Rift magmatism on the Eurasia basin margin: U–Pb baddeleyite ages of alkaline dyke swarms in North Greenland

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Abstract: The opening of the Arctic Ocean involved multiple stages of continental rifting and intrusion of extensive dyke swarms. To trace tectonomagmatic processes of the High Arctic, we present the first U–Pb ages for alkaline dyke swarms of North Greenland. Concordia ages of 80.8±0.6 and 82.1±1.5 Ma indicate that north–south and east–west dykes are coeval. The north–south dykes reflect initial east–west rifting that led to break-up along the Gakkel Ridge and formation of the Eurasia Basin. The east–west dykes reflect local variations in the stress field associated with reactivated Palaeozoic faults.

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The Arctic Ocean comprises two major ocean basins (Amerasia and Eurasia) separated by a c. 1800 km long and 50–200 km wide sliver of continental crust (Lomonosov Ridge; Fig. 1). These basins have a complex and not fully understood tectonomagmatic history involving multiple stages of continental rifting and seafloor spreading. Opening of the Eurasia Basin is considered to have taken place during chron 24 or 25 (c. 53–56 Ma; timescale after Gee & Kent 2007) (Brozena et al. 2003; Engen et al. 2008). The opening of the Amerasia Basin is more debated, but is suggested to have occurred during the Early Cretaceous period (c. 138–125 Ma) (Grantz et al. 2011; Dossing et al. 2013b). The interval between the openings of these two basins is perhaps the least understood. Dossing et al. (2013a), however, recently identified prominent extensional structures crossing the Eurasia basin margin north of Greenland (Fig. 1) and argued that the structures were formed after the cessation of seafloor spreading in the Amerasia Basin and prior to the opening of the Eurasia Basin.

Extensive tholeiitic magmatism is considered to have accompanied the opening of the Amerasia basin and to have resulted in the High Arctic Large Igneous Province (LIP) (e.g. Maher 2001; Buchan & Ernst 2006), including a major dyke swarm extending from the Canadian Arctic Islands to Franz Josef Land (Fig. 1; Dossing et al. 2013b). Whereas K–Ar dating initially suggested that that the High Arctic LIP event spanned most of the Mesozoic (e.g. Maher et al. 2001; Senger et al. 2014), recent U–Pb dating indicates two main magmatic pulses, at c. 130–120 and 100–90 Ma (Ernst & Bleeker 2010; Corfia et al. 2013; Estrada & Henjes-Kunst 2013). How these pulses relate to each other and the opening history of the Amerasia Basin, however, is not clear.

Widespread alkaline magmatism followed the main pulses of the High Arctic LIP as recorded by Late Cretaceous–Palaeogene (c. 90–60 Ma) alkaline rocks in Ellesmere Island and North Greenland (e.g. Trettin & Parrish 1987; Estrada et al. 2010; Thorarinsson et al. 2012). Although LIPs often include prolonged magmatic activity before and after the main event (Tappe et al. 2007; Tegner et al. 2008), the alkaline rocks are only partly overlapping geographically with the tholeiitic rocks of the High Arctic LIP and seem to represent prolonged magmatic activity without a main burst (Tegner et al. 2011). It is therefore questionable how and if the alkaline rocks are related to the High Arctic LIP event and alternative models have suggested a connection with rifting in the Labrador Sea–Baffin Bay system and/or early extension in the Eurasia basin (Batten et al. 1981; Estrada et al. 2001; Tegner et al. 2011; Thorarinsson et al. 2011; Dossing et al. 2013a).

One of the most conspicuous occurrences of alkaline rocks in the High Arctic is the extensive alkaline dyke swarms of North Greenland (Fig. 2). The up to 200 m thick dykes record a major episode of continental rift magmatism and have been linked to widespread extensional structures north of Greenland (Soper et al. 1982; Dossing et al. 2013a). Here we present new U–Pb age data from baddeleyite grains retrieved from two North Greenland dykes. The ages are to our knowledge the first U–Pb ages reported from North Greenland and provide new constraints on the tectonomagmatic evolution of the High Arctic.

The North Greenland dyke swarms

The North Greenland dykes have been grouped into three swarms based on structural and palaeomagnetic data (Friderichsen & Bengaard 1985; Abrahamsen et al. 1997; Buchan & Ernst 2006; Fig. 2), as follows.

(1) Approximately north–south-trending dykes (formerly ‘Nansen Land dykes’; Buchan & Ernst 2006) dominate in...
Johannes V. Jensen Land and the northern coastal areas, where they intrude Lower Palaeozoic metasediments of the North Greenland fold belt (Fig. 2; Dawes 1971; Higgins et al. 1981). The dykes are strongly deformed and altered near the Eocene Kap Cannon Thrust Zone in the north, indicating that the dykes predate the thrust (Higgins et al. 1981; Soper et al. 1982). Comparable dykes are also observed cutting Permo-Carboniferous sediments in the footwall of the thrust, but not the overlying Kap Washington Group sequence dated to 71–61 Ma by U–Pb and 40Ar–39Ar dating (e.g. Brown et al. 1987; Tegner et al. 2011; Thorarinsson et al. 2011). The north–south dykes die out southwards towards the east–west-trending Harder Fjord Fault Zone, where they cut Santonian sediments (Higgins et al. 1981; Soper et al. 1982; Piepjohn & von Gosen 2001).

(2) East–west-trending dykes (‘J. P. Koch Fjord dykes’; Buchan & Ernst 2006) mainly occur south of the Harder Fjord Fault Zone in addition to scattered occurrences further north (Fig. 2). The main part of the swarm is found within c. 20 km of the Harder Fjord Fault Zone (Higgins et al. 1981; Estrada 2000; Piepjohn and von Gosen 2001).

(3) NW–SE dykes (‘Erlandsen Land dykes’; Buchan & Ernst 2006) form a dense swarm in western Nansen Land along the Lincoln Sea coast in addition to scattered dykes in Johannes V. Jensen Land and in southern Peary Land (Fig. 2; Soper et al. 1982; Friderichsen & Bengaard 1985; Abrahamsen et al. 1997).
The dykes are characterized by high alkali contents and enrichment in most incompatible trace elements relative to mid-ocean ridge basalts (Fig. 3). They show distinctive peaks in Ba, P, Eu and Ti, and are compositionally distinct from the tholeiitic rocks of the High Arctic LIP (Fig. 3). These characteristics are shared by all three North Greenland swarms and significant geochemical differences between the swarms have not been observed (Soper et al. 1982; Estrada 2000; Estrada et al. 2001; Kontak et al. 2001).

K–Ar dating of the dykes has yielded ages from 511 to 66 Ma, but the reliability of these ages has been questioned owing to possible open-system behaviour and problems with excess argon (Henriksen & Jepsen 1970; Dawes & Soper 1971; Dawes et al. 1983). 40Ar–39Ar dating by Kontak et al. (2001) has yielded ages of 85 ± 4 Ma and 82 ± 1 Ma for NW–SE and east–west dykes, respectively (Fig. 2). Palaeomagnetic studies indicate normal and reverse magnetic polarities for the NW–SE and east–west swarms, respectively (Abrahamsen et al. 1997).

Samples and analytical methods
Five dolerite dyke samples, collected during regional mapping campaigns by the Geological Survey of Greenland (now GEUS), were selected as candidates for baddeleyite separation. The sample selection included samples from each of three swarms, but only two samples (218978 and 303646) yielded baddeleyite grains. Sample 218978 is from an east–west-trending dolerite dyke exposed in northern Johannes V. Jensen Land (Fig. 2). Sample 303646 is from a NNE–SSW-trending dolerite dyke exposed on Hanne Ø and is part of the north–south swarm (Fig. 2). The dated samples are medium grained with an intergranular texture dominated by sericitized plagioclase, augite, hornblende, ilmenite, titanomagnetite and apatite.

Approximately 25 baddeleyite grains were hand-picked from each sample after application of the Wilfley-table technique of Söderlund & Johansson (2002). The grains were 30–50 µm long, moderately brown in colour and of excellent quality. Multigrain fractions comprising 4–9 grains per fraction were prepared for U–Pb isotopic analysis at the Swedish Museum of National History. The analyses were carried out by isotope dilution thermal ionization mass spectrometry using a mixed 236–233U–205Pb spike. Blank correction was 0.8 pg Pb and 0.08 pg U. Further details of the procedure have been given by Söderlund et al. (2010). Initial common Pb was corrected using the Stacey & Kramers (1975) model and regression was done using the Isoplot software (Ludwig 2003) with U decay constants determined by Jaffey et al. (1971). All age uncertainties represent 2σ and were calculated by propagating all sources of analytical error.

Results
The baddeleyite fractions from the east–west dyke 218978 are concordant and plot within error of each other with 206Pb/238U ages exposed in northern Johannes V. Jensen Land (Fig. 2). Sample 303646 is from a NNE–SSW-trending dolerite dyke exposed on Hanne Ø and is part of the north–south swarm (Fig. 2). The dated samples are medium grained with an intergranular texture dominated by sericitized plagioclase, augite, hornblende, ilmenite, titanomagnetite and apatite.

Fig. 2. Simplified geological map of Peary Land showing locations of samples 303646 and 218978 (base map modified after Henriksen 1992). General trend and distribution of alkaline dyke swarms are shown (based on Friderichsen & Bengaard 1985; Abrahamsen et al. 1997; Buchan & Ernst 2006). It should be noted that the bars are not to scale and do not depict the actual width of the dykes. Stars show approximate locations of samples dated by Kontak et al. (2001) and 40Ar–39Ar age (±2σ) in million years. NL, Nansen Land; JVJL, Johannes V. Jensen Land; HFFZ, Harder Fjord Fault Zone; KCTZ, Kap Cannon Thrust Zone; KWG, Kap Washington Group, Age of Kap Washington Group from Tegner et al. (2011) and Thorarinsson et al. (2011). Southern limit of the North Greenland fold belt is shown by dotted line. The fold belt formed during the Ellesmerian orogeny (Devonian–Early Carboniferous), with deformation grade increasing northwards (Dawes 1971; Higgins et al. 1981).
of 81.1 ± 1.9 and 84.6 ± 2.8 Ma (Fig. 4). The relatively poor precision of the analyses is due to low contents of radiogenic Pb (common Pb/total Pb = 0.18–0.50), which is typical for young baddeleyites (French et al. 2002). This results in relatively large age errors propagated from uncertainties in the common Pb composition. The concordance and coherency of the data, however, indicate that the ages are robust and a concordia age of 82.1 ± 1.5 Ma (MSWD = 1.3) is considered the best age estimate for the emplacement of the dyke. This estimate is within error of the 81.9 ± 1.0 Ma 40Ar–39Ar age determined by Kontak et al. (2001) for an east–west dyke and is consistent with the dominantly reverse magnetic polarity of the east–west dykes (Abrahamsen et al. 1997), indicating emplacement during chron C33r (c. 79–83 Ma); that is, after the end of the Cretaceous superchron.

The baddeleyite fractions from the north–south dyke 303646 yield 206Pb/238U ages of 80.2 ± 2.9 and 80.8 ± 0.6 Ma (common Pb/total Pb = 0.29–0.17). The analyses are concordant and overlapping, and a concordia age of 80.8 ± 0.6 Ma (MSWD = 0.1) is considered the best estimate for emplacement of the dyke (Fig. 4). This is consistent with crosscutting relationships suggesting a post-Santonian (<83.5 Ma) age (see above).

The concordia ages for 218978 and 303646 are within error of each other, indicating that the north–south and east–west swarms are coeval. The NW–SE swarm is presumably of roughly similar age to the north–south and east–west dykes, as indicated by a 40Ar–39Ar age of 85 ± 4 Ma obtained by Kontak et al. (2001). However, the dominantly normal magnetic polarity of the NW–SE dykes suggests that the swarm was emplaced before the end of the Cretaceous superchron (c. 83 Ma) (Abrahamsen et al. 1997). The NW–SW swarm thus appears to predate the north–south and east–west swarms.

Discussion and conclusion
Recent U–Pb dating of tholeiitic dyke swarms and sills in the Canadian Arctic Islands and Franz Josef Land (Fig. 1) indicates emplacement during the first pulse of the High Arctic LIP at c. 130–120 Ma (Ernst & Bleeker 2010; Corfu et al. 2013). It has been suggested that the dyke swarms represent fragments of a giant dyke swarm that spread from a focal point located north of the Canadian Arctic Islands or near the southern Alpha Ridge (Fig. 1; Buchan & Ernst 2006; Ernst & Bleeker 2010; Dössing et al. 2013b). The focal point may have been associated with a mantle plume centre that caused continental break-up in the northern Amerasia Basin and emplacement of the High Arctic LIP (Buchan & Ernst 2006; Dössing et al. 2013b).

The alkaline dykes of North Greenland have previously been considered part of the High Arctic LIP event and have been included in tectonic reconstructions of the High Arctic LIP dyke swarm (e.g. Maher 2001; Buchan & Ernst 2006). The U–Pb ages presented here, however, indicate that the North Greenland dykes are 40–50 Myr younger than the inferred radiating dyke swarm and 10–20 Myr younger than the second High Arctic LIP pulse (100–90 Ma). The North Greenland dykes thus appear to record a
The Eurasia Basin (Fig. 1) opened by nearly orthogonal seafloor spreading along the Gakkel Ridge in response to northward propagating breakup stresses and seafloor spreading in the North Atlantic (Müller et al. 2008). Initial breakup along the Gakkel Ridge possibly commenced during chron C25 (c. 56 Ma) (Brozena et al. 2003; Dossing et al. 2013a, b) and is thought to have linked with the North Atlantic opening via NW–SE-trending spreading ridges in the Labrador Sea and Baffin Bay (Fig. 1). Here, significant rifting commenced already in the early Campanian (c. 80 Ma) or earlier (Chalmers & Pulvertaft 2001; Harrison et al. 2011). Following a chron C24r breakup along the Aegir and Mohns ridges in the Norwegian–Greenland Sea (Fig. 1), the dominant stress transfer between the North Atlantic and Arctic spreading systems gradually shifted to the east of Greenland (Müller et al. 2008). The overall triangular shape of the North Greenland continental margin formed at the critical juncture between these three spreading domains (Tegner et al. 2011).

Based on a new compilation of gravity data, Dossing et al. (2013a) presented a model for Late Cretaceous continental rifting and magmatism in the area north of Greenland. They identified a regionally consistent, NW–SE-trending structural grain across the northern Eurasia Basin margin, which they correlated with NW–SE dykes in North Greenland and spreading segments in the Labrador Sea and Baffin Bay (Fig. 1). The north–south dykes, on the other hand, are parallel to the inferred anomaly C25 and younger spreading anomalies along the Gakkel Ridge, and subparallel to the Mohns and Aegir spreading segments in the North Atlantic (Fig. 1). The new U–Pb ages herein indicate that the north–south swarm was emplaced at c. 81 Ma, after the Cretaceous superchron, and is thus younger than the normally magnetized NW–SE swarm (85 ± 4 Ma; Fig. 2). We therefore propose that the NW–SW dykes record a major episode of continental rifting and magmatism at 85 ± 4 Ma in response to rifting in the Labrador Sea–Baffin Bay system. The north–south dykes, on the other hand, record a transition to predominantly east–west rifting north of Greenland in response to extensional stresses that eventually led to break-up along the Gakkel Ridge and in the NE Atlantic.

The U–Pb data indicate that the east–west and north–south swarms are roughly coeval. However, the two swarms show limited geographical overlap and the distribution of the swarms indicates strong control by the Harder Fjord Fault Zone (Fig. 2). Although dykes generally propagate perpendicularly to the least compressive stress, dykes may also invade pre-existing fractures oblique to the least compressive stress if the horizontal principal stress difference is small compared with the magmatic driving pressure and/or the fractures are oriented close to perpendicular (90° ± 45°) to the least compressive stress direction (e.g. Delaney et al. 1986; Jolly & Sanderson 1995). The Harder Fjord Fault Zone initially developed as a rift system in Late Carboniferous times, and was reactivated as a dextral strike-slip fault during the Late Cretaceous epoch (Piepjohn & von Gosen 2001). We therefore propose that the east–west dykes reflect local variations in the stress field and intrusion into pre-existing fractures that were reactivated by east–west rifting north of Greenland. The east–west dykes in Johannes V. Jensen land may reflect similar conditions. Dossing et al. (2010), for example, argued that east–west rifting north of Greenland caused dextral transtension along the eastern North Greenland margin, resulting in reactivation of Late Permian–Carboniferous extensional faults and development of local pull-apart basins. The Late Cretaceous dykes in North Greenland thus reveal a complex history of alkaline rift magmatism and diverging extensional stresses in the period between the formation of the Amerasia and Eurasia basins. The shift from a NW–SE dyke swarm at 85 ± 4 Ma to a north–south dyke swarm at 80.8 ± 0.6 Ma is interpreted as a transition from a regional stress pattern associated with rifting between North America and Greenland, to a regional stress pattern linked to rifting between Greenland and Europe.

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