhagen. Data were acquired using an acceleration voltage of 15kV, an electron beam intensity of 15 nA and a 5µm spot. Acquisition time was 20s on the peak and 10s background on both sides of the peak for all elements except Na



Fig. 2. Representative field images. **A:** Diorite (sample 535055 from this location). Note the outcrop is heterogeneous with multiple slightly more mafic enclaves that are rounded and in generally advanced stages of hybridization (e.g. to the right of the hammer handle). **B:** Close up of magma-mingling textures in subhorizontal composite sill cross-cutting the diorite. **C:** Close up of monzonite (sample 535057 collected from this outcrop). **D:** Field view of syenite illustrating its generally homogeneous and relative felsic nature (sample 535058 collected from this outcrop). **E:** Close up of syenite. **F:** Composite dike cutting syenite near location for sample 535058.

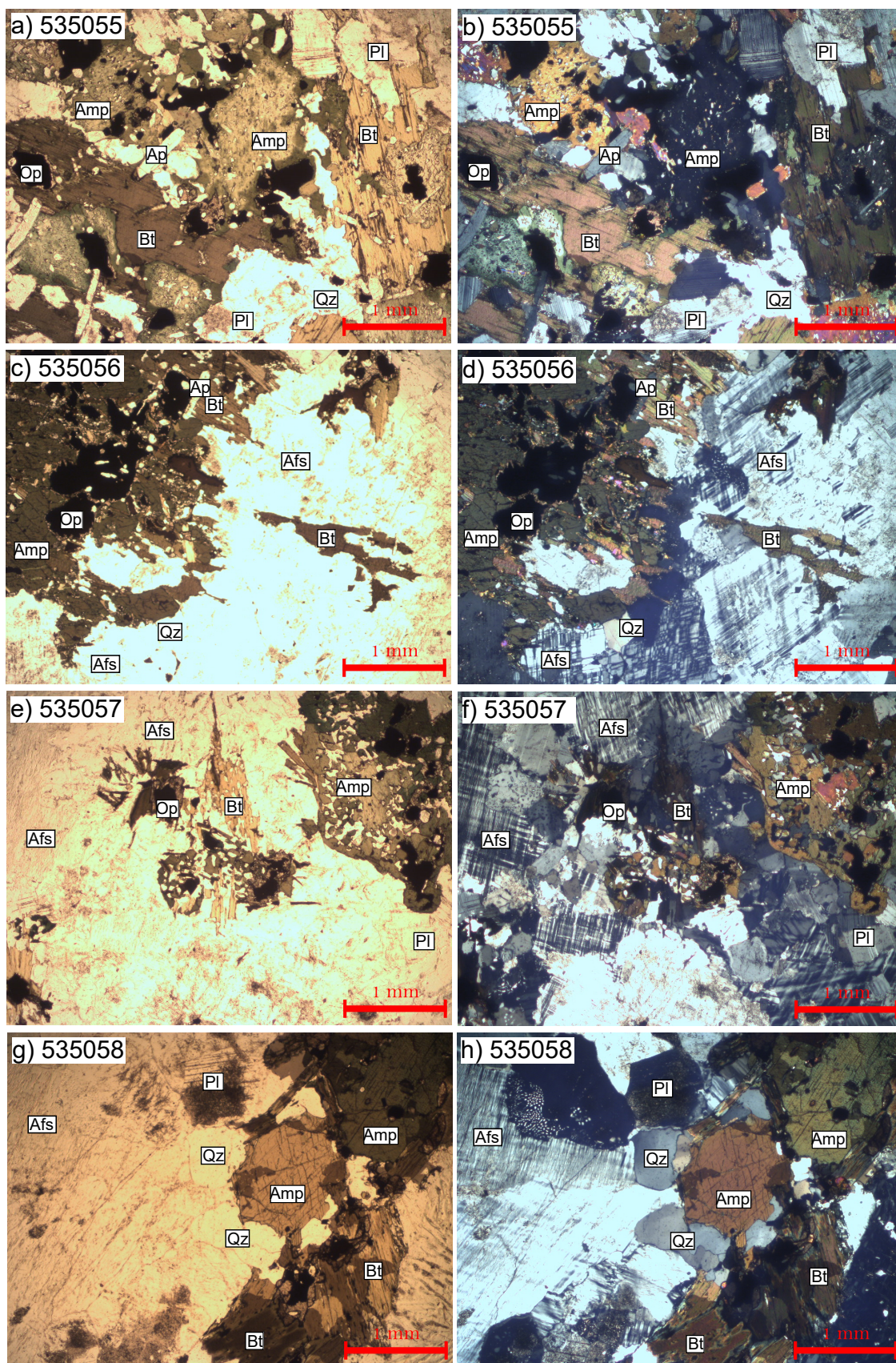


Fig. 3. Representative thin section images of Putoq samples (PPL on left, XPL on right). Note the zoning in amphibole in 535055 (a,b), abundant inclusions in amphibole in 535057 (e,f), and myrmekite in 535058 (g,h).

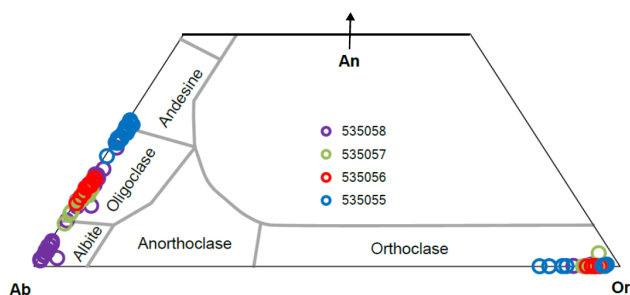


Fig. 4. Feldspar compositions. Note that plagioclase compositions in 535058 range from oligoclase to albite (at rims).

and K (10 & 5s). The instrument was calibrated using in-house silicate and oxide standards. Whole-rock geochemical data for the studied samples (published in Vestergaard *et al.* 2025) were obtained using lithium metaborate-tetraborate fusion, inductively coupled plasma – optical emission spectroscopy and ICP – mass spectrometry for major and trace element compositions, respectively. Whole-rock Rb-Sr and Sm-Nd isotope analyses were carried out in the Department of Geosciences and Natural Resource Management at University of Copenhagen using thermal ionization mass spectrometry isotope dilution methods described in detail in Scott *et al.* (2014). International standards SRM987 and JNdi were loaded and run with the samples and gave $^{87}\text{Sr}/^{86}\text{Sr} = 0.710242 \pm 4$ (2se) and $^{143}\text{Nd}/^{144}\text{Nd} = 0.512098 \pm 5$ (2se), respectively. These results are in good agreement with long term averages in the lab which indicate reproducibilities on the order of 0.002% and 0.03% for Sr and Nd isotope compositions, respectively. Zircon U-Pb geochronology was carried out by laser ablation ICP-mass spectrometry at GEUS, Copenhagen, using methods described in detail in Waight *et al.* (2017). Data were obtained using a New Wave Research NWR213 solid state Nd:YAG laser coupled to a Thermo-Fisher Scientific ELEMENT 2 double-focusing magnetic sector-field ICP-MS. Details of operating conditions are given in the supplementary data files.

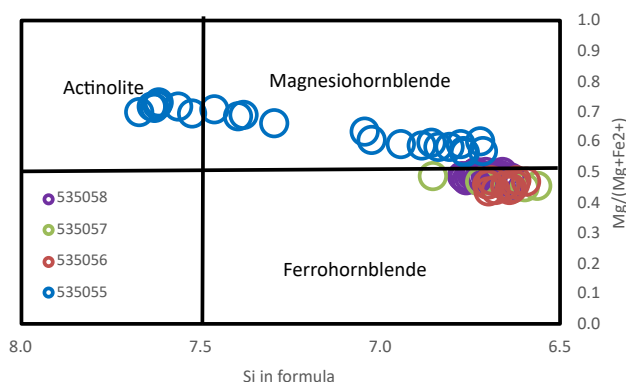


Fig. 5. Amphibole compositions in the Putoq Intrusion (classification diagram for calcic amphiboles from Leake *et al.* 1997).

During data collection, zircon standard 91500 yielded a weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1066.1 ± 6.1 Ma ($n = 51$, MSWD = 0.84), in good agreement with the age presented by Wiedenbeck *et al.* (1995) of 1065.4 ± 0.3 Ma. Zircon standard GJ-1 gave a weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 605.4 ± 4.3 Ma ($n = 69$, MSWD = 0.78), in good agreement with the age of 608.5 ± 0.4 Ma published by Jackson *et al.* (2004). Zircon standard Plešovice yielded a weighted average $^{207}\text{Pb}/^{206}\text{Pb}$ age of 333.3 ± 7.7 Ma ($n = 25$, MSWD = 1.2) which agrees with the 337.1 ± 0.4 Ma age presented by Slama *et al.* (2008). No common Pb correction was necessary in the data set. Concordia diagrams and ages were calculated using IsoplotR (Vermeesch 2018).

Results

Field geology

Representative field photos are presented in Fig. 2. The diorite (sample 535055; Fig. 2a) is a relatively mafic, medium grey equigranular heterogeneous diorite with varying contents of mafic minerals and numerous rounded more mafic inclusions in various stages of hybridization. The diorite is cut by a sub-horizontal composite intrusion comprising a relatively felsic, fine-grained, equigranular matrix that contains abundant fine-grained, equigranular mafic inclusions with lobate boundaries, indicative of mafic-felsic magma mingling (Fig. 2b). Aplite dikes are present, both cutting and being cut by the composite dike. The monzonite (samples 535056 and 535057), shown in Fig. 2c, is a light grey, equigranular, homogeneous rock containing enclaves of more mafic material; a composite dike also cuts this lithology. The syenite (sample 535058) is a white, homogeneous, equigranular rock (Fig. 2d and 2e) that is cut by a large composite dike comprising a fine-grained, light-grey matrix with lobate mafic inclusions (Fig. 2f).

Petrography and mineral chemistry

Representative microscope images are presented in Fig. 3 and mineral chemistry is given in the supplementary data files. Amphibole cations are calculated using Esawi (2004) and assuming 23 O.

Diorite – sample 535055 (Fig. 3 a,b)

Sample 535055 is a mafic-intermediate, medium- to coarse-grained, equicrystalline hornblende diorite dominated by plagioclase (60%, An_{24-31}) that occurs as anhedral crystals up to 5 mm in length, displaying zoning, polysynthetic twinning and minor sericitic alteration, with subordinate alkali feldspar (Or_{86-97} ;

Fig. 4). Mafic phases are dominated by pleochroic blue-green to brown-green hornblende (20%), present as subhedral to anhedral grains up to 4 mm in length with inclusions of quartz and opaque minerals. Amphibole commonly contains paler green pleochroic cores that may represent relict clinopyroxene. Compositions range from magnesiohornblende to actinolite (Fig. 5). The remaining mafic phases are predominantly anhedral biotite (12%, Fe/Mg = c. 1.1), pleochroic from pale yellow to dark brown (Fig. 3 a,b). Minor anhedral quartz and euhedral apatite occur, the latter commonly as inclusions in biotite and amphibole. Opaque phases (c. 3%) are mostly surrounded by a thin rim of titanite.

Monzonite – sample 535056 and 535057 (Fig. 3 c,d,e,f)

Samples 535056 and 535057 are medium- to coarse-grained, equigranular hornblende monzonites dominated by coarse-grained (up to 5mm), anhedral, perthitic and microcline-twinned alkali feldspar (c. 55%, Or₉₃₋₉₇; Fig. 4). Plagioclase is less abundant (c. 30%), present as smaller, anhedral and unzoned twinned crystals of oligoclase (An₁₄₋₁₉; Fig. 4). Myrmekite is abundant. Mafic phases are dominated by blue-

green to brown-green pleochroic, anhedral amphibole (c. 8%, ferrohornblende (Fig. 5)), and anhedral, yellow-brown pleochroic biotite (c. 5%, Fe/Mg = c. 1.5). Quartz is uncommon and the few crystals that are present are mostly anhedral and fine-grained (below 0.5mm) with undulous extinction. The opaque phases are often rimmed by titanite. Amphibole in 535057 is characterized by numerous small inclusions of quartz (Fig. 3 e,f).

Syenite – sample 535058 (Fig. 3 g,h)

This sample is a felsic, coarse-grained, equicrystalline biotite-amphibole syenite. The rock is dominated by alkali feldspar (~60%, Or₉₄₋₉₆) and plagioclase (20%) with minor hornblende (8%), biotite (<5%), quartz (~5%) and opaques (<1%). The alkali feldspar is anhedral (up to 1 cm in length), weakly perthitic and displays microcline twinning. Plagioclase grains are smaller (up to 3mm) than the alkali feldspars, subhedral, mostly sericitized, and display albite twinning as well as weak zoning with oligoclase cores (An₁₃₋₂₁) and thin albite-rich rims (An₁₋₆; Fig. 4). Plagioclase occurs both as independent crystals and as inclusions within alkali feldspar. Myrmekite is

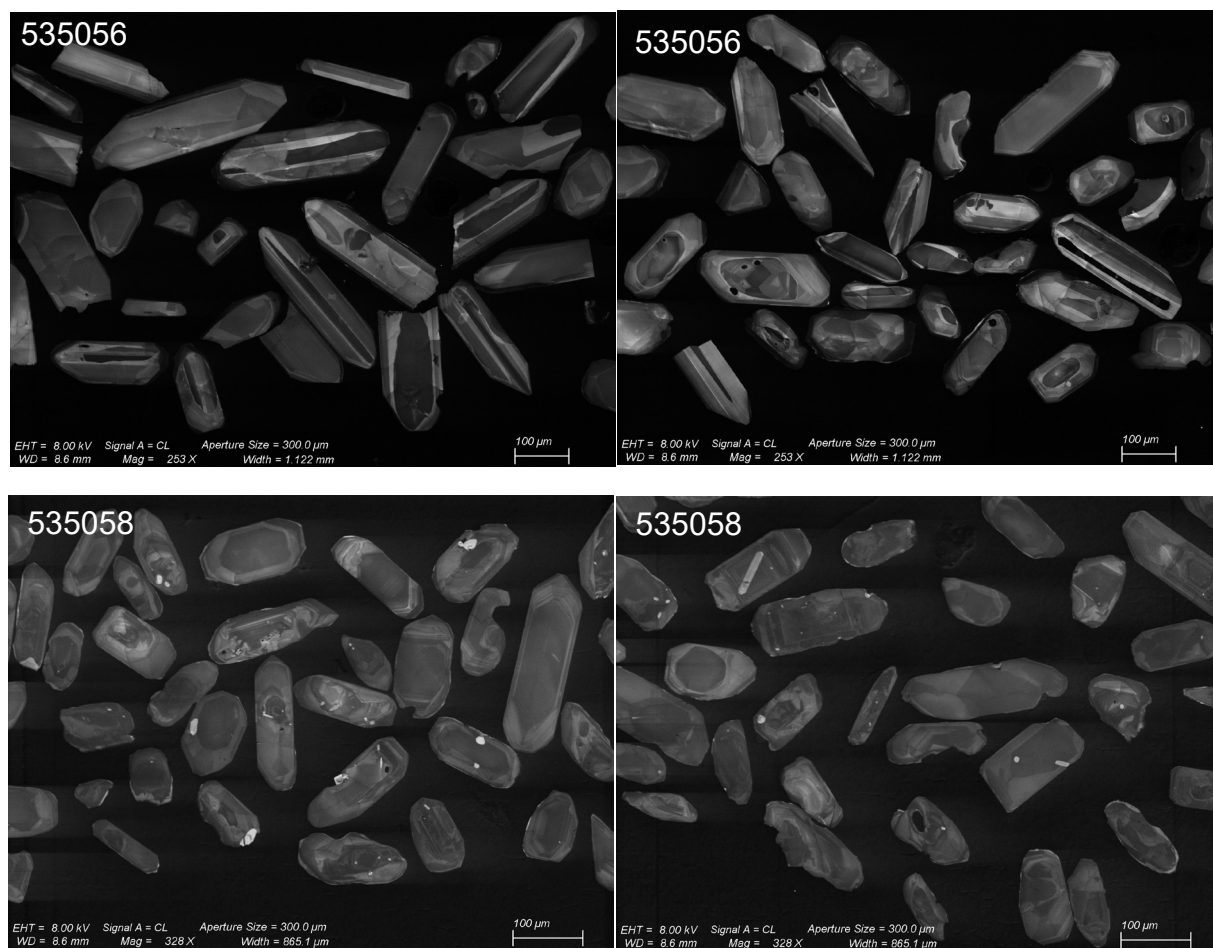


Fig. 6. Representative cathodoluminescence images of zircons from samples 535056 and 535058.

abundant. Quartz occurs as small (<1 mm), anhedral crystals with undulose extinction, interstitial to feldspars. Mafic minerals form clusters dominated by anhedral to subhedral green pleochroic amphibole (Ferrohornblende, Fig. 5) up to 2mm in size, accompanied by anhedral yellow-brown pleochroic biotite (Fe/Mg $\approx$ 1.3) that shows partial alteration to chlorite and opaque phases (ilmenite and magnetite), commonly rimmed by titanite. Accessory phases include apatite, relatively large and abundant zircon and possible magmatic epidote.

Geochronology

Zircons from samples 535056 (monzonite) and 535058 (syenite) were analysed for their U-Pb isotopic composition and results are presented in the supplementary data files. Zircons from both samples are generally euhedral, up to 300 μ m in length, showing complex concentric zoning with occasional rounded cores (Fig. 6). A total of 114 zircons were analysed in the diorite sample 535056, where all have Th/U of > 0.1 (range = 0.11 to 0.21), which is typical of igneous zircons (e.g. Hoskin and Schaltegger, 2003). The U-Pb data are mostly concordant to slightly reverse concordant, with $^{207}\text{Pb}/^{206}\text{Pb}$ ages ranging from 1766 to 1835 Ma.

They define an upper intercept age of $1806.9 \pm 2.6/4.3$ Ma (MSWD = 2.7) and a weighted average $^{207}\text{Pb}/^{206}\text{Pb}$ age of $1808.7 \pm 6.0/6.3$ Ma (MSWD = 2.3; Fig. 7a). The second, larger, uncertainties take into account the analytical uncertainty of the age with overdispersion, calculated as $z = y\sqrt{\text{MSWD}}$ (Ludwig 1998).

Ninety zircons from the syenite sample 535058 were analysed. The data are also mostly concordant to slightly reverse discordant, although, in contrast to 535056, several analyses also show normal discordance (Pb loss; Fig. 7b). The zircons have Th/U ranging from 0.10 to 0.25 (average = 0.18) and have $^{207}\text{Pb}/^{206}\text{Pb}$ ages ranging from 1784 to 1847 Ma (excluding the two most normally discordant analyses). The zircons define an upper intercept age of $1811.6 \pm 1.6/4.0$ Ma (MSWD = 6), and a weighted average $^{207}\text{Pb}/^{206}\text{Pb}$ age of $1813.8 \pm 5.9/6.3$ Ma (MSWD = 3; Fig. 7b). The relatively large MSWD on both the upper intercept and weighted mean ages likely reflects the spread in ages, which may reflect a population of slightly older potentially inherited zircons with $^{207}\text{Pb}/^{206}\text{Pb}$ dates of 1820 to 1850 Ma. Removal of zircons older than 1820 Ma reduces the weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age to $1803.7 \pm 1.6/2.1$ Ma (MSWD = 1.6). These results indicate that, within analytical uncertainty, the diorite and syenite components of the Putoq Intrusion are the same age.

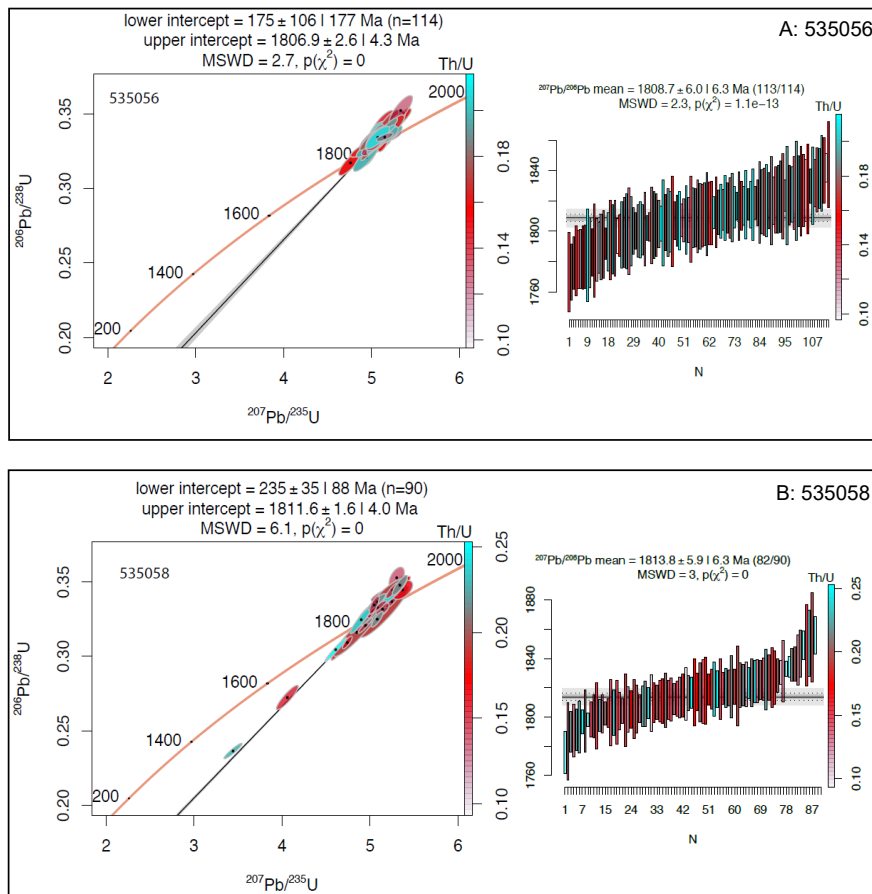


Fig. 7. Wetherill concordia diagrams and weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age plots for samples 535056 (A; diorite) and 535058 (B; syenite). MSWD: mean squared weighted deviation. The different uncertainties on ages reflect exclusion or inclusion of the analytical uncertainty of the age with overdispersion, calculated as $z = y\sqrt{\text{MSWD}}$ (Ludwig 1998).

Geochemistry

Geochemical analyses of the samples are presented

in Table 1. Selected geochemical plots comparing the Putoq Intrusion to the JIC and Adlavik Domain are presented in Fig. 8 (for more detail see Vestergaard

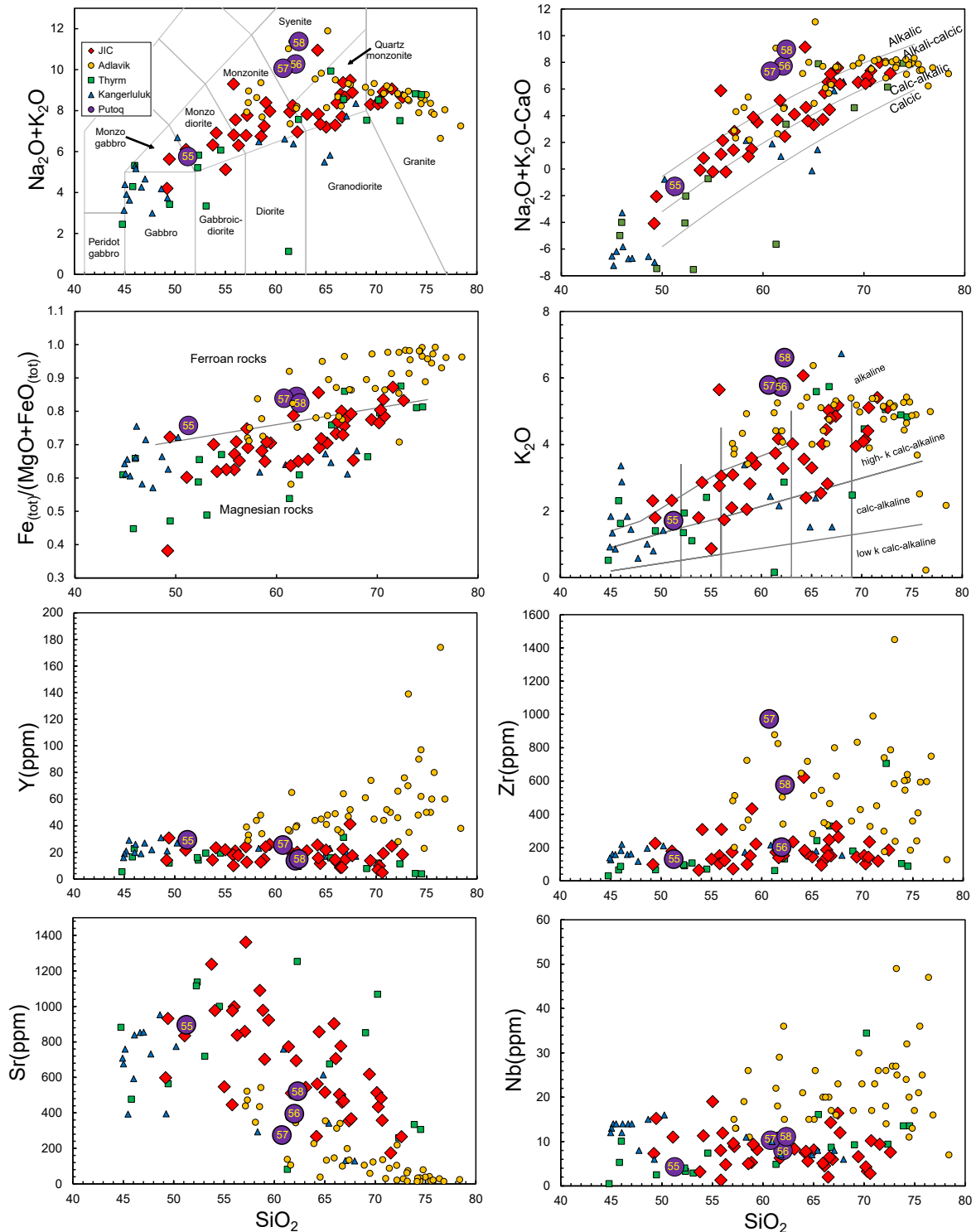


Fig. 8. Selected major- and trace element Harker diagrams with comparison to literature data. Sample numbers are shown as 56 = sample 535056 etc. Total alkalis – silica classification from Middlemost (1994), Modified alkali-lime index (Frost *et al.* 2001), Ferroan/Magnesian classification (Frost & Frost, 2008), K_2O vs silica classification from Ewart (1982). Literature data from JIC from Vestergaard *et al.* (2024), the Thym Complex (Bagas *et al.* 2020), Kangerluluk volcanic-sedimentary sequence (Stendal *et al.* 2001) and Adlavik Domain (Hinchey *et al.* 2024) included for comparison.

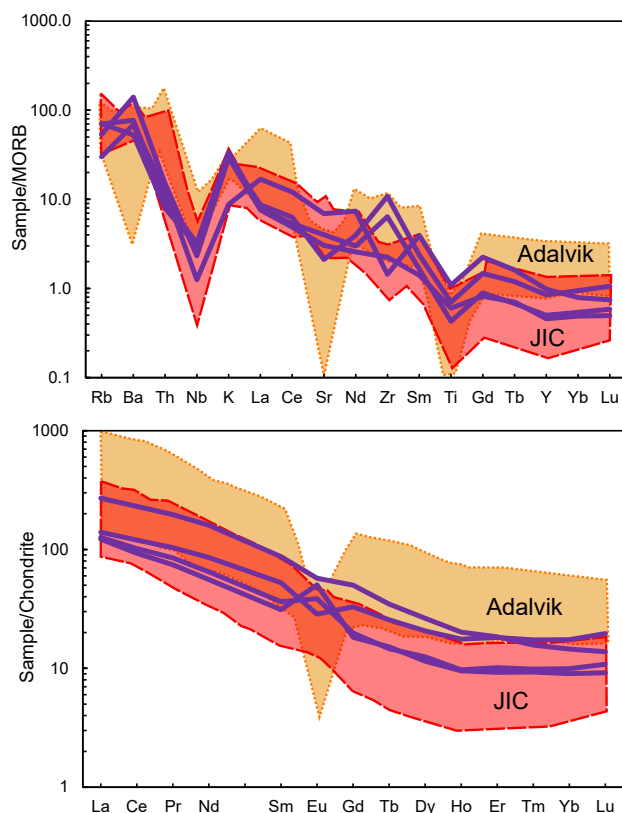


Fig. 9. MORB-normalised multi-element and chondrite-normalised diagrams (using MORB values from Arevalo & McDonough 2010 and chondrite values from Anders & Grevesse 1989). JIC data from Vestergaard *et al.* (2025), Adlavik Domain data from Hinchey (2021).

et al. 2025). Previously published JIC data from the Thrym Complex (NE JIC, Bagas *et al.* 2020) and the Kangerluluk area (SE JIC, Stendal *et al.* 2001) are also included. The Putoq Intrusion classifies as syenite and is distinct from most JIC compositions by being more alkalic (reflecting higher K and lower Ca contents) and ferroan (reflecting lower Mg contents), which is a typical feature of the contemporaneous Adlavik Domain rocks in Labrador. The Putoq Intrusion is similar to the JIC in terms of other major elements and most trace elements (Fig. 8, 9). The Adlavik Domain diverges from the JIC by having generally higher concentrations of HFSE and M-HREE such as Y, Zr, Yb and Gd and lower Sr, whereas the

Putoq rocks show some similarities to the Adlavik rocks with higher Zr and lower Sr contents (Figs 8, 9). Similarities between the Putoq Intrusion and the JIC, as well as distinctions from the Adlavik Domain, are evident in both the MORB-normalised multi-element diagram and chondrite-normalised REE diagram (Fig. 9). The Adlavik Domain is characterized by generally higher HFSE and REE concentrations and lower Sr contents. The Putoq Intrusion differs from other JIC rocks primarily in displaying positive Zr anomalies. Notably, two Putoq monzonite and syenite samples exhibit distinct positive Eu anomalies, which is a significant contrast to the Adlavik Domain rocks (Fig. 9). The Putoq Intrusion classifies as Volcanic Arc Granite together with the JIC and is distinct from Adlavik, which classifies as Within Plate Granite in the Y vs Nb (and Y+Nb vs Rb – not shown) diagrams of Pearce *et al.* (1984). High Zr contents result in two samples (535057 and 535058) classifying as A-type granites in the Zr+Nb+Ce+Y tectonic discrimination diagram of Whalen *et al.* (1987), but the others fall in the I/S/M-type granite field (Fig. 10).

New Rb-Sr and Sm-Nd isotope data were obtained for the samples 535056, -057 and -058 (Table 2). Sm-Nd data for sample 535055 (Table 2) were published in Vestergaard *et al.* (2025). At 1.8 Ga, the samples have initial Sr compositions ranging from 0.7027 to 0.7044. The Nd isotope compositions cluster around chondritic values with $\epsilon_{\text{Nd}}(1.8\text{Ga})$ ranging from +0.6 to -1.4, overlapping with other analyses from the JIC as well as the age-equivalent rocks of the Adlavik Domain in Labrador (Fig. 11). The Rb-Sr and Sm-Nd data do not define acceptable isochrons (not shown). Instead, they yield poorly constrained errorchron ages that are older than the U-Pb zircon ages and are associated with large mean square weighted deviates (MSWD).

Emplacement depths and crystallization temperatures

Zircon saturation temperatures were calculated following Crisp and Berry (2022). They are 680°C for the diorite (sample 535055), 780°C and 908°C for the monzonite (samples 535056 and 535057) and

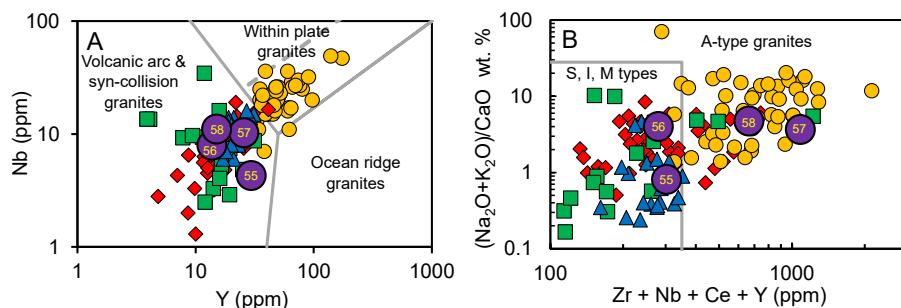


Fig. 10. Selected tectonic discrimination diagrams. A: Y vs Nb from Pearce *et al.* (1984), B: Zr+Nb+Ce+Y vs $(\text{Na}_2\text{O}+\text{K}_2\text{O})/\text{CaO}$ from Whalen *et al.* (1987). Symbols as in Fig. 8.

874°C for the syenite (sample 535058). The latter two samples are characterized by relatively high Zr concentrations and positive Zr anomalies spikes on the multi-element diagram (Fig. 9), which may reflect zircon accumulation and therefore overestimated zircon saturation temperatures. The relatively uniform amphibole compositions observed in the monzonite and syenite (Fig. 5) enable application of the Al-in-hornblende geobarometer of Anderson and Smith (1995), which is temperature dependent. Assuming a crystallization temperature of 800°C, calculated pressures of 1.9 ± 0.2 kbar, 2.2 ± 0.5 kbar and 1.6 ± 0.2 kbar (corresponding to c. 5–7 km depth) are obtained for 535056, 535057 and 535058, respectively. The quoted uncertainties are 1SD and reflect compositional variations in the amphibole. At 700°C, the calculated pressures increase to 3.8, 4.1 and 3.4 kbar (c. 11–13 km depth) for the same samples, respectively. Although these variations are large, they suggest that the Putoq Intrusion was emplaced in the middle to upper crust.

Discussion

Age and affinity of the Putoq Intrusion

The alkaline and syenitic nature of Putoq could suggest a link to the syenitic rocks of the Ilímaussaq Intrusion (1156.6 ± 1.4 Ma, Borst *et al.* 2019) of the Gardar Province, located only a few kilometres to the north. However, our new geochronological results indicating an age of c. 1.81 Ga for the Putoq Intrusion clearly excludes this possibility. Instead, this age suggests that the Putoq Intrusion is related to the

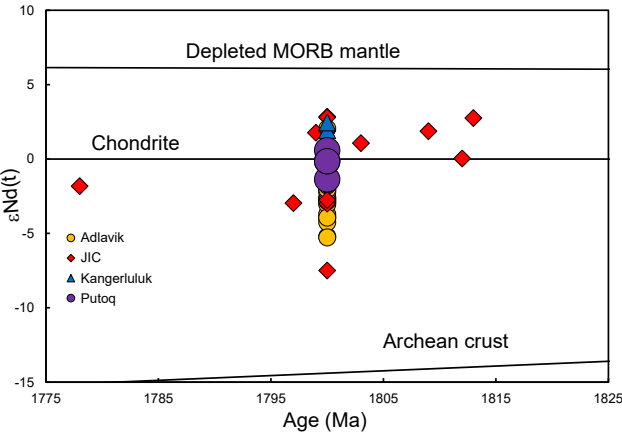


Fig. 11. Nd isotope compositions for the Putoq Intrusion (at 1.8 Ga). Data from the JIC (Vestergaard *et al.*, 2025); Kangerluluk Sequence (Stendal *et al.*, 2001) and Adlavik Domain (Hinchey *et al.*, 2024) are included for comparison. The depleted mantle curve is based on ingrowth from chondrites at 4.5 Ga to a modern composition of $\epsilon_{\text{Nd}} = +10$ ($^{143}\text{Nd}/^{144}\text{Nd} = 0.51315$, $^{147}\text{Sm}/^{144}\text{Nd} = 0.2137$). The Archean crust (North Atlantic Craton) evolution line is extrapolated from Hinchey (2021).

Ketilidian Orogen, specifically the Younger Julianehåb Igneous Suite that dominates the Central Domain (Fig. 1a; Vestergaard *et al.* 2024).

Geochemical and petrographic investigations of the JIC show that it is dominated by metaluminous,

Table 1. Major (weight %) and trace (ppm) concentrations of samples from the Putoq Intrusion

	535055	535056	535057	535058
SiO ₂	51.26	61.98	60.74	62.31
Al ₂ O ₃	15.41	17.37	16.63	18.89
Fe ₂ O _{3(T)}	11.94	4.59	6.78	3.35
MnO	0.18	0.11	0.15	0.06
MgO	3.44	0.76	1.17	0.64
CaO	7.06	2.55	2.74	2.4
Na ₂ O	4.05	4.55	4.28	4.77
K ₂ O	1.71	5.73	5.79	6.61
TiO ₂	1.54	0.85	1.00	0.61
P ₂ O ₅	1.16	0.22	0.23	0.1
LOI	1.56	0.69	0.74	0.49
Total	99.30	99.39	100.20	100.20
A/CNK	0.722	0.948	0.909	0.975
Sc	21	11	16	6
Be	1	< 1	< 1	< 1
V	187	15	28	21
Cr	< 20	< 20	< 20	< 20
Co	72	105	120	111
Ni	< 20	< 20	< 20	< 20
Cu	30	< 10	10	< 10
Zn	140	60	100	40
Ga	20	17	18	19
Ge	1.1	1.2	1.2	1
As	< 5	< 5	< 5	< 5
Rb	45	80	106	105
Sr	896	395	275	522
Y	29.4	13.7	25.5	15
Zr	130	202	973	576
Nb	4.3	8	10.3	11.1
Mo	5	< 2	< 2	< 2
Ag	< 0.5	0.5	2.7	1.7
In	0.1	< 0.1	0.1	< 0.1
Sn	1	1	1	1
Sb	0.4	0.3	< 0.2	< 0.2
Cs	1.1	1.9	4	0.5
Ba	1145	2332	876	1281
La	63.5	28.7	32.8	29.7
Ce	139	56	72.3	61.4
Pr	17.5	6.62	9.22	7.56
Nd	72.2	25.2	38.7	29.3
Sm	12.8	4.58	7.72	5.35
Eu	3.21	2.82	1.6	2.16
Gd	9.87	3.59	6.49	3.91
Tb	1.26	0.55	0.93	0.53
Dy	6.4	2.79	5.01	3.04
Ho	1.12	0.53	0.98	0.54
Er	2.93	1.47	2.89	1.61
Tm	0.38	0.225	0.42	0.238
Yb	2.37	1.47	2.84	1.62
Lu	0.335	0.223	0.477	0.263
Hf	2.8	3.8	18.8	12.7
Ta	0.66	1.2	1.31	1.36
W	357	593	713	663
Tl	0.28	0.53	0.76	0.64
Pb	9	15	17	18
Bi	0.1	< 0.1	< 0.1	< 0.1
Th	2.75	3.28	1.74	2.1
U	1.38	1.43	2.2	1.81

Data have been previously presented in Vestergaard *et al.* (2025).

Table 2. Sr and Nd isotope data age corrected to 1.8 Ga

sample	Rb (ppm)	Sr (ppm)	$^{87}\text{Rb}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr}$	2SE%	$^{87}\text{Sr}/^{86}\text{Sr}(t)$	Sm (ppm)	Nd (ppm)	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}$	2SE%	$^{143}\text{Nd}/^{144}\text{Nd}(t)$	$\epsilon\text{Nd}(t)$
535055	-	-	-	-	-	-	13.22	76.49	0.1043	0.51147	0.0039	0.51024	-1.37
535056	80	95	0.5866	0.71875	0.0008	0.70356	4.82	27.50	0.1060	0.51156	0.0021	0.51030	-0.15
535057	106	275	1.1180	0.73340	0.0007	0.70446	7.80	39.96	0.1181	0.51174	0.0021	0.51034	0.59
563058	105	522	0.5826	0.71774	0.0015	0.70266	4.94	28.53	0.1048	0.51154	0.0016	0.51030	-0.15

Data for sample 535055 are from Vestergaard *et al.* (2025).

magnesian, hornblende-bearing, and K-rich I-type granitoids with trace-element signatures (Fig. 9; large ion lithophile element enrichment and negative Nb anomalies) that are typical of magmatic rocks derived from subduction-modified sources. The Putoq Intrusion exhibits many geochemical similarities with the intrusive rocks of the JIC. In particular, the diorite sample 535055 is indistinguishable from other mafic rocks in the JIC. However, the monzonite and syenite of the Putoq Intrusion are more alkalic (primarily due to higher K and lower Ca contents) and more ferroan (due to lower Mg contents) than rocks of similar SiO_2 content from the JIC. In terms of trace elements, the evolved compositions of the Putoq Intrusion are distinguished from JIC by having higher Zr, lower Sr and in part positive Eu anomalies. Initial whole rock Nd and zircon Hf isotope compositions from the JIC are dominantly chondritic to suprachondritic, consistent with juvenile magma sources. Oxygen isotopes in zircon from the JIC are mantle-like and show no evidence for significant involvement of sedimentary crust during magma genesis (Vestergaard *et al.* 2025). Less radiogenic Nd and Hf isotope compositions are observed in the JIC towards its boundary with the Northern Domain, indicating involvement and reworking of Archean crust (Vestergaard *et al.* 2025). The initial Nd isotope compositions of the Putoq Intrusion are indistinguishable from the majority of JIC compositions in the central and southern portion of the Central Domain (Fig. 1a), and consistent with a JIC affinity. Similarly, initial Sr isotopic compositions of the Putoq Intrusion ($^{87}\text{Sr}/^{86}\text{Sr}_i = 0.7027\text{--}0.7045$) are consistent with initial compositions of 0.702–0.704 previously determined for JIC rocks from Rb–Sr whole-rock isochrons (Chadwick & Garde 1996; Van Breemen *et al.* 1974).

The JIC has previously been correlated with rocks of similar age in the Makkovik Province in Labrador, especially the Adlavik Domain, and their proximity, similar geological architecture and age suggest that they formed in the same overall tectonic setting (Hinchey *et al.* 2024; Vestergaard *et al.* 2024). Detailed comparisons by Vestergaard *et al.* (2024, 2025) have shown that both provinces are characterized by a pulse in magmatism at 1.81–1.79 Ga and have similar Nd isotope compositions. However, there are distinct geochemical differences, with the Adlavik Domain rocks being typically more ferroan and having lower Sr and higher middle-heavy REE and HFSE

(e.g. Y, Zr, Nb, Hf) concentrations, resulting in their classification as A-type or Within-Plate Granite in tectonic discrimination diagrams (Vestergaard *et al.* 2025). The relatively alkalic, ferroan and K-rich nature of the Putoq Intrusion is similar to the Adlavik Domain and could imply that the Putoq Intrusion represents an extension of the Adlavik Domain into South Greenland. If this were the case, it would provide strong evidence of petrogenetic and chronological links between Labrador and South Greenland. However, in detail, there are important geochemical contrasts between the Adlavik Domain and the Putoq Intrusion that make a direct correlation unlikely. The Putoq Intrusion (like the JIC in general) differs from the Adlavik Domain rocks by classifying as I-type or Volcanic Arc Granite in trace element tectonic discrimination diagrams (see Hinchey *et al.* 2024 and Vestergaard *et al.* 2025). This difference in trace element compositions is clear in the multi-element normalized diagram and REE plot where Putoq overlaps with JIC (Fig. 9). We therefore conclude that the Putoq Intrusion is part of the Julianehåb Igneous Complex, specifically the Younger Julianehåb Igneous Suite, and formed in a similar tectonic environment and from melting of similar sources.

The question can then be raised, how can the quartz-poor, syenitic nature of the Putoq Intrusion and especially its high K contents compared to other JIC rocks be explained. Syenites are alkali-feldspar rich plutonic rocks often linked to fractionation of alkaline magmas formed by low degrees of melting of enriched mantle sources and variable degrees of crustal contamination (e.g. Riishus *et al.* 2005; Shellenutt *et al.* 2024; Bolhar *et al.* 2025; Jung *et al.* 2025). The elevated K_2O contents and positive Eu anomalies in some (but not all) of the Putoq rocks indicate that accumulation of alkali feldspar may account for part of the geochemical signature of the Putoq Intrusion, though not all of it. Accumulation of alkali feldspar would also be expected to result in elevated Ba and Sr contents; however, no consistent trends are observed in the data set that are consistent with alkali feldspar accumulation. The elevated Zr contents in the Putoq Intrusion may also indicate the presence of cumulate zircon.

Evidence for involvement of multiple magma batches likely from multiple sources and field evidence for mafic-felsic magma mingling are relatively common in the JIC (including the Putoq Intrusion;

Fig. 2). The mafic rocks are commonly amphibole-rich and have trace-element signatures typical of magmatic rocks derived from subduction-modified mantle sources (Vestergaard *et al.* 2025). In general, the more mafic rocks of the JIC have similar or more negative ϵHf and ϵNd isotope compositions compared to the more dominant felsic rocks (as also seen in the mafic sample investigated here – 535055), and this is interpreted to indicate the involvement of an enriched lithospheric mantle source during continental arc magmatism (Vestergaard *et al.* 2025). The spread of isotopic compositions in the JIC is interpreted to reflect additional components from asthenospheric melts, juvenile mafic lower crust and limited input from Archean crust (Vestergaard *et al.* 2025). We therefore suggest that the Putoq Intrusion (monzonite and syenite) represent evolved rocks formed by fractional crystallization of mafic magmas dominantly derived from melting of enriched lithospheric mantle components in the JIC. Fractionation did not occur as a closed system as the rocks do not form acceptable isochrons and show variable initial Sr and Nd isotope signatures, notably the more felsic rocks have higher ϵNd than the mafic sample 535055. It is therefore likely that other lower crustal source components and/or asthenospheric mantle sources with more radiogenic Nd isotope compositions were also involved.

Conclusions

Petrographic, geochemical, isotopic and geochronological data are presented for the Putoq Intrusion, a distinct hornblende monzonite and hornblende syenite intrusion located approximately 17 km east of Qaqortoq in SW Greenland. The intrusion yields an age of 1.81 Ga, which indicates it is distinct from the Gardar Province syenites to the north and its affinity with the younger portion of the Julianehåb Igneous Complex. Amphibole compositions suggest the intrusion was emplaced in the mid- to upper crust. The Putoq Intrusion shares several geochemical characteristics with the Julianehåb Igneous Complex, including similar trace element signatures consistent with a subduction-related origin and overlapping Sr and Nd isotopic compositions. However, the relatively alkalic and ferroan character of the Putoq Intrusion could also indicate affinity with the similarly aged Adlavik Domain of the Makkovik Province in Labrador, Canada. Such a correlation is considered unlikely, given the distinctive trace element compositions of the Adlavik Domain, particularly its enrichments in high field strength elements that leads to its classification as within-plate granite. The syenitic and alkaline nature of the Putoq Intrusion is therefore interpreted to reflect fractionation of mafic

magmas dominantly derived from enriched subcontinental lithospheric mantle sources during the final stages of formation of the Julianehåb Igneous Complex.

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