Robust U-Pb baddeleyite ages of mafic dykes and intrusions in southern West Greenland: constraints on the coherency of crustal blocks of the North Atlantic Craton

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Sammanfattning

Sydvästra Grönlands arkeiska berggrund (North Atlantic Craton, NAC) intruderades av ett stort antal mafiska intrusioner och diabasgångar under arkeikum och proterozoikum, vars åldrar är dåligt kända. Detta arbete omfattar dateringar av fem intrusioner med U-Pb metoden av mineralen zirkon och baddeleyit från tre olika generationer av mafiska bergarter. En mafisk-ultramafisk lagrad intrusion i Fiskefjordregionen ger en U-Pb zirkon ålder på 2990,1 ± 13 Ma. Tre diabasgångar med västnordvästlig riktning i den södra delen av studieområdet, här benämnda MD3 gångar, ger åldrar på 2050,2 ± 2,0 Ma, 2040,7 ± 3,1 Ma och 2029,0 ± 3,0 Ma. Den äldsta diabasgången provtogs sydost om Ameralik Fjord och daterades till 2499,2 ± 1,2 Ma, snarlikt en tidigare rapporterad ^{40}Ar/^{39}Ar ålder för en diabasgång i Kangâmiutområdet. Jag föreslår att termen Qarliit Nunaat används för diabasgångar av åldern c:a 2500 Ma i syfte att särskilja dessa från 2050-2030 Ma Kangâmiut gångar med liknande orientering. I detta arbete diskuteras möjligheten att MD3 gångarna och Kangâmiut gångarna på sydvästra Grönland tillsammans med Iglusuataliksuakgången i Nain, Kanada, tillhör samma radierande gångsvärmsystem som påvisar en mantelplyms ankomst i västra marginalen av NAC. Vidare presenteras magmatiska "barcodes" för NAC (uppdelat i en grönländsk och en kanadensisk del) som uppvisar stora likheter med nordöstra Superior, med exakta åldersinpassningar vid 2500, 2214, 2050-2030, samt 1950 Ma. Åldersdata för magmatiska intrusioner tillsammans med diabasgångarnas orientering används för en möjlig, om än spekulativ, rekonstruktion av NAC jämsides Superiors nordöstra marginal under senarkeikum till paleoproterozoikum.

Abstract

The Archaean bedrock of southern Greenland (the North Atlantic Craton) is host to a large number of mafic intrusions and dyke swarms. This study present a robust U-Pb zircon age of 2990.1 ± 13 Ma for a mafic-ultramafic layered intrusion in the Fiskefjord region and four baddeleyite U-Pb ages of doleritic dykes that range between c. 2500 and c. 2050-2030 Ma. The dyke located SE of Ameralik Fjord is dated at 2499.2 ± 1.2 Ma, similar to a previously reported ^{40}Ar/^{39}Ar age of a dyke in the Kangâmiut area. The name Qarliit Nunaat is proposed for c. 2500 Ma dykes in order to distinguish them from intermixed 2050-2030 Ma Kangâmiut dykes with similar trends. Three WNW-trending dykes in the south, herein referred to as MD3 dykes, yield ages of 2050.2 ± 2.0 Ma, 2040.7 ± 3.1 Ma and 2029.0 ± 3.0 Ma. The results of this dating survey suggest that the MD3 dykes and the Kangâmiut dykes on SW Greenland along with the Iglusuataliksuak dyke of the Nain Province belong to the same system of a radiating swarm that manifest the arrival of a mantle plume centered on the western margin of the North Atlantic Craton. Comparison of magmatic barcodes from the Nain and Greenland portions of the North Atlantic Craton show matches at 2500, 2214, 2050 -2030, 1950 Ma to the northeastern Superior Craton. Together with age constraints based on dyke swarm trends we offer a tentative reconstruction of the North Atlantic Craton against the northern eastern margin of the Superior Craton (near the Cape Smith belt) in the late Archaean-Palaeoproterozoic.

1. Introduction

The collective masses of Archaean coastal bedrock exposures in Labrador, western and eastern South Greenland, and the Lewisian complex of Scotland together comprise the North Atlantic Craton (NAC). These crustal blocks are considered likely to have been positioned adjacent to each other during a significant period from the Late Archaean to the late Mesozoic and Paleogene, when they began to disconnect by mantle plume activity and seafloor spreading in the Labrador Sea and North Atlantic regions. The NAC has been intruded by numerous generations of mafic dyke swarms, evident from different trends and cross-cutting relationships (Nielsen, 1987). Only a subordinate number of these dykes have been dated by modern radiometric techniques such as U-Pb on zircon and baddeleyite (Fig. 3).

Although the general associations between Archaean and Proterozoic units in the NAC have been long-studied, little attention has been focused on the geometries of the basic dyke swarms and their precise geochronology in the context of Precambrian plate reconstructions. In this study, I present robust emplacement ages from several units and integrate these results with previously published ages from southern West Greenland and the Nain Province. The approach taken suggests the existence of a possible 2050-2030 Ma mantle plume centered on the eastern margin of the Nain Province. A tentative Palaeoproterozoic reconstruction of the North Atlantic and northeastern Superior cratons is presented.

2. Geological Setting

The study area is part of the Archaean NAC and is located in southern West Greenland between the Nuuk and Fiskenæsset districts (Fig. 1). Studies of protolith ages and the timing of metamorphic events in Archaean basement units characteristic of discrete terranes or blocks have permitted correlations with equivalent units in the Nain Province of Labrador (see summary by Wasteneys et al., 1996). Correlations between South-East Greenland and the Lewisian Complex of northwest Scotland have been proposed with reference to similarities in the basement and supracrustal rocks (Kalsbeek et al., 1993 and references therein). More recently, Mason and Brewer (2004) suggested that the Lewisian Complex is best considered as a mostly reworked domain of the NAC, probably best correlated with the Nagssugtoqidian orogen.

In Greenland, the Archaean NAC is bounded by the Nagssugtoqidian fold belt in the north and the largely juvenile Palaeoproterozoic accreted arc of the c. 1.8 Ga Ketilidian orogen in the south (Fig. 1). The Nuuk district consists of several distinct Archaean terranes recognised by lithological associations, constrasting ages and metamorphic grade, and which are separated by faults and mylonite zones. The amalgamation of these terranes has proven to be a complex series of crustal accretion events from c. 2950 Ma (Friend and Nutman, 2005) to c. 2600 Ma (Nutman and Friend, 2007).

2.1. Ultrabasic intrusions in the Fiskefjord area

In the Fiskefjord area north of Nuuk, two large layered complexes consisting of ultrabasic, noritic and metagabbroic rocks are intruded into supracrustal rocks (Garde 1997), or between supracrustal rocks and their gneissic basement. One complex, the Amikoq intrusion, extends for c. 25 km in a N-S direction across central Fiskefjord. These km-scale deformed bodies of mafic-ultramafic rocks may be fragments of a larger layered intrusive complex or complexes. The Amikoq complex consists of long lenses (10's to several 100's of m) or thick layers of olivine-rich ultrabasic rocks enclosed in a disrupted sheet of layered leuconorites a few 10's of m thick but occasionally up to 150 m. The leuconorites are interlayered with a relatively minor volume of pegmatoidal feldspathic pyroxenite that comprises several continuous or contiguous units or layers generally 0.5-7 m thick, and a spectacularly exposed c. 80 m thick layered sequence occurs at the southern margin of Amikoq. The upper and lower contacts of these units with the adjacent leuconorites are sharp and magmatic despite regional deformation, such that the dominant leuconorites and lesser feldspathic pyroxenites represent a layered sequence. Several feldspathic pyroxenite units can be followed over hundreds of metres, and many of the thinner units are observed to pinch out. The relationship of the olivine-rich ultramafic units to the leuconorites is unclear and is currently being investigated by NunaMinerals A/S. There is no observable evidence of intrusion of one lithology into the other, partly due to slight shearing of the contacts. While the ultramafic and noritic rocks have some shared geochemical characteristics, their spatial relations are not conclusive. For example, large ultramafic lenses occur in the amphibolites and are visually identical to the ultramafics enclosed by leuconorites, but no leuconorite occurs within the amphibolites. Rather, the leuconorites are observed at one location to intrude against the 'roof' of amphibolites. This raises a number of possible intrusive and tectonic scenarios that will be partially or completely resolved by absolute age determinations.

2.2. Inaluk, Tarssartôq and Ameralik dyke swarms

The Isukasia terrane, previously regarded as the northernmost part of the Færingehavn terrane (Friend and Nutman, 2005), contains well-preserved 3.8-3.7 Ga supracrustal rocks (the Isua greenstone belt: cf. Appel et al., 1998) as well as some of the oldest known mafic dyke swarms.

Intrusions known as the Inaluk and the Tarssartôq dyke swarms are found within the Isukasia terrane (Nutman et al., 1983). Despite the Paleoarchaean age of the dyke swarms in the Isukasia area, they are remarkably well preserved and have therefore been studied in some detail (e.g. Appel et al.,

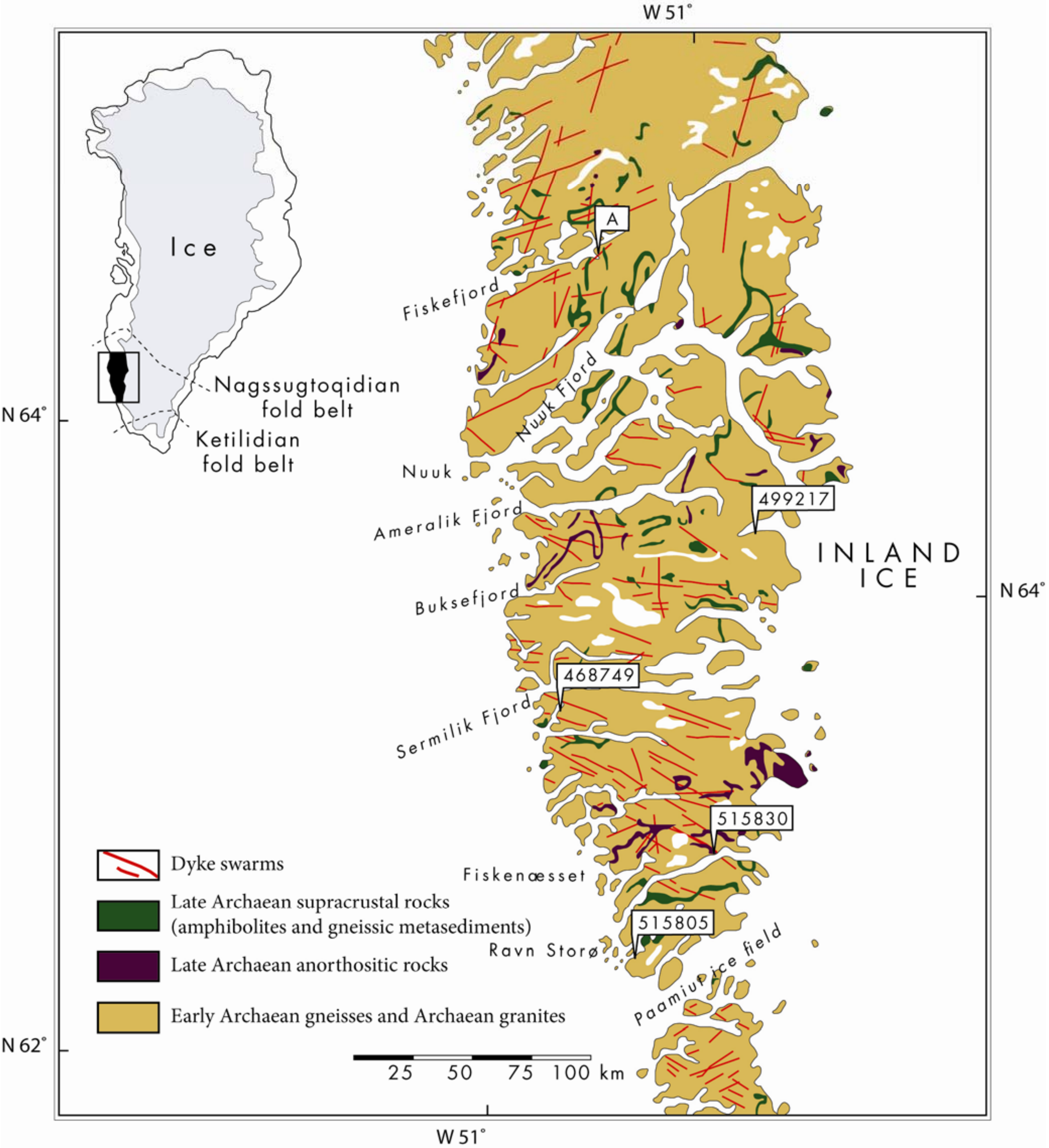


Figure 1. Simplified geological map of SW Greenland showing the occurrences and principle trends of mafic dykes and sample locations. Modified after Escher and Pulvertaft (1995) and Hall and Hughes (1987).

1998, White et al., 2000). Previous U-Pb investigations of Inaluk and Tarssartôq dykes gave intrusion ages at 3659 ± 2 Ma and 3490 ± 2 Ma (Crowley et al., 2000) respectively. The Inaluk dykes are generally 20 cm to 4 m wide and folded (White et al., 2000). The Tarssartôq dykes have E-W and N-S trends (White et al., 2000) and are sometimes referred to as the Ameralik dykes (Nutman et al., 2004). Dykes known as Ameralik dykes in the Isukasia terrane have been assigned an age of c. 3500 Ma (White et al., 2000; Nutman et al., 2004 and references therein) using a variety of radiometric methods. The Ameralik dykes of Isukasia are well preserved, unlike their namesake further to the south, which is why the term Tarssartôq dykes was introduced for the better preserved dykes in the Isukasia terrane (Nutman et al., 2004).

The gneisses in the vicinity of Nuuk Fjord and Ameralik Fjord are characterised by numerous inclusions of metabasite. These metabasite fragments are believed to represent the relicts of dolerite intrusions commonly referred to as the Ameralik dykes. The fragmentation of diabase occurred during an event reaching amphibolite facies metamorphic conditions during which these rocks were transformed into lensoid, boudinaged or tabular fragments that bear little or no resemblance to their origin (McGregor, 1973, cited in Nutman et al., 2004). The name of the dykes has caused some confusion as Ameralik dykes show a significant diversity in protolith age, ranging from c. 3.51 to c. 3.25 Ga (Nutman et al., 2004). Nutman et al. (2004) suggested that the Ameralik dykes should be referred to as the Ameralik dyke swarms.

2.3. Kangâmiut Dykes

The gneisses in the southern foreland of the Nagssugtoqidian Orogen have been intruded by at least two generations of mafic dykes (Willigers et al., 1999). The dykes are collectively termed the Kangâmiut Dykes and are dominated by NNE- and E-trending orientations in the southern foreland, but a progressive reorientation of the dyke swarm into an ENE orientation can be seen in the southern part of the orogen (Willigers et al., 1999). Three NNE- to NE-trending Kangâmiut dykes yielded U-Pb zircon ages of 2036 ± 5 Ma and 2046 ± 8 Ma (Nutman et al. 1999) and 2048 + 4 / - 2 Ma (Connelly et al. 2000). Similar $^{40}Ar/^{39}Ar$ ages of Kangâmiut dykes were reported by Willigers et al. (1999) indicating that the crust cannot have been heated significantly after c. 2.04 Ga. Willigers et al. (1999) also reported a $^{40}Ar/^{39}Ar$ age of 2528 ± 25 Ma indicating the presence of older dykes within the Kangâmiut swarm. The trend of the older dykes is NNE and appears on the whole similar in the field to the c. 2.04 Ga dykes (Willigers et al., 1999).

The NNE- to E-trending Kangâmiut Dykes stretch beneath the Greenland ice cap from west to east, as implied by a dyke in SE Greenland dated at 2015 ± 15 Ma by U-Pb on zircon (Nutman et al., 2008) which is a reinterpretation of the 2048+/-17 Ma age quoted in Nutman et al. (1999). On basis of field relationships and rock associations, the dykes of SE Greenland have also been suggested to correlate to the Scourie dykes in the Lewisian complex of NW Scotland (Wright et al. 1973). However, geochronological data of Scourie dykes have yielded ages of 2418 +7/-4 Ma and 1992 +3/-2 Ma (Heaman and Tarney 1989).

2.4. 'BN' and 'MD' dyke swarm

Hall and Hughes (1987) recognised two swarms of dykes in southern West Greenland; the 'MD' dykes and the 'BN' dykes. The 'BN' dykes are defined as noritic with high MgO content (Hall and Hughes, 1987). Similarly, parts of the Kikkertavak dyke swarm of the Archaean craton of Labrador comprise high-Mg noritic dykes, and have been proposed to be geochemical equivalents to dykes of the 'BN' swarm (Cadman et al., 1997). Dating of a Kikkertavak dyke has yielded a U-Pb baddeleyite age of 2235 ± 2 Ma (Cadman et al., 1993).

According to Hall and Hughes (1987) dykes of the 'BN' swarm are typically vertical to subvertical, have a roughly N-S trend and are distributed in an area ranging from south of the Nagsuggtoqidian to north of Nuuk, although a few dykes occur as far south as Fiskenæsset (Fig. 1).

A number of subvertical 'MD' dykes occur in the southwestern part of the Archaean craton. The term 'MD' (metadolerite) has caused some confusion as not all dykes display a significant metamorphic overprint (Kalsbeek and Taylor, 1985). Three generations of 'MD' dykes have been recognised on the basis of cross-cutting relations; MD1, MD2 and MD3 (Chadwick, 1969, cited in Hall and Hughes, 1987). The trends of these suites vary from N-S for the MD1, NE-SW for the MD2 dykes and E-W to SE-NW for MD3 (Hall and Hughes, 1987, Buchan and Ernst 2004; GSC Map 2022A). Henriksen (2000) reports one c. 2150 Ma suite of MD dykes with tholeiitic composition based on the best age estimates available.

3. Geochronology

Samples selected for geochronology were provided by the Department of Geological Mapping, Geological Survey of Denmark and Greenland (GEUS). Isotopic analysis of baddeleyite-bearing samples was performed on a Finnigan Triton thermal ionisation multicollector mass spectrometer at the Museum of Natural History in Stockholm. For one sample (pegmatoidal feldspathic pyroxenite, "A") a few fragments were cut off from a large zircon crystal and analysed by laser ablation sector-field inductively coupled plasma mass spectrometry (LA-SF-ICPMS) at GEUS. Uranium-lead Concordia plots and age calculations were made using Isoplot version 3.0 of Ludwig (2003). The isotopic composition for correction of initial Pb was taken from the model of Stacey and Kramers (1975) at the age of the sample. All U-Pb ages are given at the 95% confidence level and are interpreted as the crystallization age of the sample.

3.1. Principles of the U-Pb method

Uranium has three naturally occurring isotopes; ^{238}U, ^{235}U and ^{234}U. All three isotopes are radioactive, and ^{238}U and ^{235}U both decays to stable isotopes of Pb, while the radiogenic product of ^{234}U is Th. ^{238}U decays to ^{206}Pb in steps of successive emission of alfa- and beta-particles which produces several intermediate daughters (e.g. radon and polonium), with ^{206}Pb being the final, stable product of the decay chain. In a similar manner, ^{235}U decays to the stable ^{207}Pb. The rate of accumulation of the radiogenic product is given by the half-life of the radioactive parent, i.e. the time required for the quantity of the radioactive isotope to decay to half of its initial value. As the half-life is constant, the decay is exponential. The isotopic compositions of the sample are determined on a mass spectrometer and U-Pb dates are calculated using assumed values of the initial isotopic composition of Pb. The exponential decay of ^{238}U and ^{235}U can be plotted against each other to define a *concordia curve*, which gives the ratios of $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ at any given time. The concordance of an analyzed fraction is expressed in percent, and any value less than 100% means that the fraction is discordant. For a concordant analyzed fraction, the $^{206}Pb/^{238}U$ age is indistinguishable from the $^{207}Pb/^{235}U$. For a discordant fraction, the ages obtained from the two systems will differ from each other. Concordance of the analyses are achieved only if the:

- mineral have remained a closed system, i.e. no U, Pb or intermediate daughters in the decay chain have been lost or gained.
- decay constants are accurate.
- corrections of initial and blank Pb isotope ratios are accurate.

Only in rare cases will a mineral remain a closed system with respect to U and Pb. Chemical weathering can lead to the loss of uranium, as U is a mobile element in oxidizing environments. Furthermore, radiation damage from the emission of alfa-particles facilitates loss of Pb and intermediate daughters.

The initial isotope ratios of Pb is a substantial factor only when dating young samples, as the U/Pb ratio is low for young samples. For Archaean rocks, the U/Pb ratio is higher and the initial Pb isotopic ratios will not significantly affect the calculated U-Pb age (Faure and Mensing, 2005).

U-Pb isotope analyses of dissolved mineral grains rarely give concordant ages. Rather, the analyzed fractions from the same rock typically plot below the Concordia line indicating varying variable Pb loss. Regression of the analyses through the discordant fractions generates a *discordia line*, that intersects the Concordia curve at two points, usually referred to as the upper and the lower intercept. The upper intercept correspond to the time of formation for the analyzed mineral, while the lower intercept theoretically represents the time of an event causing Pb loss. However, if the sample has been exposed to multiple episodes of Pb loss, the intercepts will represent false ages (Faure and Mensing, 2005).

Uranium is abundant in a large number of minerals, though only a few are well-suited for dating by the U-Pb method. Suitable minerals should incorporate trace amounts of uranium, have low initial concentrations of lead, and retain uranium and the final and intermediate products of the decay chains. Examples of minerals that comply with these conditions and in addition are abundant in different rock types are zircon ($ZrSiO_4$) and baddeleyite (ZrO_2). The crystal structure of zircon and baddeleyite allows U^{4+} to replace Zr^{4+}, whereas Pb^{2+} is excluded due to radius and charge (Faure and Mensing, 2005). The high U/Pb ratios makes both zircon and baddeleyite sensitive geochronometers.

A $^{238}U/^{235}U$ ratio of 137.88 is adopted by all geochronologists to avoid confusion, although rocks depleted of ^{235}U are known in the case of natural fission reactors. However, such natural fission reactors seem to be rare (Faure and Mensing, 2005). Due to the importance of uranium in the nuclear industry, the decay constant of U is known with greater accuracy than those of other radionuclides.

Zircon is a common accessory mineral in felsic igneous rocks and is the most frequently used mineral for U-Pb dating. Though not as frequently used, baddeleyite provides a robust tool for high-precision age determination of mafic rocks, as it is a common accessory mineral in silica-undersaturated rocks. Due to the stated properties of baddeleyite and improvement of separating techniques (see Söderlund and Johansson, 2002), U-Pb baddeleyite age determinations have become a routine technique for dating of mafic rocks.

3.2. Baddeleyite U-Pb TIMS

Samples for baddeleyite U-Pb geochronology were processed at the Department of Geology, University of Lund. A sample of c. 1 kg was sawed into c. 2 cm thick slices and then crushed by hand to cm-size pieces. A mill tray was used to produce a powder. The sample was suspended in water before loading onto a Wilfley table in small portions (c. 40 g) following the procedures of Söderlund and Johansson (2002). After c. 60 seconds the smallest and densest grains remaining on the deck were collected. After repeating this procedure 3 to 4 times, the magnetic minerals were removed from the sample using a pencil magnet. Baddeleyite grains of the best quality were handpicked under a binocular microscope.

A number of baddeleyite grains (3-10) of the best quality were combined and transferred to Teflon dissolution capsules. The grains were washed in nitric acid, successively rinsed in water and then spiked with a $^{236-233}U$-^{205}Pb isotopic solution. The grains were dissolved in a 10:1 $HF:HNO_3$ solution at 210° C overnight and then evaporated on a hot plate. The samples were redissolved in 10 drops 3.1 N HCl and loaded into 50 µl columns filled with anion resin. Zr (and Hf) was removed by 3.1 N HCl, after which U and Pb were washed out with H_2O and collected in the dissolution capsules. The samples were evaporated on a hot plate after adding a small amount of H_3PO_4.

Each sample was loaded onto an outgassed Re filament together with 2 µl silica gel. All peak intensities were measured using a Secondary Electron Multiplier (SEM) equipped with an RPQ filter in peak-switching mode: Pb and U isotopic data were collected in the temperature ranges 1190-1220°C and 1350-1400°C, respectively. During the analysis pe-

Table 1. U-Pb baddeleyite TIMS data

Sample	Fraction	Number of grains	Pbc/ Pbtot 1)	^{206}Pb/ ^{204}Pb	^{207}Pb/ ^{235}U	± 2s % err	^{206}Pb/ ^{238}U	± 2s % err	^{207}Pb/ ^{235}U	^{206}Pb/ ^{238}U	^{207}Pb/ ^{206}Pb	± 2s	Concord-ance
				meas 2)	[corr] 3)					[Ma]			[%]
499217	a	3	0,019	3080	10,3784	0,21	0,45846	0,18	2469,1	2432,7	2499,2	1,6	0,97
	b	5	0,028	1978	10,3916	0,22	0,45920	0,19	2470,3	2436,0	2498,6	1,7	0,97
	c	5	0,083	629	9,7381	0,32	0,42991	0,29	2410,3	2305,3	2500,2	2,1	0,89
	d	3	0,019	2835	10,6682	0,29	0,47080	0,27	2494,7	2487,1	2500,8	1,8	0,99
	e	3	0,037	1537	10,4273	0,30	0,46083	0,29	2473,5	2443,2	2498,4	1,5	0,97
515805	a	2	0,104	521	6,2524	0,67	0,35936	0,59	2011,8	1979,1	2045,5	5,3	0,94
	b	6	0,036	1557	6,5162	0,25	0,37357	0,23	2048,1	2046,2	2050,6	3,2	0,99
	b	6	0,051	1105	5,8452	0,39	0,33716	0,36	1953,1	1873,0	2039,2	2,6	0,90
515830	a	6	0,052	1028	6,6185	0,36	0,38173	0,26	2061,8	2084,3	2039,4	4	1,02
	b	4	0,126	395	6,3352	1,19	0,36556	1,14	2023,3	2008,5	2038,5	5,5	0,96
	c	4	0,019	3058	6,5995	0,24	0,37979	0,20	2059,3	2075,3	2043,2	2,2	1,02
468749	a	6	0,037	1575	5,9474	0,31	0,34716	0,30	1968,2	1921,0	2018,2	1,9	0,94
	b	5	0,050	1166	5,3398	0,48	0,31534	0,46	1875,3	1766,9	1997,5	2,7	0,86
	c	9	0,099	570	4,6441	0,76	0,27804	0,73	1757,2	1581,5	1973,1	4,7	0,77

1) Pbc = common Pb; Pbtot = total Pb (radiogenic + blank + initial).
2) measured ratio, corrected for mass fractionation and spike.
3) isotopic ratios corrected for fractionation (0.1% per amu for Pb), spike contribution, blank (1 pg Pb and <1 pg U), and initial common Pb. Initial common Pb corrected with isotopic compositions from the model of Stacey and Kramers (1975) at the age of the sample.

riod, the SEM detector's mass discrimination correction factor was constant at 0.1% per atomic mass unit. Common lead correction was performed assuming an initial Pb composition taken from the model of Stacey and Kramers (1975) at the age of the sample. The uranium decay constant used is from Jaffey et al. (1971). The total procedural blank was estimated at 1 pg Pb and 0.2 pg U.

3.3. *Zircon LA-SF-ICPMS*

Two fragments from a single, c. 5-6 mm large zircon crystal from sample A were prepared for LA-SF-ICPMS analysis by mounting them in epoxy and polishing to their mid-sections. The mount was examined using backscattered electron and cathodoluminescence imaging in a scanning electron microscope to identify domains of pristine igneous growth and map inclusion-free zones.

The analytical method has been described in

Table 2. U-Pb Zircon LA-SF-ICPMS data

U (ppm)	Th/U$_{calc}$	^{206}Pb/^{204}Pb	^{238}U/^{206}Pb	±s (%)	^{207}Pb/^{206}Pb	±s (%)	Conc %	^{238}U/^{206}Pb$_{Ma}$	±s	^{207}Pb/^{206}Pb$_{Ma}$	±s
Sample A											
98	0,62	11099	1,73	2,4	0,2202	0,8	98	2937	56	2982	12
65	0,71	5758	1,75	2,6	0,2232	1,8	97	2915	60	3004	28
69	0,63	26476	1,73	1,9	0,2214	1,3	98	2935	44	2991	21
94	0,75	40552	1,84	4,6	0,2210	1,0	94	2795	105	2988	15
95	0,73	5554	1,78	2,3	0,2199	1,6	96	2871	52	2980	25
36	0,78	8869	1,66	5,9	0,2180	4,7	103	3046	143	2966	76
80	0,87	12861	1,77	2,7	0,2222	2,7	96	2886	63	2997	43
77	0,72	6446	1,70	1,9	0,2224	1,4	100	2988	46	2999	22
49	0,73	17983	1,72	1,8	0,2228	1,2	99	2958	43	3001	19
57	0,77	5805	1,72	2,2	0,2227	1,8	98	2953	51	3000	30
Plesovice standard											
1936	0,12	9796	18,0	1,5	0,0545	1,9	89	349	5	392	42
1819	0,12	11019	18,8	1,3	0,0551	1,5	80	334	4	418	34
1150	0,13	93277	19,0	1,6	0,0540	3,7	89	331	5	370	83
1031	0,11	8614	18,8	3,1	0,0544	1,7	86	334	10	389	38
808	0,10	99999	18,3	1,5	0,0536	1,7	97	344	5	354	39
750	0,10	35311	19,0	1,5	0,0537	2,4	93	331	5	357	55
1075	0,15	55934	19,2	1,6	0,0558	3,9	74	328	5	444	86
984	0,09	7154	18,6	1,5	0,0541	1,5	90	337	5	376	33
984	0,11	20354	19,1	3,6	0,0530	2,4	100	329	11	328	54
1050	0,12	8363	19,1	1,4	0,0541	2,9	88	330	5	377	64
2455	0,13	18665	18,3	1,2	0,0546	1,8	86	342	4	397	40
1064	0,11	4085	18,3	1,1	0,0532	1,5	102	343	4	338	35

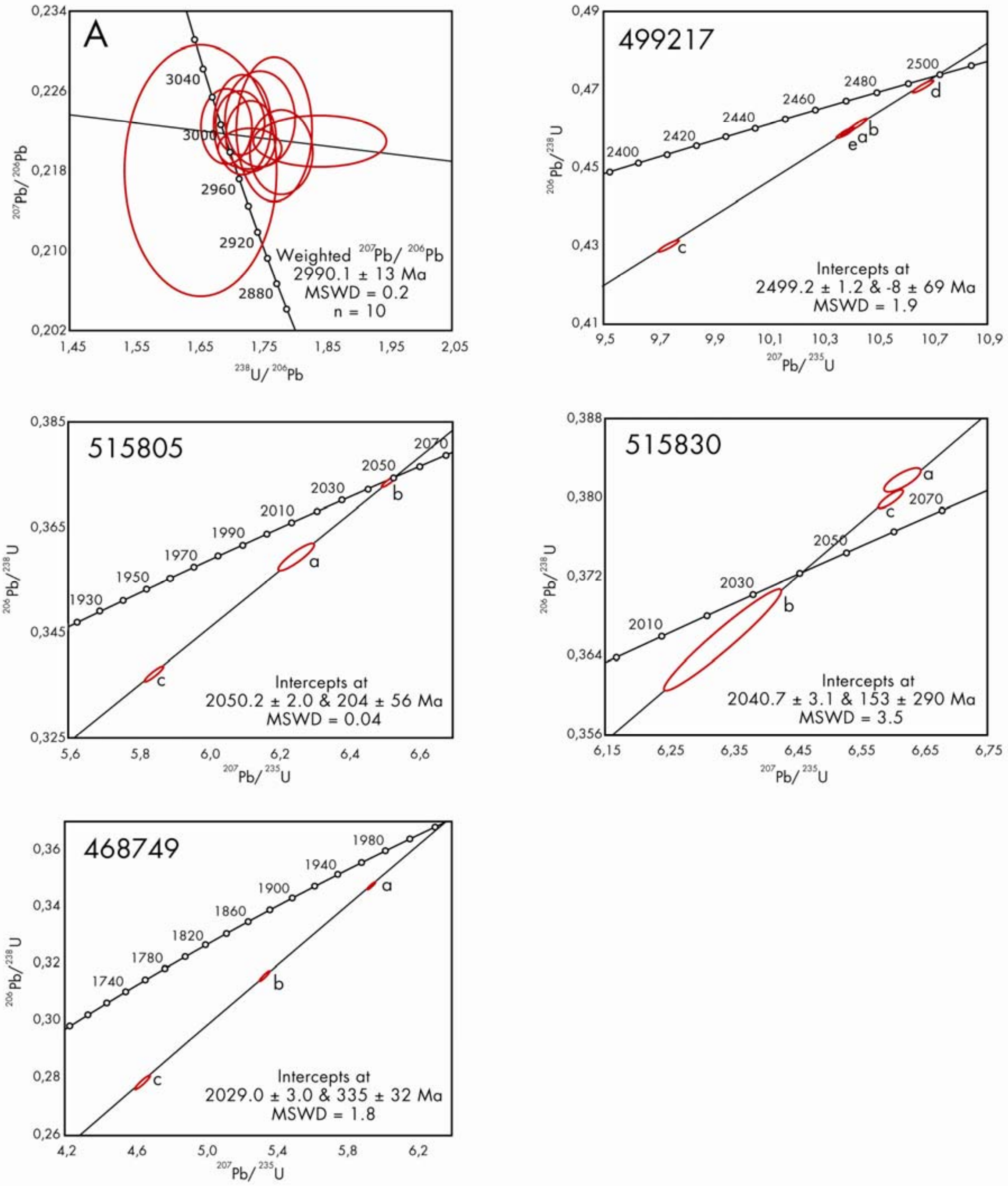


Figure 2. Tera-Wasserburg diagram of Sample A (the Amikoq intrusion) and U-Pb Concordia diagrams of 468749, 499217, 515803 and 515830, belonging to the MD3 and Qarliit Nunaat dykes.

detail by Gerdes and Zeh (2006) and Frei and Gerdes (2009), but a brief summary is given here. Samples and standards were mounted in a low-volume ablation cell specially developed for U-Pb-dating (Horstwood et al., 2003). Helium is used to flush the sample cell and is mixed downstream with the Ar sample gas of the mass spectrometer, which yields a washout time <5 s. A NewWave Research®/Merchantek® UP213 laser ablation unit equipped with a frequency quintupled ND-YAG laser emits a beam wavelength of 213 nm and pulse duration of 5 ns. We use a 10 Hz repetition rate and a nominal energy output of 45 %, corresponding to a laser fluency of 8 J/cm2. For the spot diameter (30 µm) and ablation times (30 s) used in this study, the ablated masses of zircon were approximately 150-300 ng. The ablated material is transferred in a carrier gas via Tygon® tubing into an Element2 (ThermoFinnigan®, Bremen) single-collector double focusing magnetic sector ICPMS, which is equipped with a fast field regulator for increased scanning speed. The total acquisition time for each analysis is 60 s of which the first 30 s are used to determine the gas blank. The instrument is tuned to give large, stable signals for the ^{206}Pb and ^{238}U peaks, low background count rates (typically around 150 counts per second for ^{207}Pb) and low oxide production rates

(^{238}U^{16}O/^{238}U generally below 2.5 %). ^{202}Hg, ^{204}(Pb + Hg), ^{206}Pb, ^{208}Pb, ^{232}Th and ^{238}U intensities were determined through peak jumping using electrostatic scanning in low resolution mode and with the magnet resting at ^{202}Hg. Each peak was determined at four slightly different masses and integrated sampling and a settling time of 1 ms for each isotope. Mass ^{202}Hg was measured to monitor the ^{204}Hg interference on ^{204}Pb where the ^{202}Hg/^{204}Hg = 4.36, which can be used to correct significant common Pb contributions. The laser induced elemental fractionation and the instrumental mass bias on measured isotopic ratios were corrected through standard-sample bracketing using the GJ-1 zircon (Jackson et al. 2004). Samples were analysed in sequences where three standards bracket each set of ten samples. The Plesovice zircon standard (Aftalion et al. 1989) has been used as an external reproducibility check, and yields long-term 2ó RSD precisions for the low volume cell used here (n=207) of 4.2% and 1.7% for ^{206}Pb/^{238}U and ^{207}Pb/^{206}Pb ratios respectively (Frei & Gerdes, 2009). Data for Plesovice from the analytical session when the Amikoq sample was analysed is reported in Table 2. Propagated 2σ errors ranged between 1.1 and 3.6 for ^{206}Pb/^{238}U and 1.5 and 3.7 for ^{207}Pb/^{206}Pb, which is slightly lower than the long-term reproducibility for ^{206}Pb/^{238}U, but similar to the ^{207}Pb/^{206}Pb. A concordia calculation for the Plesovice spots suggest excess scatter using these error estimates, while a more conservative error estimate with twice the error for all ratios yield a Concordia age of 338.0 ±3.7 Ma, and a weighted average ^{206}Pb/^{238}U-age of 337.1 ±4.4 Ma (MSWD = 2), which is in excellent agreement with the accepted age for the Plesovice zircon and reported LA-ICP-MS precision (Aftalion et al. 1989; Frei and Gerdes, 2009). We therefore use these more conservative error estimates and double the analytical age error for the Fiskefjord pyroxenite.

4. Results

The U-Pb data are listed in Table 1 (TIMS) and Table 2 (LA-SF-ICPMS) and age diagrams are shown in Figure 2. Ages, trends and coordinates are summarized in Table 3. The sample sites are also shown in Figure 1.

Sample A is from a pegmatoidal feldspathic pyroxenite, which is part of the layered mafic-ultramafic Amikoq intrusion in the Fiskefjord region. Two zircon fragments dated with LA-SF-ICPMS yielded a weighted ^{207}Pb/^{206}Pb mean age of 2990.1 ± 13 Ma (MSWD = 0.2), based on 10 spot analyses.

Sample 499217 is from a doleritic dyke located SE of Ameralik Fjord, close to the margin of the inland ice. The trend of this doleritic dyke was not recorded. A selection of dark brown baddeleyite grains was separated and analysed. Regression of five variably discordant baddeleyite fractions yields an upper intercept age of 2499.2 ± 1.2 Ma (MSWD = 1.9).

Sample 515805 comes from a WNW-trending ophitic dolerite dyke with coarse-grained patches, located east of Ravn Storø. Relatively large, dark baddeleyite crystals were separated. Three fractions were analysed and gave an upper intercept age of 2050.2 ± 2.0 Ma (MSWD = 0.04).

Sample 515830, located c. 50 km NNE of sample 515805 is a subophitic, medium-grained dolerite dyke, also with a WNW-trending orientation. The width of the dyke is c. 30 m. Three fractions of relatively dark baddeleyite were analysed, and while two fractions are slightly reversely discordant, all three points are essentially collinear and define a discordia having an upper intercept age of 2040.7 ± 3.1 Ma (MSWD = 3.5).

Sample 468749 is from a 100-150 m wide, fine- to medium-grained doleritic dyke near Sermilik Fjord with a E-W-trending orientation. Regression of three analyses yields an upper intercept age of 2029.0 ± 3.0 Ma (MSWD = 1.8).

5. Discussion

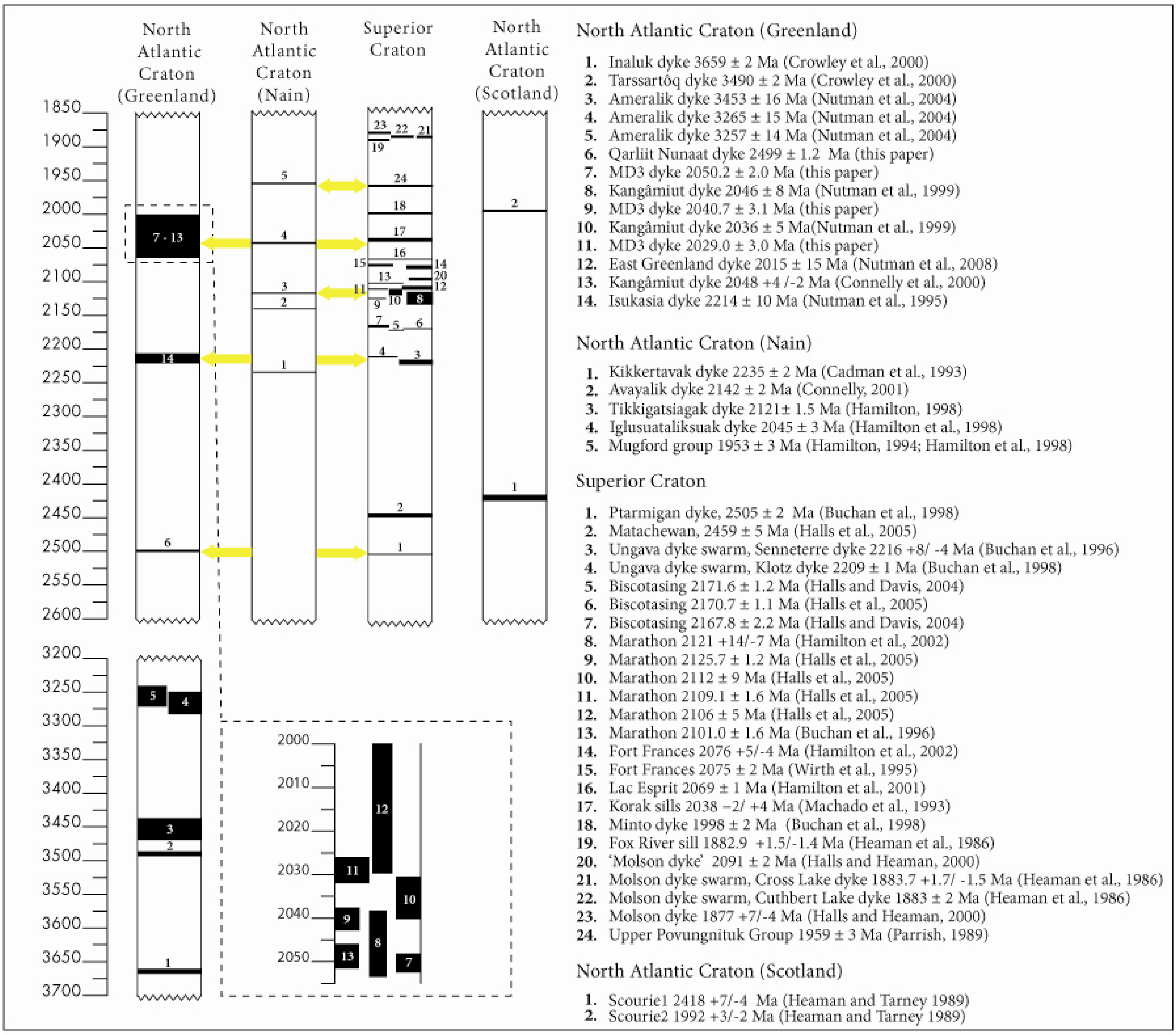
5.1. Mafic intrusions in the North Atlantic Craton of Greenland

Field relations between the feldspathic pyroxenites (Sample A) and the surrounding leuconorites suggest that these two lithologies belong to a continuous layered sequence, suggesting that the 2990.1 ± 13 Ma age of Sample A is the age of the whole sequence. However, new trace and rare earth element data indicate that the leuconorites in at least two parts of Amikoq are at very different stages of magmatic evolution (e.g. widely different Cr contents), despite their identical appearance (P. Armitage, pers. comm. 2009).

The 2499.2 ± 1.2 Ma age for sample 499217 lies close to the earlier reported ^{40}Ar/^{39}Ar age of 2528 ± 25 Ma (Williger et al. 1999) for a dyke located in the southern foreland of the Nagssugtoqidian Orogen, c. 250 km NNW of sample 499217. The same authors also presented ^{40}Ar/^{39}Ar ages of younger dykes in the same area, of which two gave typical Kangâmiut ages (c. 2028 Ma and c. 2021 Ma). As those dykes have

Table 3. Description of U-Pb dated samples

Sample name	Unit	Latitude	Longitude	Direction	Age, error (2s)
Sample A	Amikoq layered intrusion	64°55'40.65"N	51°25'37.89"W		2990.1 ± 13
499217	Qarliit Nunaat dyke	64° 6'42.34"N	49°51'7.66"W	Not recorded	2499.2 ± 1.2
515805	MD3 dyke	62°40'29.79"N	50°15'24.54"W	WNW	2050.2 ± 2.0
515830	MD3 dyke	63° 2'47.35"N	49°44'1.56"W	WNW	2040.7 ± 3.1
468749	MD3 dyke	63°25'52.58"N	51° 1'31.75"W	W	2029.0 ± 3.0



North Atlantic Craton (Greenland)

1. Inaluk dyke 3659 ± 2 Ma (Crowley et al., 2000)
2. Tarssartôq dyke 3490 ± 2 Ma (Crowley et al., 2000)
3. Ameralik dyke 3453 ± 16 Ma (Nutman et al., 2004)
4. Ameralik dyke 3265 ± 15 Ma (Nutman et al., 2004)
5. Ameralik dyke 3257 ± 14 Ma (Nutman et al., 2004)
6. Qarliit Nunaat dyke 2499 ± 1.2 Ma (this paper)
7. MD3 dyke 2050.2 ± 2.0 Ma (this paper)
8. Kangâmiut dyke 2046 ± 8 Ma (Nutman et al., 1999)
9. MD3 dyke 2040.7 ± 3.1 Ma (this paper)
10. Kangâmiut dyke 2036 ± 5 Ma(Nutman et al., 1999)
11. MD3 dyke 2029.0 ± 3.0 Ma (this paper)
12. East Greenland dyke 2015 ± 15 Ma (Nutman et al., 2008)
13. Kangâmiut dyke 2048 +4 /-2 Ma (Connelly et al., 2000)
14. Isukasia dyke 2214 ± 10 Ma (Nutman et al., 1995)

North Atlantic Craton (Nain)

1. Kikkertavak dyke 2235 ± 2 Ma (Cadman et al., 1993)
2. Avayalik dyke 2142 ± 2 Ma (Connelly, 2001)
3. Tikkigatsiagak dyke 2121± 1.5 Ma (Hamilton, 1998)
4. Iglusuataliksuak dyke 2045 ± 3 Ma (Hamilton et al., 1998)
5. Mugford group 1953 ± 3 Ma (Hamilton, 1994; Hamilton et al., 1998)

Superior Craton

1. Ptarmigan dyke, 2505 ± 2 Ma (Buchan et al., 1998)
2. Matachewan, 2459 ± 5 Ma (Halls et al., 2005)
3. Ungava dyke swarm, Senneterre dyke 2216 +8/ -4 Ma (Buchan et al., 1996)
4. Ungava dyke swarm, Klotz dyke 2209 ± 1 Ma (Buchan et al., 1998)
5. Biscotasing 2171.6 ± 1.2 Ma (Halls and Davis, 2004)
6. Biscotasing 2170.7 ± 1.1 Ma (Halls et al., 2005)
7. Biscotasing 2167.8 ± 2.2 Ma (Halls and Davis, 2004)
8. Marathon 2121 +14/-7 Ma (Hamilton et al., 2002)
9. Marathon 2125.7 ± 1.2 Ma (Halls et al., 2005)
10. Marathon 2112 ± 9 Ma (Halls et al., 2005)
11. Marathon 2109.1 ± 1.6 Ma (Halls et al., 2005)
12. Marathon 2106 ± 5 Ma (Halls et al., 2005)
13. Marathon 2101.0 ± 1.6 Ma (Buchan et al., 1996)
14. Fort Frances 2076 +5/-4 Ma (Hamilton et al., 2002)
15. Fort Frances 2075 ± 2 Ma (Wirth et al., 1995)
16. Lac Esprit 2069 ± 1 Ma (Hamilton et al., 2001)
17. Korak sills 2038 −2/ +4 Ma (Machado et al., 1993)
18. Minto dyke 1998 ± 2 Ma (Buchan et al., 1998)
19. Fox River sill 1882.9 +1.5/-1.4 Ma (Heaman et al., 1986)
20. 'Molson dyke' 2091 ± 2 Ma (Halls and Heaman, 2000)
21. Molson dyke swarm, Cross Lake dyke 1883.7 +1.7/ -1.5 Ma (Heaman et al., 1986)
22. Molson dyke swarm, Cuthbert Lake dyke 1883 ± 2 Ma (Heaman et al., 1986)
23. Molson dyke 1877 +7/-4 Ma (Halls and Heaman, 2000)
24. Upper Povungnituk Group 1959 ± 3 Ma (Parrish, 1989)

North Atlantic Craton (Scotland)

1. Scourie1 2418 +7/-4 Ma (Heaman and Tarney 1989)
2. Scourie2 1992 +3/-2 Ma (Heaman and Tarney 1989)

Figure 3. Barcode records of Archaean cratons. The width of individual bars corresponds to the 2 sigma error in radiometric

similar NNE-trending directions, Willigers et al. (1999) proposed the presence of at least two generations of dykes in the NNE-trending swarm in that area, both of which they named Kangâmiut dykes. Because of the significant age difference I propose that c. 2500 Ma dykes in SW Greenland should be called Qarliit Nunaat dykes.

The ages of 2050.2 ± 2.0 Ma, 2040.7 ± 3.1 Ma and 2029.0 ± 3.0 Ma for samples 515805, 515830 and 468749 are similar to previously published zircon ages of Kangâmiut dykes: 2036 ± 5 Ma, 2046 ± 8 Ma (Nutman et al., 1999) and 2048 + 4 / - 2 Ma (Connelly et al. 2000). However, the dykes investigated in the present study lie well outside the Kangâmiut region proper (i.e. within the Nagssugtoqidian Orogen and its southern foreland), from an area up to c. 500 km to the south. Furthermore, these dykes have W to WNW trends (Table 3) in contrast to the typical NNE to E trends of the Kangâmiut dykes. Based on their location and orientation, I assign these dykes to the MD3 swarm, described by Hall and Hughes (1987, and references therein). I conclude that the Kangâmiut and MD3 dyke swarms intruded simultaneously over a protracted period up to c. 35 Myr.

5.2. Reconstructions using the magmatic barcode record

Constraints on which crustal blocks, now dispersed, were once nearest neighbours can be estimated to some degree using the magmatic barcode record (e.g. Bleeker and Ernst, 2006). The preserved Archaean crust of southern Greenland has been correlated with NW Scotland and eastern Canada, the latter being

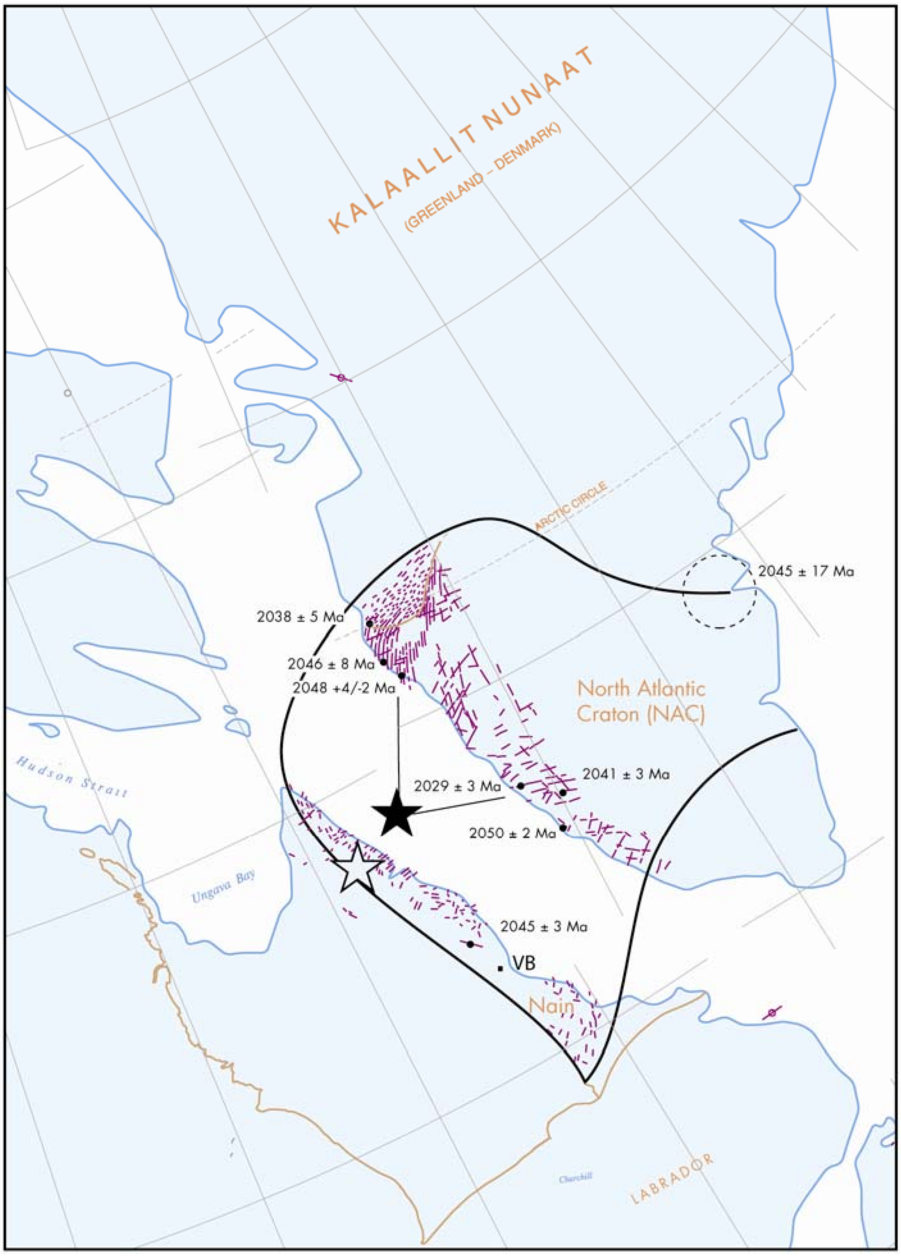


Figure 4. Distribution of Paleoproterozoic dykes associated with the North Atlantic Craton (from Buchan and Ernst 2004) in the Pre-Mesozoic configuration of Greenland and Labrador according to the reconstruction of Roest and Srivastava (1989). If there were some unaccounted crustal extension within the thinned and rifted margins, then the closure of the Labrador Sea could be more complete and the filled star marking the convergence of Kangâmiut and MD3 dykes could reach the western margin of the North Atlantic Craton (on the western margin of the Nain province; see hollow star). The proposed reconstruction also allows the Iglusuataliksuak dyke of the Nain province to converge to the same location. See further discussion in the text.

separated from Greenland by the break-up and sea-floor spreading of the Labrador Sea starting in the Late Cretaceous (Roest and Srivastava, 1989). The c. 3.5 Ga Ameralik dykes of SW Greenland are thought to correlate with the Saglek dykes of NE Labrador (Nutman et al., 2004). Rock associations and metamorphic events in Labrador and SW Greenland have also been used for this correlation (Friend and Nutman, 1994).

Figure 3 outlines a number of short-lived, mafic magmatic events, i.e. barcodes, for the North Atlantic cratonic elements (in Nain Province, south Greenland and Scotland), together with the Superior craton (i.e. a craton that we consider could have been a plausible nearest neighbour during significant periods from Late Archaean time, with emphasis on the period from 2600 Ma to 1850 Ma). The 2990 ± 13 Ma age of the feldspathic pyroxenite (Sample A) matches that of the 2989 ± 3 Ma Balmer event of Superior Province (Corfu and Andrews, 1987), and the 2990 ±

7 Ma Whim Creek Event in the Pilbara Craton (Krapez, 1993). We also note a temporal relationship to the c. 2990 Ma Usushwana Complex in the Kaapvaal Craton (J. Olsson, pers. comm., 2009) though additional matches with other Archaean cratons can be found.

Ages of c. 2.5 Ga mafic intrusions are relatively frequent on a global scale. In the Kola Peninsula precise U-Pb ages of gabbronorite-gabbro-pegmatite rock associations have yielded ages in the range 2505-2501 Ma (Amelin et al., 1995), and c. 2504 Ma dykes have been recognised in Karelia (Bleeker et al., 2008). Kullerud *et al.* 2006 recognise a distinct trend from a 2505–2490 Ma suite present in the Kola Peninsula, over a second 2460–2440 Ma suite present both in Kola and further south in Karelia, to the 2403 Ma dykes on Ringvassøy in the West Troms Basement Complex (WTBC) of North Norway. The same authors relate all of these dykes to a major Palaeoproterozoic continental break-up and suggest the regional south-/southwestward younging of the dykes implies that the locus of maximum extension and magmatic activity may have been shifting with time.

Further, the 2499.2 ± 1.2 Ma baddeleyite age of sample 499217 is close to the 2505 ± 2 Ma Ptarmigan dykes of the Superior province (Buchan et al. 1998). The Ptarmigan dykes have been suggested to be a distal component of the c. 2505 Ma Mistassini dyke swarm in SE Superior (Buchan and Ernst, 2004; Bleeker et al., 2008). Söderlund et al. (subm.) present a U-Pb baddeleyite age of 2512.3 ± 1.8 Ma for the Sebanga Poort dyke in Zimbabwe. On the basis of several age matches they inferred that Zimbabwe and Superior Cratons were nearest neighbours in the latest Archaean to earliest Paleoproterozoic, and our results indicate that the NAC might have been another block adjacent to eastern Superior (Fig. 5, Bleeker, 2003).

One dyke from the Isukasia terrane was dated at 2214 ± 10 Ma by Nutman et al. (1995). This generation of high Mg dykes of SW Greenland has been suggested to correlate with the 2235 ± 2 Ma Kikkertavak dykes of Labrador (Cadman et al., 1993). In the Superior Craton age matches are the 2216 +8/-4 Ma Senneterre dykes (Buchan et al., 1996) and the 2209 ± 1 Ma Klotz dykes (Buchan et al., 1998) of the Ungava dyke swarm. In the northernmost part of the WTBC, North Norway, a gabbro/gabbrodiorite sill have been dated at 2221 ± 3 Ma using U-Pb on zircon and titanite (Bergh et al., 2007).

The 2050-2030 Ma dykes in SW Greenland have several age equivalents in other Archaean cratons. These include, for instance, the 2045 ± 3 Ma (Hamilton et al., 1998) Iglusuataliksuak dykes of the Nain Craton and the c. 2038 Ma (Buchan et al. 2009) McKee dykes from near the boundary between the Rae and southern Slave Cratons. The Kangâmiut dykes have also been suggested to geochemically correlate to the OH (Outer Hebrides) dykes in Scotland (Mason and Brewer, 2004). In the northern (Ungava) segment of the Superior Province a gabbroic sill intruded rift-related sediments of the Povungnituk Group at 2038 +4/-2 Ma (Machado et al., 1993), and a layered intrusion in Fennoscandia, associated with the Otanmaki event, has an estimated age of c. 2040 Ma (Ernst and Buchan, 2001; Papunen, 1995). Further afield, the Ierhourtane metadolerite in the West African Craton has yielded an age of 2040 ± 6 Ma (Walsh et al., 2002).

5.3. Was the closure of the Labrador Sea greater than shown in previous reconstructions?

A limit on closure of the Labrador Sea is provided by Wasteneys et al. (1996) who obtained Precambrian basement ages from drill holes into the Labrador Sea out to about 100 km from the Canadian side, which represents close to half way in the reconstruction of Roest and Srivasatava (1989). It can be reasonably assumed that the continental crust similarly continues out into the Labrador Sea from the Greenland margin and, therefore, that the residual gap between Greenland and Labrador (Nain) as shown by Roest and Srivastava (1989) is underlain by continental crust.

However, such an inference, i.e. of continuous basement across the residual width between the NAC of Greenland and Nain Province in the Roest and Srivastava (1989) reconstruction, does not address the possibility of thinning and extension which is common along rifted margins (Turcotte and Emermen, 1983). Under the ECSOOT transect of Lithoprobe (Hall et al. 2002), there are two E-W seismic lines (5 and 6) which trend from eastern Canada just into the Labrador Sea, and these both exhibit a dra-

Table 4. Dykes belonging to the c. 2040 Ma event

Unit (Location)	Trend	Age	Reference
Kangâmiut dyke (West Greenland)	NE (deformed?)	2036 ± 5 Ma (Uz)	Nutman et al., 1999
Kangâmiut dyke (West Greenland)	NNE	2046 ± 8 Ma (Uz)	Nutman et al., 1999
Kangâmiut dyke (West Greenland)	NNE	2048 + 4 / - 2 Ma (Uz)	Connelly et al., 2000
MD3 dyke (West Greenland)	WNW	2050.2 ± 2.0 (Ub)	This paper
MD3 dyke (West Greenland)	WNW	2040.7 ± 3.1 (Ub)	This paper
MD3 dyke (West Greenland)	W	2029.0 ± 3.0 (Ub)	This paper
Deformed dyke from Bjoernebugt region in the northern part of the E. Nag. orogen (East Greenland)	?	2015 ± 15 Ma	Nutman et al., 2008
Iglusuataliksuak dyke (Nain province)	NW	2045 ± 3 Ma (Ub)	Hamilton et al., 1998

U = U-Pb, z = zircon, b= baddeleyite

matic thinning toward the Labrador margin (see especially Figure 5 in Hall et al. 2002). The magnitude of thinning is >50% and is especially clear for line 5 in their figure. If this level of thinning applies throughout the area of the remaining gap between the West Greenland portion of the NAC and the Nain Province in the Roest and Srivastava (1989) reconstruction, then a correction for rifting would require a further closure of the Labrador Sea by about half. This would also be consistent with a limit on convergence provided by potential overlap further to the north of Greenland and eastern Canada, if the remaining distance (in Fig. 4) were closed more than by about half.

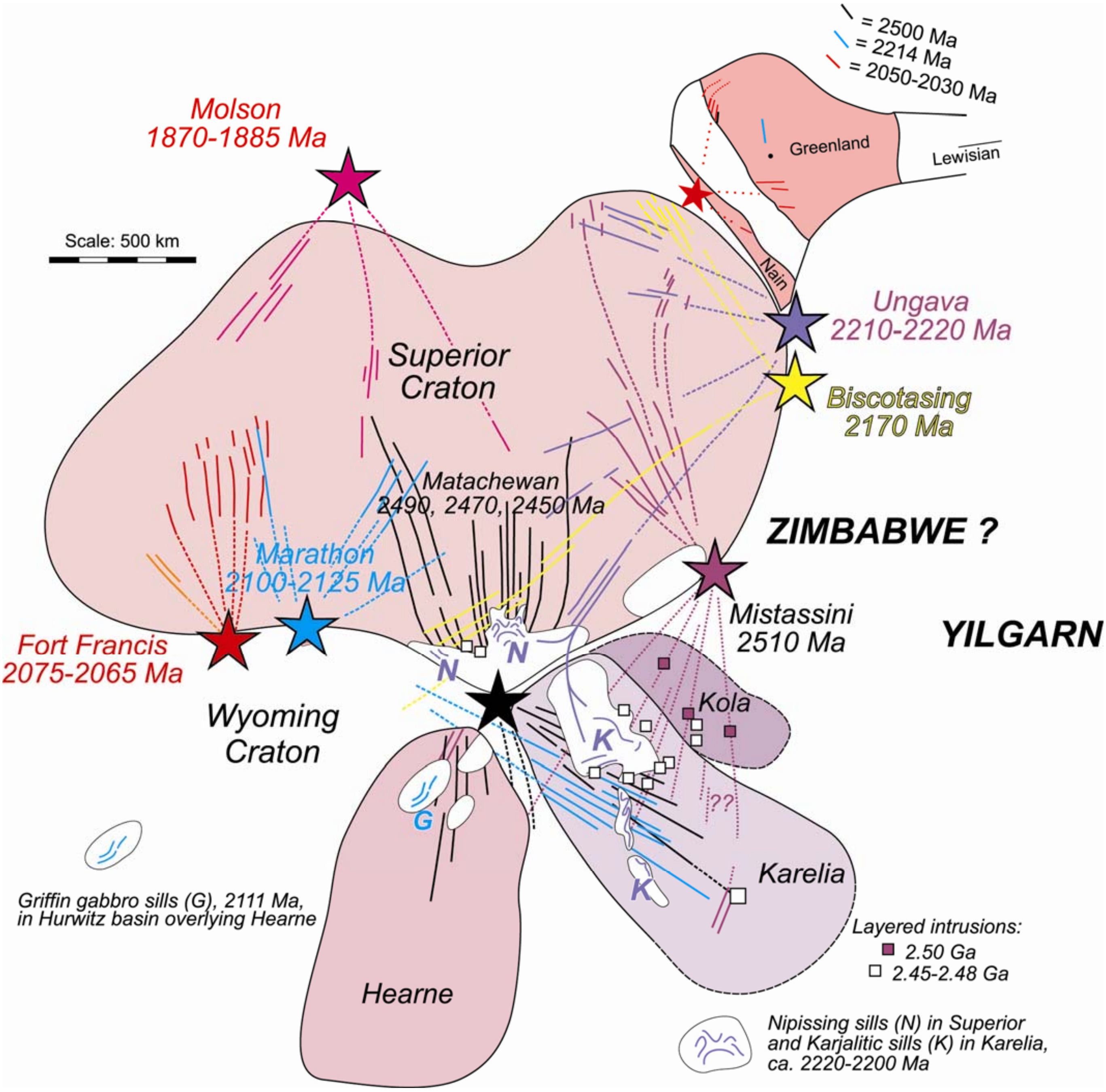


Figure 5. Possible Paleoproterozoic reconstruction of Greenland and Nain craton in a nearest neighbor situation to Superior craton, also showing earlier reconstructions of Kola-Karelia, Hearne and Wyoming cratons using the LIP record (modified after Bleeker and Ernst, 2006). Note that Zimbabwe and Yilgarn are tentatively positioned (cf. Söderlund et al., submitted). Further reconstructions would be possible by additional high-precision age determinations of the c. 2200 Ma dykes of SW Greenland. The possible match between these dykes and the 2210-2220 Ma Ungava dyke swarm could provide a major constraint and a definite reconstruction. Note also that the trend for the 2.5 Ga dyke is based on mapped dykes in the vicinity of the inves-

5.4. A tentative 2050-2030 Ma Mantle Plume Centre on the western margin of Nain Province (western North Atlantic Craton)

The Kangâmiut and MD3 dykes converge to a point within the Labrador Sea (Fig. 4). However, when the Mesozoic opening of the Labrador Sea is corrected for both the new sea floor crust (Roest and Srivastava, 1989) and the stretching of Labrador and Greenland margins during initial opening (discussed above), then the convergent point (marked by the star) could reach the western margin of the Nain Province. The 2045 ± 3 Ma Iglusuataliksuak basic dykes of the Nain Province trend approximately NW (Hamilton et al., 1998), converging to the same location, and altogether suggest that the Kangâmiut, MD3 and Iglusuataliksuak dykes define a radiating dyke swarm located on the western margin of the North Atlantic Craton.

Our new U-Pb ages from the MD3 swarm would suggest that the c. 2040 Ma event (Table 4) is associated with breakup along the western margin of the North Atlantic Craton. However, our data does not provide any clue to the identity of the conjugate margin. In van Gool et al. (2002) it is inferred that the Kangâmiut dykes were linked with breakup of the North Atlantic Craton from the Disko Craton (present -day central Greenland) to the 'north' and an unknown block to the 'west'. Due to the absence of any Paleoproterozoic magmatic barcode information from the Disko Craton (which marks central west Greenland) it would seem premature to suggest breakup from a block (Disko Craton) which it subsequently rejoined at c. 1900 Ma. A prediction of this model is that some (perhaps many) of the undated dykes along the northern Labrador coast must also belong to the 2040 Ma swarm and that those with an age of 2050-2020 Ma should have trends consistent with the radiating pattern that we are postulating.

North of Okak Fjord, Labrador, Palaeoproterozoic mafic dykes are principally thought to belong to the Napaktok (or Domes) swarm. Although not dated directly, these dykes may be equivalent in age to gabbroic dykes immediately south of Okak Fjord, dated at 2121 ± 1.5 Ma (baddeleyite + zircon; Hamilton et al., 1998). Further north, an undeformed representative of the Avayalik mafic dykes yielded a U-Pb baddeleyite age of 2142 ± 2 Ma (Connelly, 2001). Many more undated mafic dyke swarms also occur in coastal Labrador and are the subject of ongoing study.

The postulated mantle plume origin for the Kangâmiut and MD3 dykes is highly tentative, though the converging pattern of MD3 and Kangâmiut dyke swarms can be interpreted in support of such inference. Alternatively, the converging pattern relates to tilting and/or erosion of a conjugate set of dykes. When accounting all ages of dykes belonging to the c. 2040 event, the MD3 and Kangâmiut dyke swarms along with the Iglusuataliksuak dyke of the Nain province and the 2015 ± 15 dyke of East Greenland (Nutman et al., 2008) suggests a protracted period of emplacement. The maximum time span with the data available would in this case be c. 30 Myr, i.e. much longer than considered typical for mantle plume magmatism.

5.5. Barcode comparison with northeastern Superior Craton

A preliminary magmatic barcode comparison between the NAC and the Superior craton is possible based on the new ages of this study combined with previously published U-Pb ages. In addition to the 2050-2030 Ma events discussed above, the present study reveals a 2500 Ma age for the possibly NNE trending Qarliit Nunaat (based on the orientation of the c. 2528 Ma dyke dated by Willigers et al. (1999)). In addition there is the previously published 2214 ± 10 Ma age for the N-trending Isukasia dyke (Nutman et al., 1995), which is part of the MD1-BN1 swarm (see summary in Buchan and Ernst 2004; GSC Map 2022A). Thus, in the Paleoproterozoic, there are three barcode lines for the North Atlantic Craton (2500 Ma, 2214 Ma and c. 2040 Ma). A fourth possible match within this range would be 2130-2140 Ma dykes in W Greenland with age equivalents in Labrador, the latter represented by the Tikkigatsiagak or Avayalik dykes. However, precise correlatives of this age from Greenland have not been encountered so far. There are some individual matches around the world (e.g. Ernst and Buchan 2001), but the strongest match for all three ages is with the eastern / northeastern Superior Craton. Specifically:

1. The 2500 Ma Qarliit Nunaat is matched with the Mistassini plume centre (and associated Ptarmigan dykes) of the eastern and northern Superior Craton.
2. The 2214 Ma age of the N-trending Isukasia dyke (Nutman et al., 1995) which is part of the MD1-BN1 swarm (see summary in Buchan and Ernst 2004; GSC Map 2022A**)** can be matched with the Ungava radiating swarm of the eastern Superior Craton.
3. The c. 2040 Ma event can be matched with the 2038+4/-2 Ma Korak sills (Machado et al, 1993) of the Cape Smith belt of northeastern Superior Craton.

These matches would suggest that during the Palaeoproterozoic the North Atlantic Craton may have lain adjacent to north eastern Superior Craton. Furthermore, a specific orientation for this reconstruction can be deduced using dyke trends. Specifically, the North Atlantic Craton could be orientated (Figure 5) so that the Qarliit Nunaat, if NNE-trending, would trend toward the Mistassini plume centre and the N-trending 2214 Ma Isukasia dyke would point toward the Ungava plume centre.

Further, a tentative age correlation between the 1959 Ma Upper Povungnituk Group volcanics from the Cape Smith Belt with the 1953 Ma Mugford Group volcanics of the Nain Province is suggested. Palaeoproterozoic rifting of the western margin of Labrador portion of the NAC resulted in the deposition of local passive margin sequences (Ramah Group, lowermost Mugford Group, and Snyder Group sediments). The thick, upper part of the Mugford Group is a sequence of continental tholeiites with intercalated felsic tuffs that have been dated at 1953 ± 3 Ma (Hamilton, 1994; Hamilton et al., 1998). Undated but presumably correlative gabbroic sills in the Ramah Group in northern Labrador suggest that mafic rift-related magmatism at this time was widespread. By comparison, rocks of the Upper Povungnituk Group in the Cape Smith Belt of the northern Superior Province margin comprise a sequence of mostly LREE-enriched continental tholeiitic and locally alkaline volcanics. Zircon from minor intercalated rhyolite near the top of this sequence has been dated at 1959 ± 3 Ma (Parrish, 1989). Apart from the suggestion that these c. 1950 events may be connected, they could also herald the final stages of rifting of these margins. In this study's proposed reconstruction (Fig. 5), the 2235 Ma Kikkertavak dykes and the 2178 ± 4 Ma (Ketchum et al., 2002) Post Hill Group, both of the Makkovik Province, would be adjacent to the Ungava and Biscotasing plume centres. Thus, the Ungava plume centre is implied to be a precursor (c. 20 Myr) event to the Kikkertavak dykes. We speculate that the 2178 ± 4 Ma Post Hill Group could be an earlier stage of the Biscotasing event, which starts at 2171-2175 Ma (Halls et al., 2008; Hamilton and Stott 2008). Furthermore, if our reconstruction is correct, the Post Hill Group together with the Moran Lake Group (considered part of a passive margin sequence in Ketchum et al. (2002) belongs to the 2170-2140 Ma Cycle 1 magmatic event of the Labrador Trough.

5.6 Correlation with Lewisian, Scotland

An anorthosite from the Lewisian Complex has yielded U-Pb zircon ages of 2491 +31 / -27 Ma and 2855 +16 / -14 Ma (Mason et al., 2004). The same authors recognise a lower intercept disturbance for both samples. For the 2855 Ma sample the disturbance is at 2049 +78 / -80 Ma, possibly due to dyke emplacement. Though the lower intercept age is indistinct, it nonetheless suggests that c. 2040 Ma dykes could be present in the Lewisian. Further data to complete the barcode for the North Atlantic Craton as a whole (including Nain, South Greenland and NW Scotland) would provide the tools for a more precise correlation and palaeoreconstruction (Fig. 5) than suggested here.

6. Conclusions

- The mafic-ultramafic intrusion in the Fiskefjord region yielded an age of 2990.1 ± 13 Ma.
- The oldest dyke dated yielded an age of 2499.2 ± 1.2 Ma. It is here proposed that dykes of this generation should be termed Qarliit Nunaat dykes in SW Greenland.
- Three dykes belonging to the MD3 swarm yielded ages of 2050.2 ± 2.0 Ma, 2040.7 ± 3.1 Ma and 2029.0 ± 3.0 Ma.
- Age matches of dykes in NAC and NE Superior are found at 2500, 2214, 2050-2030 and 1950 Ma. On the basis of these results I suggest a position of NAC adjacent to NE Superior in the late Archaean early Proterozoic.
- The Kangâmiut, MD3 and Iglusuataliksuak dykes define a possible radiating dyke swarm, pointing at an ancient mantle plume centre on the western margin of NAC.
- A further closure of the Labrador Sea between the W Greenland portion of NAC and the Nain Province in Canada is suggested.

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