The newly discovered Attu carbonatite of West Greenland: a Mesoproterozoic dyke intrusion enriched in primary Sr-Ba-REE minerals

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Abstract

A newly discovered ca. 1.5 Ga old carbonatite dyke in central West Greenland is characterized by very high contents of rare earth elements (REE), Sr and Ba (up to 12.4 wt.% total REE, 14.6 wt.% SrO and 12.4 wt.% BaO). The dyke occurrence is named 'Attu carbonatite' after the nearby village Attu. The carbonatite is primarily composed of carbonate minerals such as Sr-rich calcite ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$), huntite ($Mg_3Ca(CO_3)_4$), strontianite ($SrCO_3$), alstonite ($CaBa(CO_3)_2$), burbankite ($(Na,Ca)_3(Sr,Ba,Ce)_3(CO_3)_5$) and daqingshanite ($(Sr,Ca,Ba)_3(Ce,La)(PO_4)(CO_3)_{3-x}(OH,F)_x$). In addition to the wide range of carbonate minerals, the carbonatite contains coarse-grained monazite(-Ce), apatite and magnetite. Barite occurs as discrete crystals together with the rock-forming carbonates. Texturally, the carbonatite rock displays abundant intimately intergrown fine- to medium-grained Ca, Sr, Ba and REE carbonate minerals, which exhibit prominent exsolution textures within calcite, burbankite, strontianite and dolomite hosts, as well as in the apatite crystals. Several different exsolution textures are observed: 1) alstonite in calcite; 2) daqingshanite in calcite; 3) daqingshanite in burbankite; 4) Mg-Ba carbonate in strontianite; 5) Mg-Ba carbonate in calcite and strontianite in dolomite; 6) strontianite in apatite; and 7) monazite(-Ce) in apatite. The carbonatite dyke is foliated and exsolution textures are observed internally in the foliation-defining minerals indicating that exsolution occurred after the main deformation event.

The carbonatite magma intruded into Archaean basement gneisses that had been affected by the Nagssugtoqidian tectono-metamorphic event at approximately 1850 Ma. Magmatic monazite(-Ce) crystals from the carbonatite yield a U-Pb age of 1565±53 Ma, which is the current best estimate of dyke emplacement. Monazite(-Ce) that exsolved from apatite and calcite yields a U-Pb age of 1492±33 Ma, which is within the analytical uncertainty of the primary magmatic monazite U-Pb age. However, the U-Pb age determinations suggest that mineral exsolution occurred a few million years after carbonatite magma emplacement, in response to further cooling of the deep-seated dyke (tectonically-induced uplift?). Dyke emplacement may have occurred within an active ductile shear zone, which helps to explain the foliation of the carbonatite rock, predating cooling-related mineral exsolution. Country rock fenitization by fluids that emanated from the carbonatite dyke intrusion is recorded by the increasing abundance of mafic silicates such as Ba-rich phlogopite at the contact zone.

1 Introduction

Carbonatites are volumetrically minor but geologically significant igneous rocks that potentially provide important information about mantle processes and the deep carbon cycle (Bell et al. 1998; Woolley and Kjarsgaard, 2008; Yaxley et al. 2022). They are not only of special interest to the scientific community, but also to the mining industry and thus human society, because they host the most important niobium (e.g., Araxa, Brazil (Mitchell, 2015) and rare earth element (REE) deposits (e.g., Bayan Obo, China (Drew et al., 1990), Mountain Pass, U.S.A. (Olsen et al. 1954), Mt. Weld, Australia (Willett et al*.* 1986; Chandler et al. 2024)). In addition, the REE-rich carbonatites provide particularly important constraints on crystallisation and subsequent alteration processes in carbonatite magmatic systems (Moore et al. 2015; Anenburg et al. 2021).

Carbonatites are composed of more than 50 vol.% primary (i.e., magmatic) carbonate minerals, and the bulk rock compositions typically have less than 20 wt.% SiO_2 (Le Maitre et al. 2002). A special subgroup of carbonatites containing wt.% levels of REE has been reported from different locations and tectonic settings worldwide (e.g., Bayan Obo, China (Drew et al. 1990), Mountain Pass, U.S.A. (Olsen et al. 1954), Fen, Norway (Andersen, 1986), Qaqarssuk, Greenland (Knudsen 1991), Kangankunde, Malawi (Wall and Mariano, 1996; Broom-Fendley et al. 2017), Khibina, Russia (Zaitsev et al. 1998)). The mineralogy of such Sr-Ba-REE-rich carbonatite types is complex and typically includes an alteration mineral assemblage (e.g., Zaitsev et al. 1998). Metasomatic alteration (fenitization) of the surrounding country rocks is common (Le Bas, 2008; Elliott *et al.* 2018; Yaxley et al. 2022).

Several episodes of carbonatitic magmatism are recognized in Greenland, and the following five broad age groups can be discerned:

1. Late Archaean (3.0-2.5 Ga): Skjoldungen (Nielsen and Rosing, 1990), Fiskenaesset (Bollingberg et al. 1976) and Tupertalik (Larsen and Pedersen, 1982; Bizzarro et al. 2002).
2. Middle Proterozoic (ca. 1.3 Ga): e.g. Qassiarssuk (Stewart, 1970; Andersen, 1997) and Grønnedal-Ika (Emeleus, 1964).

3. Late Proterozoic (590-550 Ma): e.g. Sarfartoq (Secher and Larsen, 1980; Larsen and Rex, 1992; Tappe et al. 2011, 2012).
4. Jurassic (175-150 Ma): e.g. Qaqarssuk (Larsen et al. 1983; Knudsen, 1991) and Tikiusaaq (Steenfelt et al. 2006; Tappe et al. 2009, 2012, 2017; Secher et al. 2009).
5. Palaeogene (ca. 56 Ma): Gardiner (Gleadow and Brooks, 1979; Nielsen, 1980).

Note that recently a Paleoproterozoic carbonatite magmatic event (ca. 1859 Ma) was proposed for central West Greenland based on monazite mineralization in the Karrat Isfjord area. However, the suggested ferrocarbonatite source to this deposit is yet to be discovered (Mott et al. 2013).

In this paper, we report U-Pb monazite ages for the newly discovered Attu carbonatite (named after the village Attu in southern West Greenland), followed by a discussion of the mineralogy and geochemistry of this dyke intrusion. In addition to reporting the presence of several rare carbonate minerals and exsolution textures, we will also discuss the petrogenetic role of the mineral daqingshanite, which comprises both phosphate and carbonate components (Table 1). The occurrence of daqingshanite as exsolution lamellae appears to prevent the formation of secondary REE-carbonate minerals such as bastnäsite and synchysite. Although economic REE mineralization is typically hosted by carbonatite systems that went through multiple stages of autometasomatic overprinting (e.g., Bayan Obo, Wu 2008), the unique exsolution textures documented here show that secondary upgrading of carbonatites is not always required in the formation of high-grade REE mineralization.

1.1 Geological setting and field relationships

The Attu carbonatite dyke is located at the southern end of Uperniviarsuk island approximately 10 km NE of the village Attu between Sisimiut and Aasiaat in southern West Greenland (Fig. 1). The bedrock in the area is mostly Archaean in age, mainly comprising tonalitic to granodioritic gneisses, which have been overprinted by a regional amphibolite to granulite facies metamorphic event at ca. 1850 Ma (Kalsbeek et al., 1987), during a period of major crustal accretion and collision as part of the Paleoproterozoic Nagssugtoqidian orogeny (e.g., Nutman et al., 2008). The carbonatite dyke is located in the northernmost part of the Nordre Strømfjord Shear Zone (Bak et al., 1975; Sørensen, 1983), an area that has been intensely deformed during the Nagssugtoqidian orogeny. Granitic pegmatite magmas formed during this tectono-metamorphic event as late as 1770 Ma (Willigers et al., 2001), and possibly even as late as 1676 Ma based on U-Pb rutile ages (Connelly et al., 2000). Lamprophyres and lamproites located just north of our study area (Marker and Knudsen, 1989) yield an age of ca. 1750 Ma (Larsen and Rex, 1992).

The pinkish carbonatite body occurs as an up to 1 m wide, steeply to vertically dipping dyke that strikes in NW-SE direction at 128° and can be traced for approximately 50 m along strike (Fig. 2). Close to the northeastern contact, it occurs between a 20 m thick NW-SE trending, steeply dipping meta-dolerite dyke (to the left on Fig. 2A) and granulite facies gneisses that dominate the basement in the area (to the right on Fig. 2A). To the southeast, the carbonatite dyke likely continues beneath the sea and to the northwest its contact is covered by overburden at the bottom of a small gully (Fig. 2A). The carbonatite dyke is slightly zoned with light-colored carbonates in the central region and darker pinkish carbonates at the contact to the wall-rocks. Along the contact to the wall-rocks, there is a 5 to 10 cm thick reaction zone (Fig. 2) consisting of a mixture of carbonate minerals and Ba-rich phlogopite plus biotite. Samples 463373 and 463374 represent this transition zone in proximal and distal positions to the carbonatite dyke, respectively (Table 1).

In the core of the carbonatite dyke, the rock is coarse (grain sizes of up to several mm) and mainly composed of pink carbonates (mostly calcite) with brownish red monazite(-Ce) crystals. Up to 2 cm large magnetite crystals occur locally. Pink calcite hosts red strontianite inclusions up to 100 µm across in a schlieren-like pattern (Fig. 3). The gneisses and dolerite of the immediate country rock to the carbonatite dyke are characterized by an approximately 20 m thick zone of yellow to orange staining with mm-thick ankerite-rich veins and disseminated ankerite. This zone is best described as a fenitized halo surrounding the carbonatite body (Fig. 2B).

2 Analytical methods

2.1 Whole-rock major and trace element compositions

Whole-rock major and trace element analyses were performed at ACME Laboratories in Canada in 2009, and the data are reported in Table 1. The results for standards analysed alongside our samples are provided in the Supplementary Materials. Cleaned rock samples were jaw crushed to 80% passing (10 mesh, 2 mm). A 250 g aliquot was then riffle split and pulverized in a mild-steel ring-and-puck mill to 85% passing (200 mesh, 75 µm). A 200 mg aliquot was weighed into a graphite crucible and mixed with 1.5 g of $LiBO_2/Li_2B_4O_7$ flux. Crucibles were then placed in an oven and heated to 980°C for 30 minutes. The cooled bead was dissolved in 5% HNO_3 (ACS grade nitric acid diluted in demineralised water). Calibration standards and reagent blanks were included in the sample sequence for analysis. Sample solutions were aspirated into an ICP emission spectrograph (Spectro Ciros Vision or Varian 735) to determine the concentrations of SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, Na_2O, K_2O, MnO, TiO_2 and P_2O_5, as well as the concentrations of Sc, V, Cr, Co, Ni, Cu, Zn, Rb, Sr, Y, Zr, Nb, Cs, Ba, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Hf, Pb, Th and U. Loss on ignition (LOI) was determined by igniting a 1 g sample split at 950°C for 90 minutes and then measuring the weight loss. Total carbon and sulphur contents are determined by the Leco method. The geochemical data obtained for the carbonatite dyke record magmatic to late-magmatic processes as is suggested by the pristine mineralogy and cooling textures. Secondary alteration is largely absent so that significant post-magmatic element mobility can be ruled out.

2.2 Mineral major and minor element compositions by EPMA

Mineral analyses were carried out with a JEOL JXA-8200 electron microprobe at the University of Copenhagen. Many of the rock-forming minerals of the Attu carbonatite dyke have unconventional compositions, and most minerals are Sr- and Ba-rich. Quantitative EPMA data for monazite(-Ce) ((Ce,La)PO_4) were obtained using the analytical protocol of Scherrer *et al.* (2000). Kα X-ray lines were used for Si, Fe, Ca, P and Al; Lα lines for Y, Ce, La and Er; Lβ lines for Pr, Dy, Sm, Gd; Mα lines for Th; and Mβ lines for Pb and U. For Nd, the most intense Lα line was preferred over the Lβ line as proposed by Scherrer *et al.* (2000), because the interference with the Lβ line of Ce is negligible (<1% uncertainty in the Nd elemental value). Standards analysed included synthetic REE glasses, as well as natural silicate and phosphate minerals. The EPMA operating conditions were set to 15 kV accelerating voltage and 50 nA beam current at 5 µm spot size, and the $\phi(\rho Z)$ matrix correction was applied to the raw data.

For the Ca-Sr-Ba-REE phosphate-carbonate daqingshanite, La, Ce, Nd, P, Ca, Sr, Ba, F, Pr and Sm were measured by EPMA. The mineral grains were screened for Th and Al, which were always below detection limit. We measured the Ce Lβ line and the La Lα line applying the LiF crystal of the instrument. The Lβ lines for Pr and Sm, and the Lα lines for Ba (LiF) and Sr (PET) show no overlap with the elements in daqingshanite. There was a complete overlap between F and Th. However, Th contents were always below method detection limit of 0.01 wt.%, which implies low F contents. This also shows that the Th-F peak overlap was unlikely to affect the accuracy of the EPMA measurements. For daqingshanite analyses, the operating conditions were set to 15 kV, 7 nA and a beam size of 10 µm because carbonates are unstable under the electron beam.

2.3 U-Th-Pb age determinations by laser ablation ICP-MS analysis

Monazite(-Ce) U-Th-Pb geochronological analysis was performed on thin sections by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) at the Geological Survey of Denmark and Greenland in Copenhagen. A NWR213 solid state Nd:YAG laser system from New Wave Research (ESI) mounted with a standard TV2 ablation cell was coupled to an ELEMENT 2 single-collector magnetic sector-field ICP-MS instrument from Thermo-Fisher Scientific. The mass spectrometer was equipped with Ni cones, a Fassel type quartz torch shielded with a grounded Pt electrode and a quartz bonnet. To ensure stable laser output energy, a laser warm-up time of 15 minutes was applied before operation, which results in flat ablation craters by a "resonator-flat" laser beam. The mass spectrometer ran for ca. one hour prior to analysis to stabilize the background signal. Samples and standards were carefully cleaned with ethanol in an ultrasonic bath to remove surface contamination. The ablation cell with the inserted sample holder was flushed with helium gas to minimize and stabilize the gas blank level. The ablated material was swept by the helium carrier gas and mixed with argon gas before entering the plasma torch. The ICP-MS instrument was optimised for dry plasma conditions through continuous linear ablation of the GJ-1 zircon standard (e.g., Jackson et al. 2004). The signal-to-noise ratios for the heavy mass range (i.e., ^{202}Hg to ^{238}U), emphasizing on ^{238}U and ^{206}Pb, were maximized, while simultaneously opting for low element-oxide formation levels by minimising the ^{238}UO/^{238}U ratio. To minimize the effect of instrumental drift, a standard-sample-standard analytical protocol was followed, bracketing the samples by 3 standard measurements. For data quality control, the Plesovice zircon (Slama *et al.* 2008) and the monazite(-Ce)s A49H and A276C (pers. comm. Y. Lahaye, GTK) were measured regularly as secondary standards during the analytical session, yielding accuracies and precisions of the age results within 5% of the recommended values (typically even better). Data were acquired from single spot analysis using a laser spot size of 25 µm, a nominal laser fluence of 10.5 J/cm^2 and a pulse rate of 10 Hz. Total data acquisition time for a single analysis was at maximum 2 minutes, including 30 seconds gas background followed by laser ablation for 30 seconds, and washout for 35 seconds. Factory-supplied software was used for the acquisition of the transient data, obtained through automated running mode of pre-set analytical locations. Data processing was carried out off-line using the software Iolite v. 2.5 (Hellstrom *et al.* 2008; Paton *et al.* 2011), and the Iolite-integral VizualAge data reduction scheme of Petrus and Kamber (2012). The VizualAge data reduction scheme includes a correction routine for down-hole isotopic fractionation (Paton *et al.* 2010). Monazite(-Ce) ages were obtained using the Tera-Wasserburg inverse concordia diagram and a linear best fit correction intercept procedure to determine an average lower intercept age for the monazite(-Ce) population from each sample analysed (e.g., Vermeesch, 2020).

3 Petrography and mineral chemistry

The carbonatite rock has a coarse-grained texture defined by large subhedral crystals of monazite(-Ce), apatite, magnetite and dark mica set in a matrix composed of finer-grained carbonates such as Sr-rich calcite and dolomite ($(MgCa)(CO_3)_2$), huntite ($Mg_3Ca(CO_3)_4$), strontianite ($SrCO_3$), alstonite ($Ba,Ca(CO_3)_2$), burbankite ($(Na,Ca)_3(Sr,Ba,Ce)_3(CO_3)_5$) and daqingshanite ($(Sr,Ca,Ba)_3(Ce, La)(PO_4)(CO_3)_{3-x}(OH, F)_x$). The high abundance (5–10 vol.%) of up to 5 mm large pink monazite(-Ce) crystals is rather unique among known carbonatites worldwide (Fig. 3). Centimeter-sized composite calcite-dominated carbonate grains with parallel layers of mainly strontianite are common and suggest that these grains once constituted larger single crystals (Fig. 3). The rock typically exhibits a foliation expressed by parallel alignment of 1 mm thin apatite schlieren (up to 5 mm long) that are visible with a hand lens. The foliation is also visible microscopically as parallel arrangement of the carbonate mineral grains (Fig. 5).

3.1 Carbonates

The groundmass of the carbonatite rock is dominated by a wealth of intimately intergrown small- to medium-sized (10-500 µm) crystals of calcite, dolomite, daqingshanite, burbankite and alstonite (Figs. 4-9). A dominant textural feature is exsolution among the different carbonate phases. Calcite is characterized by very high Sr contents, on the order of 5 – 7 wt.% SrO (Table 2). Calcite also contains 0.5 to 1 wt.% BaO (Table 2). Generally, calcite is fine-grained and intimately intergrown with the other carbonate minerals (Figs. 4 and 6). However, calcite crystals may have been originally much larger, forming poikilitic crystals that enclosed monazite(-Ce) and apatite, with subsequent exsolution and deformation as indicated by the parallel rows of strontianite. The strontianite rows probably represent exsolutions from the calcite host along preferred crystallographic directions (Fig. 3). Similar textures have been reported from Italian carbonatitic rocks (Vichi *et al.* 2023). Dolomite is also very rich in Sr (up to 4 wt.% SrO; Table 2). Alstonite ($Ca,Sr,Ba(CO_3)_2$) is common in the core of the carbonatite dyke (#334669) occurring as 50 × 200 µm large grains that may define a foliation in the rock (Fig. 5; Table 2).

Daqingshanite ($(Sr,Ca,Ba)_3(Ce, La)(PO_4)(CO_3)_{3-x}(OH, F)_x$) is present in all the carbonatite samples examined. In the core zone of the dyke, it occurs as elongated 25 × 200 µm large grains defining a foliation in the rock (Fig. 5) together with various Ba- and Sr-carbonates. Daqingshanite is also present as exsolution lamellae in burbankite (Fig. 8). Representative EPMA data for daqingshanite are listed in Table 3 where they are compared to daqingshanite data from the Bayan Obo (China) and Nkombwa Hills (Zambia) carbonatites (Appleton *et al*. 1992).

Microprobe analyses confirm that burbankite $(Na,Ca)_3(Sr,Ba,Ce)_3(CO_3)_5$ occurs in the core zone of the carbonatite dyke together with alstonite, forming 25 × 75 µm large grains that locally exhibit exsolution of daqingshanite lamellae (Fig. 8).

In general, different types of exsolution can be observed in the mineral constituents of the Attu carbonatite dyke:

1. Strontianite occurring as elongated lamellae in calcite (Fig. 9). The strontianite lamellae locally follow two discrete crystallographic orientations in the calcite crystal hosts (Fig. 9D),

and they are typically folded (Fig. 10). Where larger strontianite lamellae (or schlieren) are observed, they typically contain a core of monazite(-Ce) (Figs. 6 and 10).

2. Mg-Ba carbonate in calcite occurring as submicroscopic to 5 µm long elongated blebs (Fig. 10D).
3. Alstonite occurring as 1 µm thick exsolution lamellae in calcite exhibiting perthite-like textures (Fig. 6).
4. Strontianite occurring in dolomite as rounded submicroscopic blebs up to 1 µm in diameter (Fig. 6).
5. Alstonite occurring as 1–5 µm large blebs in strontianite typically with daqingshanite inclusions (Fig. 7A).
6. Elongated lamellae of daqingshanite occurring in alstonite along cracks or crystallographic planes (Fig. 7B).
7. Approximately 1-3 µm thick and 5-50 µm long lamellae of daqingshanite occurring in burbankite (Fig. 8).
8. Slightly bent composite lamellae of alstonite, daqingshanite and barite occurring in calcite, which are 1 µm thick and up to 20 µm long (Fig. 8).

3.2 Phosphates

3.2.1 Apatite

Apatite occurs as 0.5 to 3 mm large, light-green colored, rounded crystals macroscopically visible in hand specimen (Fig. 3). Locally, apatite forms schlieren defining a foliation that is visible with a hand-lens. Apatite contains abundant irregular inclusions of strontianite and monazite(-Ce), and it may be surrounded by a corona consisting of these same minerals (Figs. 4 and 11). The inclusions are mainly located along 20 µm wide parallel zones (darker in BSE images) crossing apatite grains (Figs. 4 and 11). These zones have lower contents of heavy elements such as Sr and REE, and the texture is best interpreted as exsolution of monazite(-Ce) and strontianite from apatite.

In addition, there are parallel, minute monazite(-Ce) and strontianite needles included in apatite (Fig. 11). The Sr content in apatite is generally high, with 5-6 wt.% SrO substituting for Ca (Table 5). Total Rare Earth Oxide (TREO) contents are typically high between 2 and 4 wt.%. The REE^{3+} in apatite are charge-balanced by Na^+ (0.3 to 0.5 wt.% Na_2O; Table 5). Apatite is common in the mica-rich zones at the contact to the basement gneisses, and there is also apatite with elevated TREO contents present in the fenite aureole bordering the carbonatite dyke. In these apatite crystals, a decreasing content of Sr and REE is observed from core to rim. Apatite in the fenite typically contains 1 to 10 µm large monazite(-Ce) inclusions located in bands with weaker (darker) BSE intensity. Although F dominates the anion site in apatite from the Attu carbonatite and associated fenite, Cl and OH groups are also present.

3.2.2 Monazite(-Ce)

Monazite(-Ce) at the Attu carbonatite occurs in four different modes (listed in order of decreasing abundance), with only Mode-1 exhibiting primary magmatic features. In contrast, Mode-2, -3 and -4 are best described as reaction products and local exsolution features in which both Th and U contents are below EPMA-method detection limit (Table 6).

- Mode-1: Round, brownish pink, 0.5 to 2 mm large crystals (Fig. 3) that exhibit sector zoning (Fig. 12). The Th-zonation is broadly concentric, but with variable styles of embayment and irregularities. Crystal cores generally have the highest Th contents (on average 0.5 wt.% ThO_2), with marked decrease towards the rims (Table 6). Uranium contents are below EPMA-method detection limit. This monazite mode of occurrence is by far the volumetrically most significant.
- Mode-2: Monazite(-Ce) occurs together with strontianite as coronas around large apatite crystals (Figs. 4 and 11).

- Mode-3: Between 1 and 50 µm thick, composite strontianite-monazite(-Ce) grains and schlieren occur in calcite, and these rather elongated features may be folded (Fig. 10), with monazite(-Ce) in the core.
- Mode-4: Approximately 5 × 10 µm large, round to irregular inclusions of monazite(-Ce) in apatite, typically together with strontianite (Figs. 4 and 11).

3.3 Other rock-forming minerals

In the core of the carbonatite dyke, silicate minerals represent less than 10 vol.% of the rock, and silicate modal abundances increase towards the contact with the country rocks (Fig. 2D). The most common silicate mineral in the carbonatite is a Ba-mica with a structural formula of $Ba_{0.41}K_{0.35}Na_{0.19}$ $(Mg,Fe^{2+},Mn)_{2.88}Ti_{0.16}$ $Si_{2.56}Al_{1.35}$ $(OH)_2$ O_{10} (Table 7). The Ba-endmember for phlogopite (kinoshitalite-ferrokinoshitalite; Tracy 1991, Bigi *et al.* 1993, Gnos and Armbruster 2000) represents the closest match to the Ba-mica compositions reported here for the Attu carbonatite. The euhedral, pleochroic Ba-mica crystals (olive to light brown) reach up to 10 mm in size. Bending of the (001) plane may be observed indicating kink deformation of the micas (Fig. 4).

Tremolite, magnetite and ilmenite are also observed in the Attu carbonatite (Table 7). Barite is included in most of the carbonate minerals such as in burbankite, daqingshanite, strontianite, alstonite and calcite (Fig. 5). Allanite is present in the alteration zone that was caused by the fenitization associated with carbonatite magma emplacement (Fig. 13).

4 Whole-rock geochemistry

The whole-rock Sr, Ba and REE (TREO) contents of the Attu carbonatite reach major element concentration levels for this dyke intrusion (Table 1). Our samples exhibit strong enrichment of the LREE relative to the HREE (La_N/Lu_N ~ 2000) (Fig. 14), which is very typical for intrusive carbonatites from localities worldwide (Woolley and Kempe, 1989; Harmer and Nex, 2016), including other occurrences in West Greenland (Knudsen 1991; Tappe et al. 2017). At Attu, the

LREE (La, Ce, Pr, Nd, Sm) account for more than 99 wt.% of the TREO (Table 1). The chondrite-normalized REE pattern is slightly concave downwards indicating a relative enrichment in the MREE (Fig. 14). The apparent positive Yb anomaly could be an analytical artifact caused by oxide interference from the very high concentrations of the LREE. This may also explain the apparent negative Tm anomaly.

Sample 463369 is a Sr- and Ba-rich variety of the carbonatite, with SrO plus BaO accounting for 27 wt.% of the rock (Fig. 5). In some samples, REE-bearing carbonates such as burbankite and daqingshanite are rock-forming minerals and present the main REE repositories. In other samples, monazite(-Ce) is the main carrier of the REE because it occurs as a common rock-forming mineral, either in the form of phenocrysts or as an exsolved phase together with strontianite (Figs. 4 and 11).

The mica-rich glimmeritic transition between the carbonatite and the basement country rock is also enriched in Sr, Ba and the REE (#463373; Fig. 14). The glimmerite is also enriched in Nb relative to the carbonatite core, as is also observed in the Jurassic Qaqarssuk carbonatite complex some 300 km farther south in West Greenland (Knudsen, 1991). The fenitized basement sample 463374 is also enriched in the LREE, Sr, Ba and Th compared to the mafic rocks of the basement in the study region (Fig. 14).

5 U-Th-Pb geochronology

Conventionally, the U-Pb system in geochronology relies on the dual decay of ^{238}U and ^{235}U to stable radiogenic ^{206}Pb and ^{207}Pb, respectively. The $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ ratios therefore define the so-called concordia curve. Another decay chain that can be coupled to the U-decay scheme is the Th-Pb system, where ^{232}Th decays to stable radiogenic ^{208}Pb (e.g., Janots et al. 2012; Janots and Rubatto 2014). Recently, Vermeesch (2020) developed an algorithm that helps to visualize coupling between the $^{208}Pb/^{232}Th$ and $^{206}Pb/^{238}U$ dates on a U-Th-Pb concordia curve by performing a joint isochron regression between the U-Th-Pb chronometers. This novel visualisation tool allows investigation of radiogenic to common-Pb ratios (more precise mass spectrometry counting statistics are achieved by measuring mass-208 as the most abundant Pb isotope), thus improving the numerical accuracy of monazite(-Ce) age dates.

The monazite(-Ce) recovered from four carbonatite samples were dated by U-Th-Pb geochronology using the LA-ICP-MS technique. The large spread in U/Pb isotopic ratios allows for calculation of lower intercept dates, interpreted as the crystallisation age of these crystals (Fig. 15). The analysed monazite(-Ce) grains from sample 463369 and 463371 represent mm-sized crystals with sector zoning (Fig. 12). They are best interpreted as primary igneous monazite(-Ce) and the lower intercept age of 1565 ± 56 Ma in Tera-Wasserburg concordia space determines magma emplacement and crystallization (Fig. 15A). Using the combined U-Th-Pb systematics, we obtained an age of 1565 ± 34 Ma.

Phosphorous, REE and Sr now residing in strontianite and monazite(-Ce) coronas are unlikely to have been introduced into the carbonatite rock from external sources, but rather were mobilized internally from very REE- and Sr-rich apatite and calcite. Monazite(-Ce) that occurs as coronas on apatite (Figs. 4 and 11) and aggregates together with strontianite (Figs. 6 and 10) may represent monazite(-Ce) exsolved from apatite and calcite under solid state conditions. These unmixed domains yielded a lower intercept age of 1492 ± 33 Ma, which is within the uncertainty of the 1565 ± 34 Ma age. However, the slightly younger formation age of the unmixed monazite domains compared with the older crystallisation age of the primary igneous monazite(-Ce) is consistent with our textural interpretation (Fig. 15B).

6 Discussion

The origins of REE-rich carbonatites, such as the newly discovered occurrence at Attu, have been debated over decades (Mariano, 1989a; Chakhmouradian and Zaitsev, 2012; Moore et al. 2015; Anenburg et al. 2020, 2021), with the majority of authors interpreting the REE mineralization in terms of fluid-related processes that affected the carbonatite bodies at a late stage in their magmatic-hydrothermal evolution (e.g., hydro/carbothermal or metasomatic fluids and brine melts). Examples are Bayan Obo in China (Wu 2008; Fan et al. 2016); Qaqarssuk in West Greenland (Knudsen 1991); Gakara in Burundi (Ntiharirizwa et al. 2018) and Khibina on the Kola Peninsula in NW Russia (Zaitsev et al. 1998). However, Mariano (1989b) and Poletti et al. (2016) proposed that the Mountain Pass REE-carbonatite in the western U.S.A. crystallized from a primitive melt that had intruded into Precambrian basement rocks (Olsen et al. 1954). This model is in accordance with Wyllie and Jones (1985) who found that such REE-rich carbonatites can be formed directly from a carbonatite melt. We also interpret the REE mineralization of the Attu carbonatite to have a primary magmatic origin mainly because of the phenocrystic nature of monazite(-Ce) and apatite. The very high abundance of both monazite(-Ce) and apatite, combined with their coarse crystal sizes and association with cm-sized magnetite crystals (Fig. 3), may suggest that the carbonatite dyke represents a cumulate rock. However, the Sr-Ba-REE-rich nature of apatite and groundmass carbonates indicates that the carbonatite melt was originally very enriched in these elements (e.g., Sartori et al. 2023).

6.1 The different types of monazite(-Ce) and their ages

The monazite(-Ce) phenocrysts characterised by sector zoning and compositional Th zoning appear to represent a primary magmatic phase crystallized directly from a carbonatite melt, which supports a magmatic model for this REE-rich carbonatite. Compositional data for primary monazite(-Ce) from carbonatites show high Th/U ratios (Zhu and O'Nions 1999). The high Th/U nature of monazite(-Ce) is also reflected in the bulk rock compositions (Table 1). The 1565 ± 56 Ma U-Pb age (Fig. 15A) obtained for the Th-rich cores of the monazite(-Ce) crystals constrains the primary crystallisation age. Rims on the large phenocrystic monazite(-Ce) grains have lower Th content compared to the cores, either reflecting Th decrease in the magma or changing conditions of

Th incorporation into the monazite(-Ce) structure. Regardless of the exact mechanism, the compositions and zoning trends of the phenocrystic monazite crystals are best interpreted as primary magmatic features.

Aggregates of strontianite and monazite(-Ce) are observed in calcite where they form a regular pattern probably following crystallographic planes in the host phase (Fig. 9D). These are also developed as schlieren-like stringers (Fig. 10) that range in thickness from 1 to 50 µm. This texture is interpreted as having developed by exsolution of Sr and REE from the primary calcite and apatite to form strontianite and monazite(-Ce). These exsolution textures have subsequently been folded during ductile deformation of the dyke.

The monazite(-Ce) found within apatite along sub-parallel ‘corridors’, occurring together with strontianite, is associated with apatite that has lower content of Sr and REE as evident from the lower (darker) BSE intensity (Fig. 11). These strontianite and monazite(-Ce) crystals were likely exsolved from apatite along these sub-parallel zones. Prokopyev et al. (2017) observed similar exsolution textures in the Seligdar apatite deposit (Central Aldan, Russia) and suggested that late-stage chlorine-rich brines were responsible for the REE mobilization. Burtseva et al. (2013) also observed monazite(-Ce) coronas on apatite in the Khamambettu carbonatites (Tamil Nadu, India) and ascribed these textures to late-stage reactions. Harlov et al. (2002, 2003, 2005) conclude that monazite(-Ce) can form over a wide range of temperatures (300-900°C) and pressures (500-1000 MPa), but only in the presence of a fluid phase, which indicates that the monazite(-Ce) inclusions in the Attu carbonatite may be a product of fluorapatite/fluid interaction. The fluids responsible for REE transport and deposition are typically considered to have a high activity of ligands such as F, Cl and CO_2 (Williams-Jones et al. 2012; Broom-Fendley et al. 2016). However, recent experimental work has demonstrated the crucial role of the alkali metals (Na and K) and silica dissolved in such fluids (Anenburg et al., 2020).

Th-monazite(-Ce) found in aggregates together with strontianite as well as in “pearls on a string” textures inside apatite yield a 1492 ± 33 Ma U-Pb age (Fig. 15B), which is potentially younger than, but within uncertainty of, the proposed magma emplacement age of 1565 ± 56 Ma (Pb-closure temperature for monazite is approximately 700°C). Given that the above-described textures are related to solid-state unmixing during slow cooling, the potentially younger U-Pb age of the secondary monazite(-Ce) provides an estimate for the timescales of unroofing and cooling of the originally deep-seated carbonatite dyke. In other words, the U-Pb data imply that approximately 900°C hot carbonatite magma emplaced at deep crustal level (approximately 400°C at 10 km depth), with a subsequent dyke unroofing history on the order of tens of millions of years. The evidence presented so far suggests that although monazite(-Ce) is the main REE carrier in the Attu carbonatite rock, REE contents were also high in apatite and calcite during carbonatite magma crystallization, reinforcing our argument that the REE mineralization is mainly magmatic in nature.

6.2 Apatite compositions

Primary apatite in the Attu carbonatite is rich in Sr and REE (Table 4). There is simple substitution of Ca ⇔ Sr, whereas the amount of REE^{3+} is counterbalanced by monovalent Na in apatite:

$Na^{+} + REE^{3+} \Leftrightarrow 2\ Ca^{2+}$,

or coupled substitution of the type:

$Si^{4+} + REE^{3+} \Leftrightarrow P^{5+} + Ca^{2+}$.

Fluorapatite from the Attu carbonatite shows both types of substitution for the REE. Upon cooling, apatite exsolved lamellae of strontianite and monazite(-Ce), which sequestered a significant portion of the REE. In addition, CO_2 was probably also involved during REE mobilization from apatite. For this to occur, reactions with the surrounding primary carbonates or interactions with CO_2-rich fluids are necessary. The rims on and cracks in apatite have lower REE contents, also evident from their lower BSE intensity (Fig. 11). These zones in apatite host abundant monazite(-Ce) and strontianite inclusions. Similar observations were made by Prokopyev et al. (2017), who invoked hydrothermal brines to be responsible for the removal of REE from apatite to form monazite(-Ce) at the rims and along cracks in apatite.

6.3 REE carbonates as rock-forming minerals

REE carbonates such as alstonite, burbankite and daqingshanite occur as minor components in many carbonatites worldwide (e.g., Mitchell 2024). Inclusions of REE carbonates in other rock-forming minerals, such as burbankite in apatite or calcite, are reported by Chakhmouradian and Dahlgren (2021) from the Fen carbonatite complex in southern Norway. These authors interpreted the exotic inclusions as primary crystals subsequently overgrown by calcite, dolomite and apatite. In contrast, Platt and Woolley (1990) interpreted similar inclusions in dolomite from the Chipman Lake carbonatite as precipitated from an immiscible fluid.

The REE carbonates alstonite, burbankite and daqingshanite are major rock-forming phases in the Attu carbonatite (Figs. 5, 6, 7, 8), together with strontianite, calcite, dolomite and barite. The carbonatite rocks typically show a fabric with parallel alignment of these minerals (Fig. 5). They are intimately intergrown and appear to define a tectonic foliation rather than crystal alignment due to magmatic flow (i.e., a tectonic rather than magmatic foliation).

6.4 Exsolution textures among the carbonate minerals

A feature that distinguishes the Attu carbonatite from most other carbonatite occurrences worldwide is the wealth of different exsolution textures among the Sr-, Ba- and REE-bearing carbonates and phosphates. We identified at least 8 different exsolution textures in the carbonates from the Attu carbonatite. In general, exsolution textures in carbonatites are fairly common; for example, droplets of dolomite in calcite, as well as burbankite and ancylite in calcite (Qaqarssuk carbonatite in West Greenland; Knudsen, 1991), drop-like inclusions of burbankite in calcite (Khibina carbonatite in

NW Russia; Zaitsev et al. 1998), and calcite with exsolution lamellae of carbocernaite (Rajasthan carbonatite in India; Wall et al. 1993). In the latter example, the exsolution blebs and lamellae of carbocernaite and strontianite in Sr-rich calcite were interpreted as features that formed upon cooling and pressure decrease (Wall et al. 1993), which was probably a consequence of unroofing of this carbonatite dyke. This model is supported by the mineral compositions of the carbonatite dyke, which indicate a purely magmatic crystallization with only little or no evidence for hydrothermal overprinting (Wall et al. 1993).

For the Attu carbonatite in West Greenland, the very wide range of REE-, Ba- and Sr-rich carbonates exsolving from each other suggests that the precursor carbonates started crystallization at high temperatures and pressures above a miscibility gap where incorporation of the REE, Ba and Sr was possible. Unfortunately, there are at present no experimental data to constrain the precise conditions at which this may have occurred, but deep crustal levels are implied (>10 km depth), also on the basis of the ductile (shear) deformation of the Attu carbonatite rocks. It is considered likely that the carbonatite was injected as a very REE-, Sr- and Ba-rich melt from which the precursor REE-, Sr- and Ba-rich minerals crystallized together with monazite(-Ce) phenocrysts and Sr-REE-rich apatite. From the latter phase, monazite(-Ce) and strontianite were exsolved during exhumation of the Precambrian metamorphic basement of West Greenland.

6.5 The Attu carbonatite in a regional geological context

The Archaean to Paleoproterozoic basement of southern West Greenland was deformed and metamorphosed during the extensive Nagssugtoqidian orogeny at ca. 1850 Ma. Emplacement of the Attu carbonatite occurred much later at ca. 1565 Ma, and to the best of our knowledge no major regional tectonic event, such as continental rifting, is known from the greater region during this time. The only other known igneous events that affected the study region belong to the late phase of the Nagssugtoqidian orogeny, such as ca. 1750 Ma old lamprophyres and lamproites (Marker and

Knudsen 1989; Larsen and Rex 1992), as well as granitic pegmatites at ca. 1770 Ma (Willigers et al. 2001) and also at 1676 Ma (Connelly et al. 2000). Although this may appear surprising at first glance, global databases for carbonatites (Woolley and Kjarsgaard 2008; Humphreys-Williams and Zahirovic 2021) and kimberlites (Tappe et al. 2018) reveal frequent decoupling of such deep-sourced CO_2-rich magmatism from large-scale tectonic events, which testifies to their dominant intraplate character and an association with unusually thick and stable continental lithosphere. To date, no associated igneous silicate rocks have been identified to accompany the Attu carbonatite dyke, which suggests that – based on global statistics (e.g., Woolley and Kjarsgaard 2008) – the study region is underexplored for carbonatites and related rocks. For example, in other parts of Greenland and eastern Canada, carbonatite intrusive bodies typically do not occur in isolation but are accompanied by coeval kimberlites (Nielsen et al. 2009; Tappe et al. 2017), aillikites (Tappe et al. 2006, 2008, 2012; Secher et al. 2009), melilitites-nephelinites (Nielsen and Buchardt 1985; Gudelius et al. 2023), as well as phonolites and syenites (Andersen 1997; Finch et al. 2001; Hutchison et al. 2021). Given the very high contents of REE-Sr-Ba in the Attu carbonatite dyke, which we ascribe to a magmatic origin, one may look at a highly fractionated endmember composition that likely evolved from less enriched calcite- or dolomite carbonatite magmas and associated silicate melts. An interesting feature of the Attu carbonatite is that the plentiful exsolution textures developed both before and after the deformation that led to the prominent foliation of the rock. This suggests carbonatite magma emplacement into and crystallization within an active shear zone at deep crustal level (>10 km depth), an inference that may guide continued rare-metal exploration efforts in West Greenland and similar Precambrian basement provinces worldwide (Goodenough et al. 2016). The full size of the Mesoproterozoic intrusion near Attu is currently unknown and further exploration work is required to understand the extent of this newly discovered carbonatite-hosted REE mineralization.

Commented [ST1]: Hutchison, W., Finch, A.A., Borst, A.M., Marks, M.A.W., Upton, B.G.J., Zerkle, A.L., Stüeken, E.E., Boyce, A.J., 2021. Mantle sources and magma evolution in Europe's largest rare earth element belt (Gardar Province, SW Greenland): New insights from sulfur isotopes. Earth and Planetary Science Letters 568, 117034.

7 Conclusions

The Attu carbonatite dyke is composed of carbonates such as Sr-rich calcite, Sr-rich dolomite, strontianite, alstonite, burbankite and daqingshanite, as well as of phosphates such as monazite(-Ce) and apatite. Monazite(-Ce) phenocrysts and monazite(-Ce) related to exsolution textures are dated to 1565 ± 56 Ma and 1492 ± 33 Ma, respectively. At the dyke contact to the country rocks, the content of mafic silicates, mainly Ba-rich phlogopite in glimmerite domains, increases and developed into a fenite zone.

Individual mineral phases have compositions that are dominated by extremely high contents of Sr, Ba and REE, probably due to high formation temperatures, rendering this deposit primary magmatic in nature. The very REE-, Sr- and Ba-rich carbonate minerals were unstable during cooling, and a wealth of exsolution textures developed in calcite, burbankite, strontianite and dolomite as well as in apatite. Chondrite-normalized REE distributions show an overall LREE enrichment as is typical for carbonatites. There is a slight MREE enrichment, which we interpret as a consequence of monazite(-Ce) and apatite accumulation in the dyke. However, the very high contents of Sr and REE in apatite indicate that the carbonatite magma was extraordinarily enriched in these elements.

Despite the very high REE concentrations, the economic potential of the Attu carbonatite appears to be small because the deposit has a limited tonnage based on current geological data. However, this sparsely explored region in West Greenland may host similar deposits and comprise an important carbonatite-related REE district (cf., Mott et al. 2013).

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Figure captions

Figure 1 Location of the Attu carbonatite dyke on the geological map of West Greenland. The carbonatite is marked with an asterisk.

Figure 2 Illustrations of the mode of occurrence of the newly discovered Attu carbonatite dyke:

A) View of the locality from SE. The carbonatite dyke is ca. 1 m wide at this location.

B) View of the locality from above. The carbonatite has apophyses into the meta-dolerite wall-rock. The yellow stain in the circled area is tied to ankerite-rich veins. The position of sample 463374 is indicated.

C) Pink carbonatite with a black reaction rim (above hammer) that is composed of >90 vol.% dark mica (glimmerite) within the surrounding gneiss.

D) Small carbonatite vein and pink carbonate in the altered wall-rock consisting of glimmerite. The position of sample 463373 is indicated.

Figure 3 Detail of the central part of the carbonatite dyke, mainly consisting of pink calcite and light red monazite(-Ce). Calcite hosts exsolved rows of minute pink strontianite grains. Black opaque crystals are Fe-oxide minerals. Matchstick for scale.

Figure 4 Electron backscatter photomicrograph of sample 463370 (center of dyke). Large apatite crystals in a carbonate matrix (more details in Figure 5). There is a bright rim on apatite consisting of strontianite and monazite(-Ce). The apatite crystal has exsolved strontianite and monazite(-Ce) seen as “pearls on a string” (Fig. 6). The carbonatite contains Ba-rich phlogopite, monazite(-Ce) and ilmenite. The Ba-rich phlogopite is slightly deformed. In the upper right part of the photomicrograph, parallel arrangement of strontianite in a schlieren-like texture is seen in medium-grained calcite and burbankite aggregates (a), as well as in a fine-grained calcite-burbankite aggregate (b).

Figure 5 False colour electron backscatter photomicrograph of sample 463369 (center of dyke). Foliated REE-rich carbonatite consisting of calcite (dark blue), strontianite (light blue), burbankite (green), alstonite (yellow), daqingshanite (orange) and barite (red). A tectonic foliation is defined by parallel arrangement of alstonite, burbankite, calcite and daqingshanite crystals. Calcite contains composite lamellae of alstonite, daqingshanite and barite. Strontianite contains blebs of alstonite and daqingshanite. This image was generated by assigning colours to the different grey levels of the original backscatter electron image.

Figure 6 Electron backscatter photomicrograph of the carbonate textures in sample 463370 (dyke center; enlargement of Figure 4). The darkest mineral is dolomite exhibiting small exsolution blebs of strontianite in the central parts of the grains. Calcite is slightly brighter and shows perthite-like exsolution patterns of light grey alstonite. The large medium grey crystals are burbankite, light grey crystals are strontianite and the white crystals are monazite(-Ce).

Figure 7 False colour electron backscatter photomicrograph of sample 463369 (dyke center; enlargement of Figure 6). Strontianite (light blue) contains blebs of alstonite (yellow), some of which also contain minor blebs of daqingshanite (orange). Alstonite exhibits elongated lamellae of daqingshanite along cracks or crystallographic directions. This image was generated by assigning colours to the different grey levels of the original backscatter electron image.

Figure 8 False colour electron backscatter photomicrograph of sample 463369 (dyke center; enlargement of Figure 6). Calcite (dark blue) contains elongated exsolution lamellae of a Mg-Ba carbonate. Burbankite (green) contains elongated parallel exsolution lamellae of daqingshanite. This image was generated by assigning colours to the different grey levels of the original backscatter electron image.

Figure 9 Electron backscatter photomicrographs of carbonatite samples from the Attu dyke:

A) Large monazite(-Ce) (Mz) and magnetite (Mt) crystals set in a carbonate matrix in sample 463371 (dyke center). Within the carbonates, elongated strontianite crystals form a folded schlieren-like pattern (more details in Panel B).

B) Elongated strontianite (white) in calcite (medium grey) and dolomite (dark grey). The brighter parts of the calcite have higher contents of Sr, Ba and REE.

C) Large euhedral monazite(-Ce) (Mz), magnetite (Mt) and calcite crystals with exsolution of strontianite (more details in Panel D; #463373 dyke center).

D) The exsolution blebs in the upper right calcite crystal consist of a Mg-Ba carbonate, whereas the exsolution lamellae in the lower left calcite crystal have strontianite composition, following two crystallographic orientations in the calcite host (lower left).

Figure 10 Electron backscatter photomicrograph of sample 463369 (center of dyke). Approximately 1-5 µm thin folded lamellae of strontianite occur in calcite. The larger, irregular, light grey areas consist of strontianite with cores of monazite(-Ce). The lighter grey areas in calcite have higher contents of Sr relative to the darker areas.

Figure 11 Electron backscatter photomicrograph of sample 463370 (center of dyke; enlargement of Figure 4). Large apatite crystal with a corona consisting of strontianite (light grey) and monazite(-Ce) (white). Within the apatite crystal, rows of monazite(-Ce) and strontianite grains form an irregular pattern especially in the darker areas of the apatite. Needle-shaped strontianite follows a ‘N-S’ orientation in the apatite host, which presumably presents crystallographically controlled exsolution. The darker apatite domains are depleted in heavy elements such as Sr and REE relative to the brighter apatite domains. The thin ‘N-S’ vein is composed of barite. The dark mineral to the left is dolomite.

Figure 12 Electron backscatter photomicrograph showing complex zoning in a large monazite(-Ce) crystal from carbonatite sample 463369 (center of dyke). Alternating grey-levels characterize the core of the monazite crystal, whereas the rim shows slightly lower BSE intensity. The entire crystal is cut by 5 to 20 µm wide sector zones with a brighter shade of grey oriented parallel to a cleavage plane in the monazite host. The BSE grey-level mainly reflects Th variations.

Figure 13 Electron backscatter photomicrograph of country rock sample 463374. Large allanite crystal together with smaller allanite grains along rock-forming silicate grain boundaries. Ankerite crystals and veins are also present within the country rock.

Figure 14 REE normalized to chondrite in representative samples from the Attu carbonatite. Samples 463369, -70, -71, -72 are taken from the carbonatite dyke. Sample 463373 represents the transition from the carbonatite dyke into the wall-rock. Sample 463373 represents fenitized basement rock with ankerite veins. Chondrite values are from Sun and McDonough (1989).

Figure 15 Tera-Wasserburg concordia diagrams showing the LA-ICP-MS U/Pb data for monazite(-Ce) from the Attu carbonatite in southern West Greenland. Primary monazite(-Ce) in Panel A is from samples 463369 and 463371, whereas secondary monazite(-Ce) in Panel B is from samples 463370 and 463373.

Table captions:

Table 1	Geochemical analyses of representative samples from the Attu carbonatite dyke
Table 2	Representative chemical compositions of carbonate minerals
Table 3	Representative chemical compositions of daqingshanite
Table 4	Representative chemical compositions of burbankite
Table 5	Representative chemical compositions of apatite
Table 6	Representative chemical compositions of monazite(-Ce)
Table 7	Representative chemical compositions of silicate minerals

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