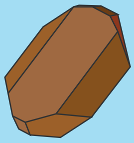
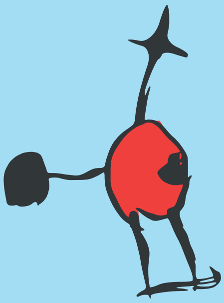
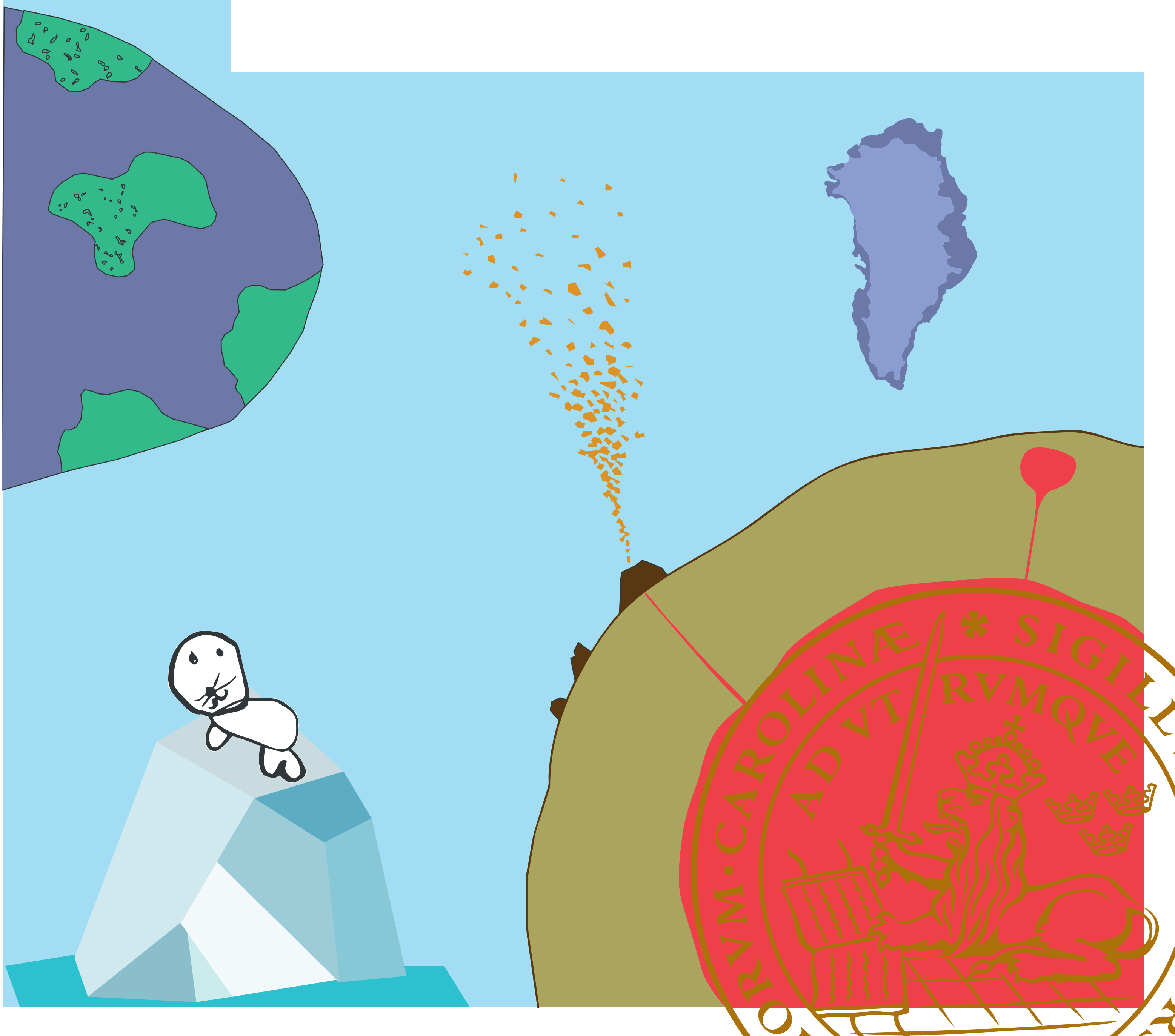
LITHOLUND THESES 27



New constraints on paleoreconstructions through geochronology of mafic dyke swarms in North Atlantic Craton



MIMMI NILSSON
LITHOSPHERE AND BIOSPHERE SCIENCE | DEPARTMENT OF GEOLOGY | LUND UNIVERSITY 2016



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Mafic dykes in SE Greenland, photo M. Nilsson

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New constraints on paleoreconstructions through geochronology of mafic dyke swarms in North Atlantic Craton

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UNIVERSITY

Lithosphere and Biosphere Science
Department of Geology

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Abstract

Earth history is punctuated by a series of events of supercontinent amalgamation and break-up. Fragments of old continents display rifted margins and orogenic sutures that testify their involvement in supercontinent cycles. Periods of break-up are associated with widespread magmatism due to extensional thinning and rifting of the lithosphere and in some instances the arrival of mantle plumes. Mantle plumes are thought to, at least in part, be responsible for Large Igneous Provinces (LIPs for short), voluminous short-lived outburst of mafic magmatism, whose products are continental flood basalts and oceanic plateaus, layered intrusions, sills and dykes. While continental flood basalts and oceanic plateaus are sensitive to subsequent erosion and subduction, the plumbing system of LIPs comprising deep-seated intrusions, sills and dykes have a high preservation potential. Thus, these events should be possible to trace back in time through multiple supercontinent cycles. LIPs typically have temporal scales of a few million years, but spatial scales of several hundred to thousand kilometers. After break-up and subsequent ocean basin opening, the products of LIPs may end up on different continents. Ancient crustal fragments, or cratons, have experienced a number of magmatic events, and thus have their individual record. Cratons that were once adjacent in a single landmass should share a part of their magmatic record during the interval of time they were connected. Because mafic rocks contains trace amounts of baddeleyite (ZrO_2), and because baddeleyite incorporate abundant uranium but only neglible amounts of lead in its crystal structure, we can age determine mafic intrusions using U-Pb geochronology. Hence, we can elucidate these events, craton by craton, and compare them to each other. Multiple individual age matches between different cratons suggest a common ancestry in a supercontinent or supercraton. In addition, dyke swarms provide geometric information as they often display radiating or parallel patterns. Fragments of ancient supercontinents or larger landmasses can thus theoretically be reconstructed by comparing geometry of dyke swarm matches in the magmatic record.
My PhD-project has been focused on Paleoproterozoic mafic dykes from the present-day southern Greenland part of the Archean North Atlantic Craton (NAC). Precise U-Pb baddeleyite age determinations of multiple events of dyke emplacement are presented in this thesis at ca. 2500, 2375–2365, 2215–2210, 2165–2160, 2125 and 2050–2020 Ma. This magmatic record show temporal correlations with a number of Archaean cratons worldwide, and notably share multiple matches with Superior and Dharwar cratons in present day Canada and India, respectively. A tentative paleoreconstruction of possible cratonic configurations of North Atlantic, Superior and Dharwar cratons during the time interval 2.37–2.17 Ga is presented in the context of supercraton Superia.

Key words: baddeleyite; U–Pb; North Atlantic Craton; paleoreconstruction; dyke swarms; Large Igneous Provinces; mantle plumes;

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Contents

List of papers

This thesis is based on the four papers listed below, which have been appended to the thesis. Paper I and II is reprinted under permission of Elsevier Limited. Paper III is reprinted under permission of RSC publishing. Paper IV is a manuscript.

Paper I
Nilsson, M.K.M., Söderlund, U., Ernst, R.E., Hamilton, M.A., Scherstén, A., Armitage, P.E.B., 2010. Precise U–Pb baddeleyite ages of mafic dykes and intrusions in southern West Greenland and implications for a possible reconstruction with the Superior craton. Precambrian Research 183, 399–415.

Paper II
Nilsson, M.K.M., Klausen, M.B., Söderlund, U., Ernst, R.E., 2013. Precise U–Pb ages and geochemistry of Paleoproterozoic mafic dykes from southern West Greenland: Linking the North Atlantic and the Dharwar Cratons. Lithos, 174, pp. 255–270

Paper III
Wohlgemuth-Ueberwasser, C. C., Söderlund, U., Pease, V., Nilsson, M. K., 2015. Quadrupole LA-ICP-MS U/Pb geochronology of baddeleyite single crystals. Journal of Analytical Atomic Spectrometry, 30(5), 1191–1196.

Paper IV
Nilsson, M. (manuscript) 2.17-2.12 Ga mafic magmatism in North Atlantic Craton. In preparation.

Acknowledgments

In 2007 I applied for a job as a field assistant to Nora Noffke, who were going to Greenland to look for microbial mats, i.e. the earliest life on Earth. There were two prerequisites for getting the job: 1) you had to be fluent in Danish, and 2) you had to have had experience with setting up a VHF radio. Although I did not in any way meet either of the requirements, I got the job, and thus got to spend my first ever field work in the 3.8 billion year old rocks of Isua. The non-geologist needs to know that this is one of most geologically spectacular place there is. Not only does the Isua Greenstone belt comprise the about the oldest rocks you can find, but the bedrock is also spared from being covered by soil and other younger cover. Well, with exception for the inland ice. There's just no going back to working in the woods of Sweden, where you painstakingly have to try and find a small outcrops here and there.

From the ground level geology courses at the department I knew that I wanted to work with Ulf Söderlund. As a teacher, he speaks with great passion and warmth about geology, and throughout my years as a student his door has been consistently kept wide open to invite anyone who might have questions. He has not once been too busy to sit down and explain geological concepts. In 2009 I found myself lucky to be able to combine the two equally great concepts of Greenland and Ulf in a magistrate project. Anders Scherstén, who until then only knew me as someone who was allegedly attacked by a reindeer in the 2008 field season, provided samples and later became my co-supervisor. The influence of Anders can be exemplified by a recent discussion I had with Andreas Petersson: we were debating proper usage of terminology, and one argument was what we imagined Anders would say of the issue. We concluded that he was probably right. There are not many people that with a single, elegantly presented argument can win a debate they never took part in. Anders is one of the few. In addition to his aura of being technically correct, i.e. the best kind of correct, he also laughs at silly puns, which is gratefully acknowledged.

The Greenland-Ulf coalition continued in my PhD-project. Ulf has certainly lived up to being a supervisor. As a visor is something you put on to protect your head from objects that might otherwise harm you, so logically a supervisor must be someone who protects you to a more extreme degree. Ulf has always done just that, whether the objects in question have been internal politics, self-doubt or strangely coloured beads of dissolved baddeleyite.

Mike Hamilton, who has always taken the time to reply to my various questions with answers the size of extended abstracts, often including references as well as a silly youtube-link. I'm always excited to find an email from you in my inbox, and your support has meant more than you can imagine. Here's one for you: www.youtube.com/watch?v=qmsbP13xu6k

Johan Olsson. Johan is the most consistently friendly and well-meaning person I have ever met, and I do not believe there exist a single positive adjective that cannot be applied to him. I fondly remember our Germany trip, the glöl and va!? Thank you for never-ending support in all things academia and life.Sanna and Carl Alwmark, I look up to your massive integrity and humorous approach to things while still keeping the science bar high. Me, Sanna and Andreas Petersson have followed each other since day one in our geology education, and have shared an office during our time as PhD-students. As all three of us have gone on multiple years of parental leave, we have not have very much overlap of office time. Nevertheless, the small overlap we've had have been immensely valuable. Andreas, in a model of my growth during the last 10 years, a large part of the juvenile material can be traced back to you, a reservoir that I'm very grateful for. Lorraine, thank you for the supply of French treats and good discussions. Ashley, I know you haven't learnt as much Swedish as you originally planned, but if if you only learn one word, make it "urgasade".

Thanks also to everyone I've encountered in the hallways at the Museum of Natural History, Stockholm, and especially Per-Olof Persson and Hans Schöberg. Thanks to the many friendly people at GEUS, who have assisted with sampling and more, and allowed me to attend their 2012 SEGMENT project in SE Greenland. Thanks to Svetlana Bogdanova, for being so absolutely caring, my co-supervisor Richard Ernst and Wouter Bleeker for warmly welcoming me to the LIP-project, to my co-supervisor Martin Klausen for great field work company in SE Greenland.

As a concluding remark: Petersson (2015), argues that he became a doctor before me. However, when normalizing the data set against date of birth, it turns out that A. Petersson became a doctor after 13002 days. For M. Nilsson, the value is 12481 days, i.e. more than 500 days less than the A. Petersson value. Based on these results, I herein strongly suggest that I became a doctor before you.

References

Petersson, A., 2015. Evolution of continental crust in the Proterozoic -growth and reworking in orogenic systems. Litholund Thesis Doctoral Dissertations, 24.

Abbreviations and definitions

CFB – Continental Flood Basalt

Craton – a segment of continental crust that has maintained long-term stability, commonly applied to Archaean crustal segments.

Ga – billion years ago

Hot spot – locality with unusual hot mantle, used herein without genetic consideration

ID-TIMS – Isotope Dilusion Thermal Ionization Mass Spectrometry

LA-ICPMS – Laser Ablation Inductively Plasma Mass Spectrometry

LIP – Large Igneous Province

Ma – million years ago

NAC – North Atlantic Craton: the Archaean craton found in present day Labrador, Canada, southwest and southeast Greenland, and northwest Scotland. Note that some workers instead use the name Nain [craton]. Herein North Atlantic Craton is preferred to avoid confusion as Nain [province] also is used to denote only the western flank of North Atlantic Craton.

Supercontinent – using the definitions of Meert (2012), a supercontinent should constitute >75% of preserved continental crust at the time of maximum packing. This allows for inclusion of Pangea in the definition (85-90%), while Gondwana (ca. 60%) is defined instead as a supercraton (sensu Bleeker, 2003) or semi-supercontinent (sensu Evans et al., 2016).

1. Introduction

In this thesis, a large number of precise and accurate U–Pb baddeleyite ID-TIMS ages are reported for mafic dykes from North Atlantic Craton, southern Greenland. All U–Pb ages presented in this thesis were performed on a Triton Finnigan TIMS at the Museum of Natural History in Stockholm, with the exception the Iglusuataliksuak dyke which was analysed by M. Hamilton at Jack Satterly Geochronology lab, Toronto. Three papers and one manuscript are included, listed on page 6 and summarized in section 2. Additional peer-reviewed papers produced during my PhD not included in the thesis are listed in Appendix A.

My PhD-project has been integrated and partly funded by an industrial-academic-governmental research program (2009–2015): “Reconstruction of Supercontinents Back To 2.7 Ga Using the Large Igneous Province (LIP) Record, with Implications for Mineral Deposit Targeting, Hydrocarbon Resource Exploration, and Earth System Evolution”. Additional funding was provided through grants from the Swedish Research Council (to Ulf Söderlund) and from the Royal Physiographic Society of Lund (to Mimmi Nilsson).

2. Summary of papers

2.1. Paper I

Nilsson, M.K.M., Söderlund, U., Ernst, R.E., Hamilton, M.A., Scherstén, A., Armitage, P.E.B., 2010. Precise U–Pb baddeleyite ages of mafic dykes and intrusions in southern West Greenland and implications for a possible reconstruction with the Superior craton. Precambrian Research 183, 399–415.

In Paper I, five U–Pb baddeleyite ID-TIMS ages of mafic dykes are presented, and one U–Pb zircon LA-ICPMS date of a pyroxenite. In southern West Greenland (Fig. 1), three dolerite dykes belonging to the roughly WNW-trending MD3 dyke swarm yielded precise ages of 2050 ± 2, 2041 ± 3 and 2029 ± 3 Ma. These ages are similar to those of Kangâmiut dykes, a NNE-trending swarm up to 500 km north of the MD3 dykes. Dykes of the Kangâmiut swarm has been previously dated by the U–Pb zircon method, yielding ages of 2036 ± 5, 2046 ± 8 and 2048 +4/-2 Ma (Nutman et al., 1999; Connelly et al., 2000). A dyke from South-East Greenland gave a slightly younger age of 2015 ± 15 Ma, still indicating that the Kangâmiut dykes extends beneath the ice cap (Nutman et al., 2008). Additionally, an age of 2045 ± 2 Ma is presented for the SE-trending Iglusuataliksuak dyke from Nain province in Canada. These dykes are speculated to belong to the same event of protracted mafic magmatism, spanning at least 20 Myr from ca. 2050 to 2030 Ma. The trends of the NNE-trending Kangâmiut dykes and the NNE-trending MD3 dykes in southern West Greenland, together with the Iglusuataliksuak dyke in Nain province, collectively define a radiating pattern with a focal point that indicates the location of a hypothesized mantle plume.

2.2. Paper II

Nilsson, M.K.M., Klausen, M.B., Söderlund, U., Ernst, R.E., 2013. Precise U–Pb ages and geochemistry of Palaeoproterozoic mafic dykes from southern West Greenland: Linking the North Atlantic and the Dharwar Cratons. Lithos, 174, pp. 255–270

Paper II presents new geochronological results (U–Pb baddeleyite ID-TIMS) of six mafic dykes from the southern West Greenland portion of the Craton (Fig. 1). In addition, geochemical data from 42 dyke samples from the same area is presented. Two E-W trending dykes yield ages of 2365 ± 2 Ma and 2374 ± 4 Ma, and the name Grædefjord dykes is proposed for this previously unknown generation of dykes. One NE-SW trending dyke is age determined to 2209 ± 5 Ma, within errors coeval with a 2214 ± 10 Ma age for a N-S trending BN dyke (Nutman et al., 1995). Further, three dykes belonging to the MD3 swarm yield ages of 2053 ± 2, 2049 ± 6 and 2042 ± 2 Ma. The results are discussed in the context of an intracratonic setting as well as in a global context of paleoreconstructions. A proposed connection between the ca. 2370 Ma Grædefjord dykes and the coeval Dharwar Giant dyke swarm (Halls et al., 2007; French and Heaman, 2010; Kumar et al., 2012; Demirer, 2012) together with further barcode matches at ca. 2215 and 2210 Ma provides the basis for tentative paleoreconstructions of the North Atlantic and Dharwar cratons. Several possible paleogeographical reconstructions for the relative positions of the two cratons during this time interval are proposed.

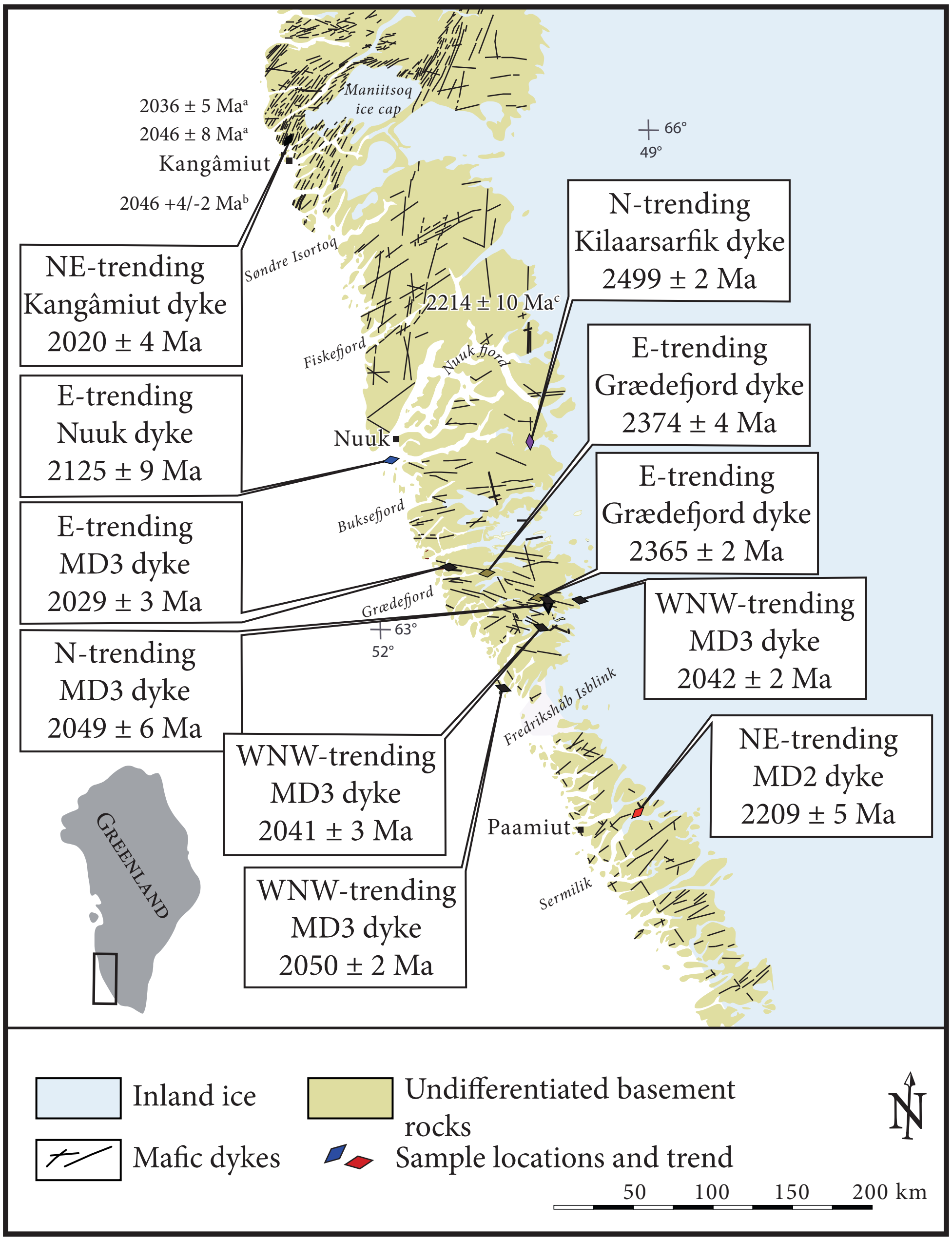

Fig. 1. Sketch map of southern West Greenland showing dykes and U–Pb age results extracted form papers included in this thesis (boxed). Previously published ages of mafic dykes are unboxed. Letters in superscript refers to the following mafic dykes and age references: a–Kangâmiut dykes (Nutman et al., 1999); b–Kangâmiut dyke (Connelly et al., 2000) c–BN dyke (Nutman et al., 1995). Map modified after Escher and Pulvertaft (1995), Hall and Hughes (1987) and Nilsson et al. (2013).

2.3. Paper III

Wohlgemuth-Ueberwasser, C. C., Söderlund, U., Pease, V., Nilsson, M. K., 2015. Quadrupole LA-ICP-MS U/Pb geochronology of baddeleyite single crystals. Journal of Analytical Atomic Spectrometry, 30(5), 1191-1196.

There are a number of elemental (and isotopic) biases inherent in LA-ICPMS owing to e.g. crystallographic orientation (Wingate et al., 1999), down-hole fractionation and other matrix affects (e.g. Sylvester et al., 2008). In this paper a method is presented using a matrix matched standard for external calibration, i.e. the FC-4b baddeleyite in lieu of zircon standards. Ablation rates and U/Pb fractionation differs significantly between baddeleyite and zircon, why downhole and interelement fractionation correction using zircon as the external standard is problematic. Two other baddeleyite standard materials, Phalaborwa and Sorkka, were treated as unknowns. The FC-4b yielded a concordia age of 1099 ± 8 Ma, in excellent agreement with the published age of 1099 ± 1 Ma (Schmitz et al., 2003). Excess uncertainties from the FC-4b was applied to the Phalaborwa and Sorkka analyses. Phalaborwa yielded a concordia age of 2060 ± 6 Ma, while the published age is 2060 ± 1 Ma (Heaman and LeCheminant, 1993). The presented 1256 ± 6 Ma con-

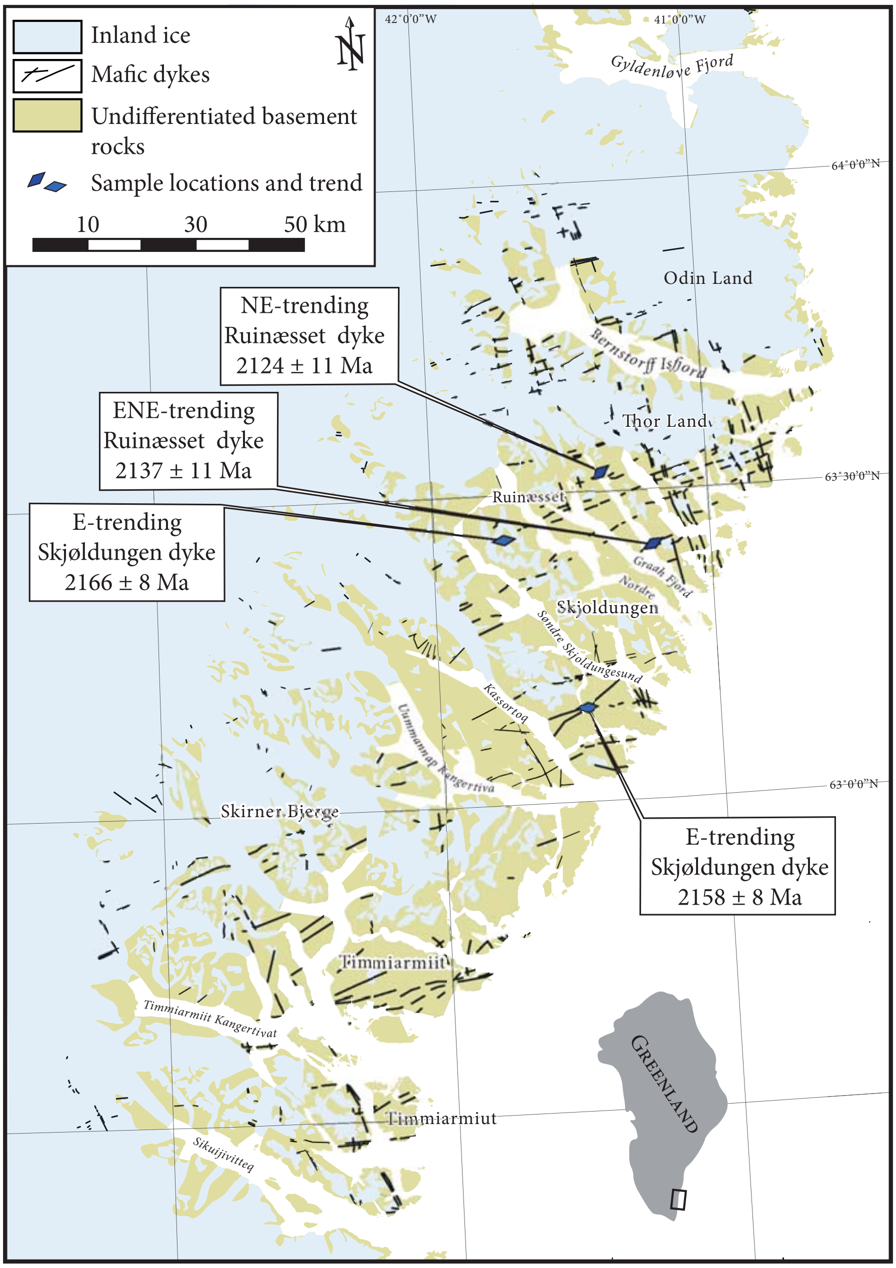

Fig 2. Sketch map of South-East Greenland showing dykes and U–Pb age results extracted form papers included in this thesis. Modified after Kolb et al. (2013) and Escher (1990).

cordia age for Sorkka is indistinguishable from the published TIMS age of 1256 ± 1 Ma (Söderlund et al., 2004) for the same material. The precision obtained is 0.7% for FC-4b, 0.3% for Phalaborwa and 0.5% for Sorkka (2σ).

2.4. Paper IV

Nilsson, M., in preparation. 2.17-2.12 Ga mafic magmatism in North Atlantic Craton

This study presents ages of two mafic dykes from southern West Greenland (Fig. 1) and four from South-East Greenland (Fig. 2). The two dykes from southern West Greenland have published $^{40}Ar/^{39}Ar$ dates of ca. 2.5 Ga, why these were selected for U–Pb analyses to investigate if they might belong to the 2.5 Ga Kilaarsarfik dykes. One of the dykes gave a zircon U–Pb age of 2021 ± 4 Ma. As the dyke is located in the Kangâmiut area, it is proposed to belong to the Kangâmiut dyke swarm (sensu strictu), which has earlier published ages of ca. 2040 Ma. The other dyke yielded a U–Pb baddeleyite age of 2125 ± 9 Ma, and the name Nuuk dykes are proposed for this suite in SW Greenland. This age is indistinguishable from the result of age determination of one SE Greenland dyke: 2124 ± 11 Ma. Together with another dyke from SE Greenland which yielded an age of 2137 ± 11 Ma, the name Ruinæsset dykes is suggested. Two slightly older ages of dykes from the same area are also presented, yielding U–Pb baddeleyite ages of 2166 ± 8 Ma and 2158 ± 8 Ma. The name Skjøldungen dykes is proposed for this dyke generation. Global temporal correlatives of the Skjøldungen and Ruinæsset-Nuuk dykes are discussed, and a tentative paleoreconstruction of North Atlantic and Dharwar cratons within supercraton Superia is presented.

3. Background

3.1. The supercontinent cycle

Since Wegener (1915; 1922) defined Pangea, it has become evident that Earth history is punctuated by a number of supercontinent events comprising episodic assembly of crustal blocks and subsequent breakup. Pangea – being the most recent – is unsurprisingly the most rigorously defined supercontinent in Earth history, yet Pangean paleoreconstructions are under continuous refinement (e.g. Domeirer et al., 2012). Reconstructions of pre-Pangean supercontinents and their temporal frameworks become gradually more conceptual going back in time as the preserved geological record decreases. Although their exact configurations are debated, there is a growing consensus for the existence of at least two pre-Pangean supercontinents: early Neoproterozoic (ca. 0.6–1.1 Ga) Rodinia (McMenamin and McMenamin, 1990; Li et al., 2008) and Palaeoproterozoic (ca. 1.3–1.8 Ga) Nuna/Columbia (Hoffman, 1997; Rogers and Santosh, 2002). A global compilation of U–Pb ages of zircon (Fig. 3) from orogenic granitoids and detrital zircon data display a number of peaks, reflecting periods of granite preservation and/or production, in turn thought to correlate with supercontinent assembly (Condie, 1998; Hawkesworth et al., 2009, 2010; Condie and Aster, 2010). Correspondingly, the troughs in the age spectrum are thought to reflect periods of supercontinent stasis or break-up. Hawkesworth et al. (2010) note that Pangea, Rodinia and Nuna/Columbia assembly are clearly defined in the age spectrum, as is a smaller peak prior to Pangea thought to correlate with assembly of Gondwana supercraton. Additionally, the zircon age peak hints at late Archaean supercraton assembly (~2.6 Ga), referred to as Sclavia/Superia, although Hawkesworth et al. (2010) note the possibility that the peak reflects a period of continental crust generation without a supercraton/supercontinent.

3.2. Late Archaean assembly of cratons

Although all pre-Pangean supercontinents are conjectural in both existence and paleogeography (Reddy and Evans, 2009), the presence of a larger craton assembly in the late Archaean is indicated by U–Pb zircon age peaks (Fig. 3; e.g. Condie, 1998; Hawkesworth et al., 2009, 2010; Condie and Aster, 2010). Bleeker (2003) recognizes three end member solutions of Archaean cratonic assembly: (1) a single supercontinent, (2) a few supercratons, or (3) many dispersed supercratons and craton-size landmasses. A palaeogeographically unspecified late Archaean supercontinent comprising the Archaean provinces in North America was suggested by Williams et al. (1991), which he termed Kenorland, after the Kenoran orogeny that is hypothesized to reflect the amalgamation of crustal blocks. Aspler and Chiarenzelli (1998) further suggested the inclusion of Siberia and Baltica in the Kenorland configuration, and proposed a second, coexisting super-

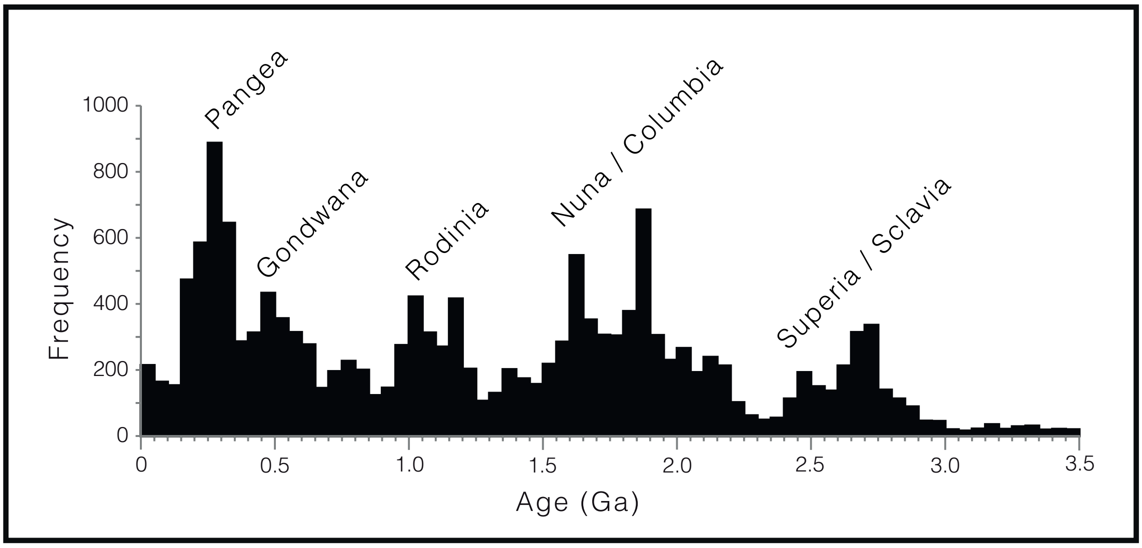

Fig. 3. U–Pb age distribution of detrital zircons and conjecturally correlative supercontinents and supercratons. Modified after Grenholm and Scherstén (2015) with data from Belousova et al. (2010) and Campbell and Allen (2008), and references therein.

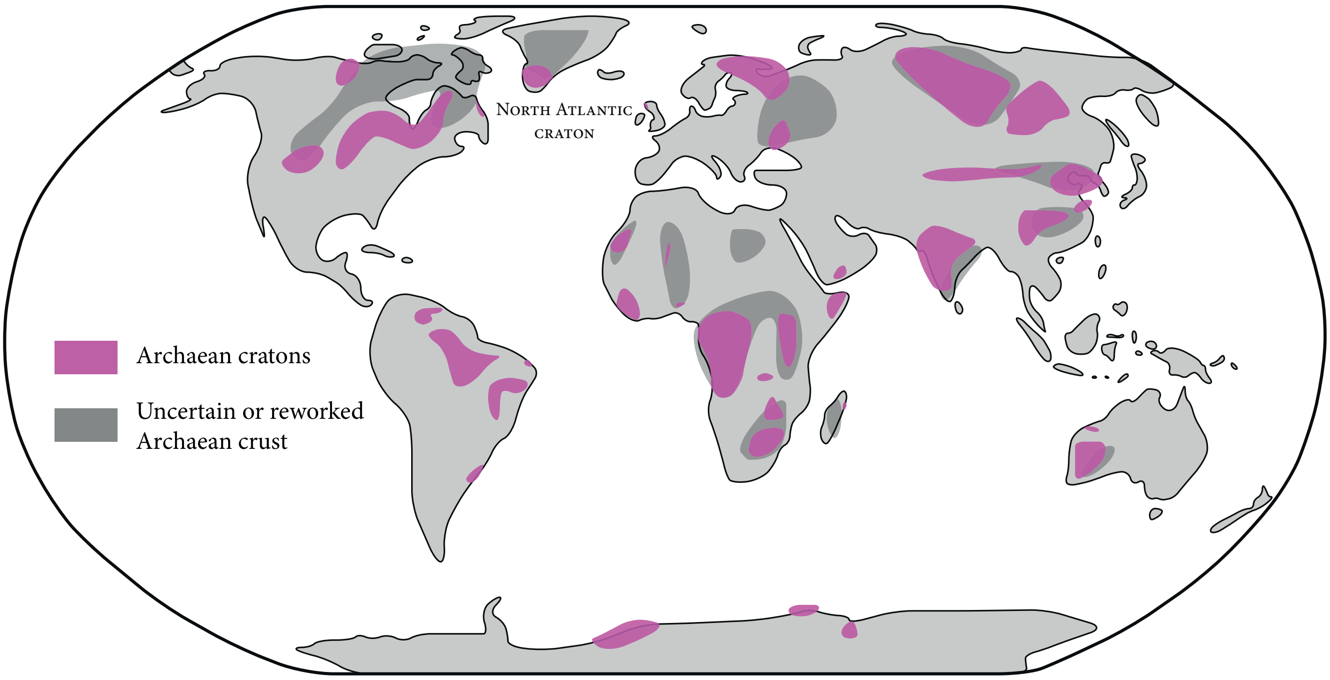

Fig. 4. Worldwide schematic distribution of Archaean crust (purple). Dark grey denotes areas of uncertain or reworked Archaean crust. After Condie et al. (2009).

continent, Zimvaalbara, that encompassed the Zimbabwe, Kapvaal, Pilbara and São Francisco cratons, and possibly cratonic blocks in India.

Bleeker (2003) instead refers to Kenorland as having included all, or the majority of, preserved Archaean cratonic elements, i.e. an end member solution of a single supercontinent. He further suggested a solution comprising a few supercratons, namely Superia, Sclavia and Valbaara. The existence of Valbaara was first suggested by Cheney (1996) and its configuration has since been rigorously tested in regards to correlation of tectonostratigraphical units as well as paleomagnetic data (e.g. Zegers et al., 1998; Wingate, 1998; de Kock et al., 2009). The configurations of Sclavia and Superia have been the scope of a number of recent studies (e.g. Bleeker, 2003; Bleeker and Ernst, 2006; Nilsson et al., 2010; French and Heaman, 2010). By the very nature of supercontinent cycles, a large percentage of the rocks produced are subsequently destroyed, most notably the subduction of ocean floor basalts. Correspondingly, initial continental rifts might become obscured within deformed and metamorphosed collisional margins, and ultimately lost through erosional removal. Today, there are approximately three dozen preserved Archaean cratons dispersed globally (Fig. 4), many showing rifted or faulted margins, which infers that they are mere fragments of larger ancestral landmasses (Williams et al., 1991; Bleeker et. al, 2003). In addition, there is a lesser defined number of poorly preserved slivers of pre-2.5 Ga crust (Bleeker, 2003).

So how do we begin to recognize and reconstruct something that is in large parts vanished?

3.3. Large igneous provinces and supercontinent reconstruction

Formation of large igneous provinces (LIPs) is commonly linked to supercontinent break-up (Storey, 1995; Courtillot et al., 1999) and can be dated with high precision and accuracy utilizing ID-TIMS U–Pb on zircon and baddeleyite (Krogh et al. 1987; Heaman and LeCheminant, 1993). While the voluminous flood basalts that are produced during LIP events are sensitive to erosion, their deep-seated plumbing systems of mafic dykes, sills and layered intrusions have high preservation potential. The components of major LIPs can have spatial scales of several thousand kilometers. Following break-up of a supercraton or supercontinent, these components might end up on different crustal fragments. A well-known recent example is the continental flood basalts, dykes and sills in the Paraná-Etendeka provinces in present day South America and Africa. Dykes of the Paraná province (Brazil) and those of the Etendeka (Namibia) all intruded at around 130 Ma, and converge towards a focal point that is commonly inferred to mark initial impact of the Tristan da Cunha plume at the time of dyke intrusion (e.g. Gibson et al., 2006).

Morgan (1971) proposed that hot spot volcanism is the surface expression of active thermal upwelling, or mantle plumes, originating from the core–mantle boundary. The origins, mechanics as well as the existence of mantle plumes have been under debate since. There is a general agreement that plumes must originate from

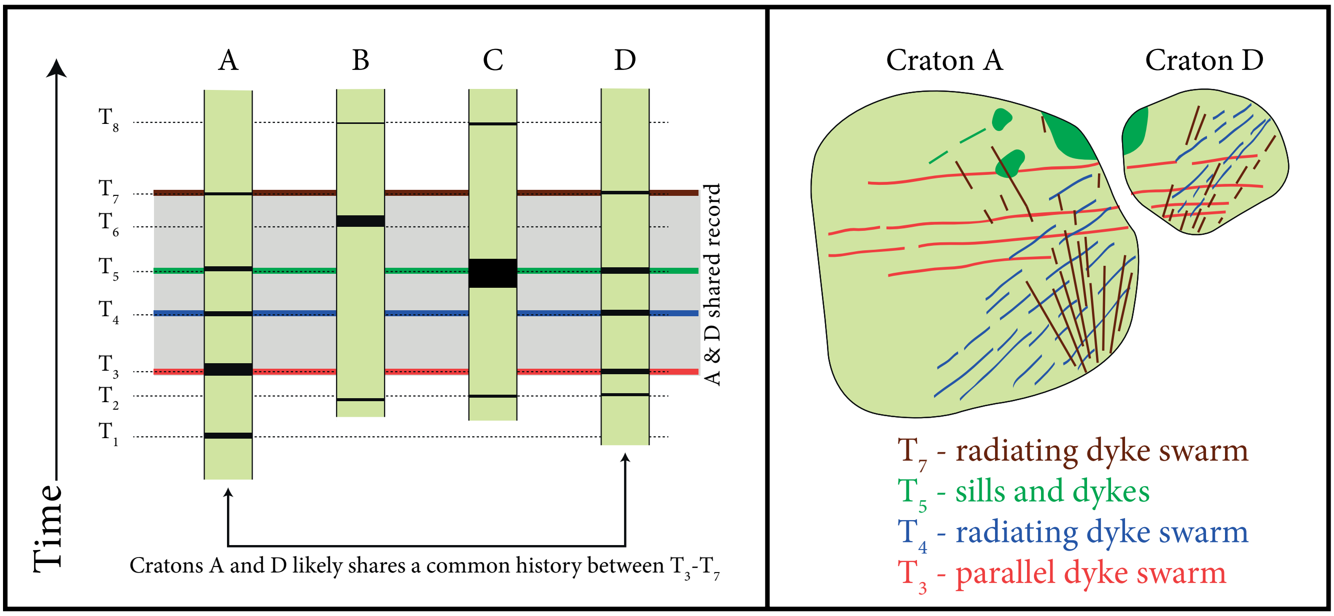

Fig. 5. *Left:* Hypothetical 'barcode', illustrating ages of magmatic events in craton A-D. Individual bars represent U–Pb ages, with line thickness depicting age uncertainty at 2σ level. Cratons A and D show multiple individual matches at T_3, T_4, T_5 and T_7. This suggests that these cratons shared a common history in an ancestral landmass between T_3 and T_7. Cratons B and C are unrelated to A and D. *Right:* Paleoreconstruction of a hypothetical supercraton involving cratons A and D using geometry of coeval dyke swarms and sills. The craton margins have been abraded and modified since break-up.

a thermal boundary layer, but whether that layer is the core–mantle boundary as postulated by Morgan (1971) have been discussed. On the basis of a two layer convective model for the mantle, other workers have suggested that plumes might nucleate from a proposed thermal instability at the upper–lower mantle boundary (Campbell, 2001).

Some workers reject the mantle plume theory altogether, while others argue that mantle plume modeling has become a paradigm used without considerations to the physical properties that is expected of an ascending and impacting plume (McHone, 2000; Hawkesworth and Scherstén, 2007), i.e. regional doming, large degrees of partial melting and voluminous outpourings of basalt.

As shown in laboratory experiments by Campbell et al. (1989), a starting plume consists of a large bulbeous head and a narrow conduit or tail. With a sufficient supply of source material, the tail constantly feeds the head which continuously grows as it ascends. Campbell (2005) calculated the diameter of the head of a plume originating from the core-mantle boundary to be ~1000 km before impact with the lithosphere. As the plume reaches shallow enough depths, melting occurs as a consequence of decompression. The diameter doubles as the plume head impinges on the lithosphere and flattens out (Campbell, 2005). Magmatism related to a plume head is commonly described as producing short lived magmatic events (1–10 Myr) which results in outpourings of massive volumes of basalts, i.e. continental flood basalts or oceanic giant plateaus. Magmatism related to the hotter, but narrower conduit is represented by prolonged events with smaller volumes of magma, typified by aseismic ridges. Courtillot et al. (2003) argues that plume conduits lasts on the order of 130 Myr, based on the observation that hot spots with trap magmatism aged 100 Ma or less are still active (Ethiopia-Yemen/Afar, Greenland/Iceland, Deccan/Reunion), those with trap magmatism aged 140–100 Ma may be failing (Ontong-Java/Louisville, Paraná-Etendeka/Tristan) and those older than 150 Ma do not have an active trace (Karoo, Camp, Siberia, Emeishan).

The few well-studied examples of Archaean cratonic remnants reveal multiple episodes of mafic dyke intrusion, often defining relatively short-lived bursts of typically radiating or parallel swarms (Bryan and Ernst, 2008). Therefore, each cratonic block preserves a specific record of mafic magmatism. A barcode (Fig. 5) is a way to visualize periods of mafic magmatism and thus compare records between cratons. Every line denotes a precise age from a dyke swarm, sill or continental flood basalt. Periods of limited continental extension are theoretically represented by the absence of barcode lines, however, a lack of geochronological data due to e.g. sampling bias would also be represented by the absence of barcode lines. The method of using precise U–Pb ages to create barcodes for individual cratons or terranes provides a way to asses which cratons or terranes might once have been contiguous crustal fragments, or "nearest-neighbours", over the time interval barcode matches can be identified. Together with structural information of dyke swarm geometry (Fig. 5) this can be used to assess paleoreconstructions in deep time.

4. Geochronology

U–Pb dating is based on the radioactive decay of ^{238}U to ^{206}Pb and ^{235}U to ^{207}Pb. The half-lifes currently adopted are those of Jaffey et al. (1971), determined to 0.70381 Gyr for ^{235}U and 4.4683 Gyr for ^{238}U. Due to the different rates of decay the ratios of radiogenic ^{207}Pb and ^{206}Pb change continuously over time, making the common-lead corrected $^{207}Pb/^{206}Pb$ ratio itself a direct expression of time. Agreement between the two U–Pb chronometers implies that the two decay systems have not been disturbed in any way, i.e.in any loss or gain of Pb or U. The continuous change in Pb/U ratios can be graphically visualized in the concordia diagram (Fig. 6) with $^{206}Pb/^{238}U$ versus $^{207}Pb/^{235}U$ (Wetherill, 1956). Analyses where the two isotopic systems are in agreement, i.e. plot on the concordia trajectory, are termed concordant. Fractions that plot below or above the concordia are termed discordant, and reflects disagreement between the $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ dates. For analyses of zircon, this is often attributed to loss of Pb. In young samples, a lack of secular equilibrium in the intermediate decay chains would also result in discordance. Baddeleyite fractions that plot discordant often reflects a mixture of primary baddeleyite and secondary zircon rims (Heaman and LeCheminant, 1993).

Negatively discordant analyses plots above the concordia curve. Technically, a negative discordance could be achieved by loss of U or Pb gain, however, neither is a probable process in geological samples. It is far more likely that negative discordance reflects an analytical error, overestimation of blank levels being the most probable cause.

Baddeleyite (ZrO_2; Fig. 7) constitutes a common accessory phase in a wide variety of rocks, including basalt, dolerite, gabbro, anorthosite, picrite, pyroxenite, kimberlite and carbonatite (Heaman and LeCheminant, 1993). In dolerites and gabbros, baddeleyite crystallize as a late stage accessory phase and thus tend to occur in interstices. The crystals take the form of thin plates or needles typically 20–80 µm in the longest direction. Baddeleyite incorporates U (usually between 200 and 1000 ppm, Heaman and LeCheminant, 1993) in its crystal structure, but only allows for negligible amounts of initial Pb, which makes is an ideal mineral for U–Pb geochronology. In response to increased silica activity during metamorphism, baddeleyite readily transforms into zircon ($ZrSiO_4$). Polycrystalline zircon rims are therefore commonly found as rims around igneous baddeleyite grains in mafic rocks that have undergone metamorphism even at low conditions (Heaman and LeCheminant, 1993; Söderlund et al., 2013). Moreover, baddeleyite formed during metamorphism is rare with only few reported cases in the peer-reviewed literature (Kato and Matsubara, 1991,

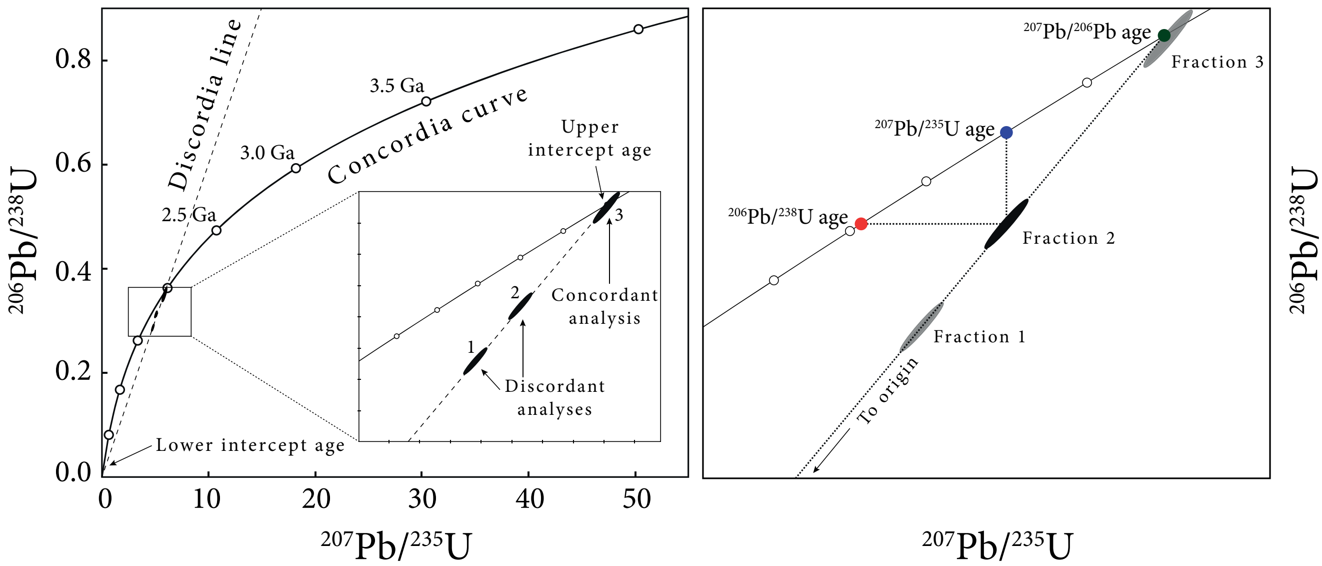

Fig. 6. Principle concordia diagram. *Left:* The concordia trajectory is an exponential curve composed of concordant $^{207}Pb/^{235}U$ and $^{206}Pb/^{238}U$ ages from present time to 4.6 Ga. The concordia diagram is a method to graphically plot and evaluate discordant U–Pb data. In this example, fraction 3 is the only concordant analyses whereas fraction 1 and 2 are variably discordant. A best-fit regression line (discordia) through all three analyses defined two intercepts. The upper intercept were the discordia intersects the concordia curve is usually taken as the age of the sample. The lower intercept reflects the age discordance developed, for instance by Pb-loss. In this case the lower intercept age is 0 Ma, i.e. the crystals have experienced recent Pb-loss. *Right:* $^{207}Pb/^{235}U$ (red), $^{206}Pb/^{238}U$ (blue) and $^{207}Pb/^{206}Pb$ (green) ages for fraction 2. The $^{207}Pb/^{206}Pb$ age is defined by the intersection between the concordia curve and a discordia line for this individual fraction (through the analysis and origin) and is in this case not affected by recent Pb-loss. In the case of normal discordance, a $^{207}Pb/^{206}Pb$ age represents a minimum age of the sample. For the concordant fraction 3, $^{207}Pb/^{235}U$, $^{206}Pb/^{238}U$ and $^{207}Pb/^{206}Pb$ ages are statistically identical (i.e. concordant).

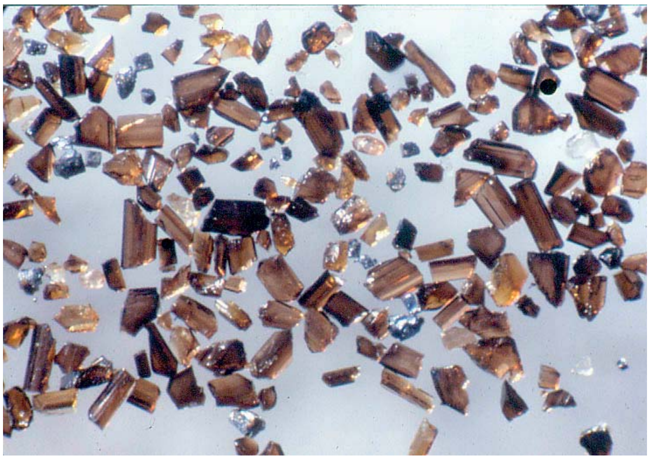

Fig. 7. Striated and dark to medium brown baddeleyite grains and fragments. Photo by M. Hamilton.

cited in Heaman and LeCheminant, 1993; Rubatto and Scambelluri, 2003; Fraser et al., 2004). Xenocrystic baddeleyite has only been reported from rapidly ascending kimberlite magmas (Schärer et al., 1997). Owing to these qualities, interpretation of baddeleyite U–Pb age determinations is relatively uncomplicated. Baddeleyite U–Pb ID-TIMS (isotope dilution thermal ionization mass spectronomy) is an analythical method which typically yield ages with a precision better than 0.1% at 2σ.

Recent advances in our ability to recover minute baddeleyite grains from almost all mafic dyke swarms (Söderlund and Johansson, 2002), and to date these with high-resolution U–Pb geochronology (Krogh et al., 1987; Heaman and LeCheminant, 1993) allows for comparison of magmatic records between now globally-dispersed cratonic fragments. Thereby plate reconstructions can be tested at least back to the Archaean-Proterozoic boundary. In addition to carrying baddeleyite, mafic dykes contain minerals ideal for preserving primary paleomagnetic information allowing for determination of paleolatitude and azimuthal orientation at the time of crystallization.

5. North Atlantic Craton

To avoid confusion, some notes regarding the nomenclature of North Atlantic Craton needs to be addressed. By some workers, Nain [craton] is used to denote the Archaean of NE Labrador (i.e. Nain province), along with SW and SE Greenland and the Lewisian Complex in Scotland. Others restrict the use of Nain to mean Nain [province] sensu strictu, i.e. the westernmost flank of the once contiguous craton which as a whole is termed North Atlantic Craton. The latter usage is employed herein.

North Atlantic Craton is postulated to have been a contiguous landmass from late Archaean to late Mesozoic and Palaeogene rifting and opening of northern Atlantic Ocean and Baffin Bay, Davis Strait and Labrador Sea (e.g. Hall et al., 1990; Bridgwater et al., 1973). Correlations between present day western Greenland and eastern Canada margins have been the subject of many studies focusing on tectonostratigraphy and orogenic, magmatic and metamorphic histories (e.g. Korstgård et al., 1987; Friend and Nutman, 1994; Connelly et al., 2006; St-Onge et al., 2009). Both Nain province and southern West Greenland constitutes accreted arc terranes of mainly Mesoarchaean TTG-derived gneisses (Friend and Nutman, 2005; Steenfelt et al., 2005; Windley and Garde, 2009). While southern West Greenland is well-studied, the amount of published peer-reviewed papers regarding the Archaean of south East Greenland is very limited. The Lewisian Complex in NW Scotland constitutes a small sliver of the North Atlantic Craton, commonly postulated to have been closely associated throughout the Proterozoic and Archaean (Bridgwater et al., 1973; Myers, 1987; Hall et al., 1990).

5.1. Palaeoproterozoic mafic dykes in the Greenland portion of North Atlantic Craton

2500 Ma Kilaarsarfik dykes

The Kilaarsarfik dykes (single purple line in Fig. 8) are so far only constrained by two U–Pb age determinations at 2499 ± 2 Ma (Nilsson et al., 2010) and 2541 ± 60 Ma (E. Rehnström, pers. comm.). Most likely, these two samples are from the same dyke, as they were collected just a few hundred meters apart in the N-S direction of strike of the dyke. In older literature this generation is termed MD1, but since that subdivision also includes E-W trending dykes (herein termed Grædefjord dykes, see below) as well as younger N-S trending dykes (ca. 2215 Ma, Nutman et al., 1995), the name Kilaarsarfik dykes is preferred. As only a single, or possibly two, dykes of this age have been dated, their regional extent in southern West Greenland is virtually unknown. A N-S trend is shared by younger Palaeoproterozoic dykes: the 2050-2030 Ma MD3 dyke swarm (Nilsson et al., 2010; 2013) and 2215 Ma BN dykes (Nutman et al., 1995) making it unlikely the Kilaarsarfik dykes occur in any great density in the area.

2375–2365 Ma Grædefjord dykes

Two Grædefjord dykes (brown lines in Fig. 8) have been age determined by U–Pb baddeleyite at 2374 ± 4 Ma

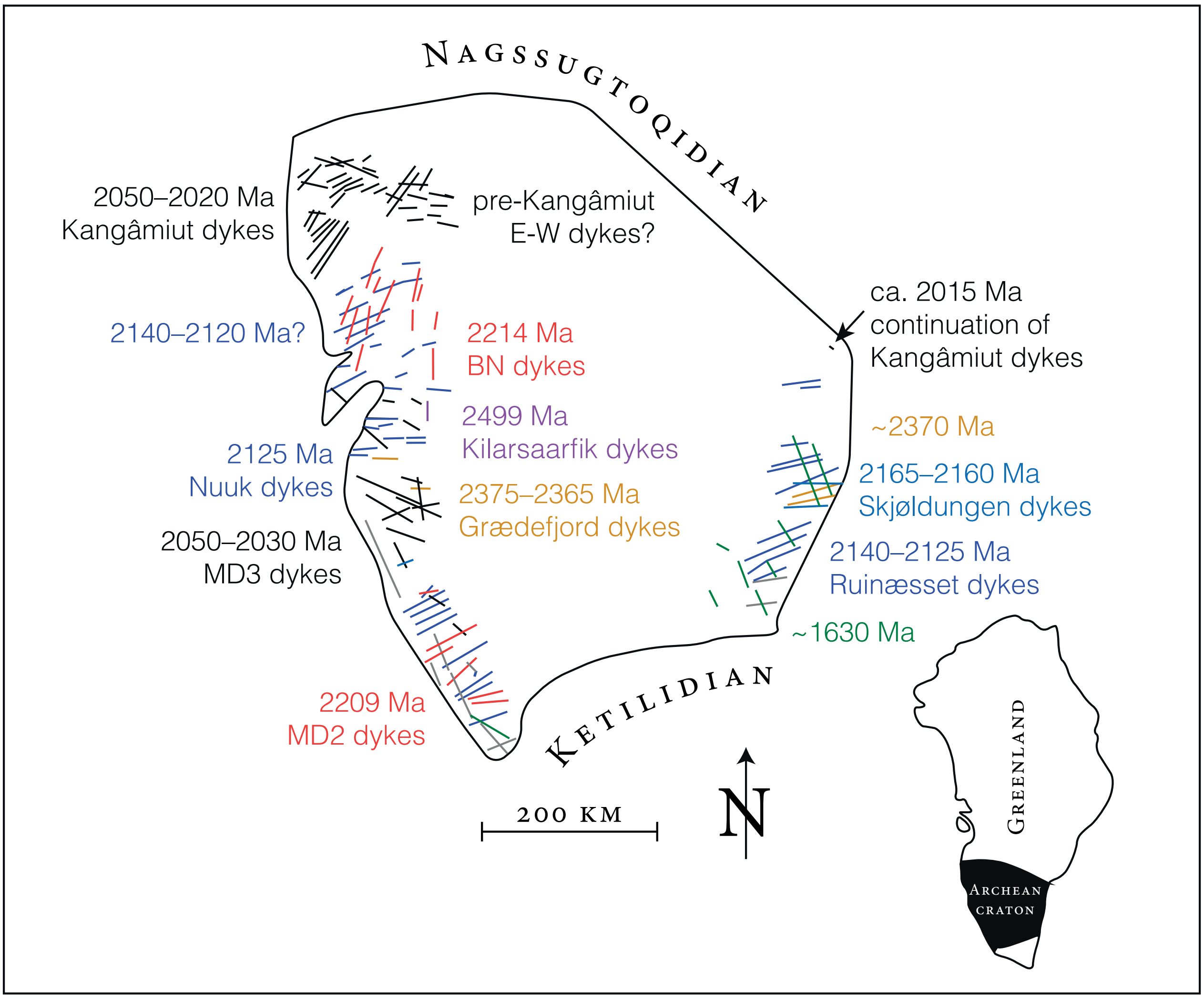

Fig. 8.

Principle Palaeoproterozoic dyke swarms in the Greenland portion of the North Atlantic Craton. Note that grey lines denotes younger suites of dykes: E-W trending ca. 1270 BD/Gardar dykes and coast-parallel Mesozoic to Paleogene dykes (Larsen et al., 2009; Bartels et al., 2016). Age references are: Kangâmiut dykes: Connelly et al. (2001); Nutman et al. (1999; 2008), BN dyke: Nutman et al. (1995), Kilaarsarfik dyke: Nilsson et al. (2010), Graedefjord dykes: Nilsson et al. (2013), Nuuk dyke: Nilsson (in prep.), MD2 dyke: Nilsson et al. (2013) Skjøldungen and Ruinæsset dykes: Nilsson (in prep.), ~1630 and ~2370 Ma dykes in SE Greenland: M. Nilsson, preliminary data.

and 2365 ± 2 Ma (Nilsson et al., 2013). Preliminary U–Pb results (M. Nilsson, unpublished data) suggest that this swarm extends beneath the inland ice to South-East Greenland.

2215 Ma BN dykes

The BN dykes (red lines with N-S trend in Fig. 8) belong to a suite named for their boninitic-noritic composition. They intruded the central part of southern West Greenland and has an overall N-S trend. A noritic BN dyke yielded an age of 2214 ± 10 Ma (Nutman et al., 1995). According to Nutman et al. (1995), the sample had a very low yield of zircon grains (only three from 500 g of sample) and notes the possibility they could have been lab contaminants. Nutman et al. (1995) originally interpreted the dyke as a member of the MD1 swarm.

2210 Ma MD2 dykes

The MD2 dykes belong to a NE-trending swarm named on the basis of trend and crosscutting relations with the older MD1 (i.e. 2.5 Ga Kilaarsarfik and 2.37 Ga Grædefjord dykes) and younger MD3 swarms (Chadwick, 1969; Rivalenti, 1975; Hall and Hughes, 1987). A MD2 dyke has yielded an age of 2209 ± 5 Ma (Nilsson et al., 2013), which is within errors coeval to the BN dykes. In Figure 8, the MD2 dykes are illustrated as red lines with a NE-SW trend.

2165–2160 Ma Skjøldungen dykes

Two E-W trending dolerite dykes from the Skjøldungen area in SE Greenland (light blue lines in Fig. 8) have been age determined at ca. 2165–2160 Ma (Nilsson, in prep.). They may be correlative to the Iggavik suite in SW Greenland, which has given an approximate Rb–Sr age of 2180 ± 100 Ma (Kalsbeek and Taylor, 1985). It is also possible that the Iggavik suite is correlative with the ca. 2210 MD2 dykes or younger Ruinæsset dykes (below), both of which have trends more similar to the Iggavik dykes.

2140-2125 Ma Ruinæsset-Nuuk dykes

In the vicinity of the Skjøldungen dykes in SE Greenland, two ENE- and NE-trending dolerite dykes have been age determined to ca. 2140 and 2125 Ma, respectively (dark blue lines in Fig. 8; Nilsson, manuscript in preparation). A single E-W trending dyke from the Nuuk area yielded an age of 2125 ± 9 Ma (Nilsson, in prep). Dykes of similar age also occurs in Nain province (2121 ± 2 Ma Tikkigatsiagak dyke, Hamilton et al., 1998 and 2142 ± 2 Ma Avayalik dyke, Connelly, 2001) Dark blue lines in Fig. 8 show a tentative distribution of dykes of similar age in Greenland. The interpretation of their occurrence intermixed with BN dykes is largely based on trend and extrapolated extension of Domes dykes in Nain province, which is probably correlative to the 2121 Ma Avayalik dyke (Hamilton et al., 1998; Connelly, 2001).

2050–2030 Ma MD3 dykes

Dykes belonging to the NW-SE to E-W trending MD3 swarm (black lines in the central west craton in Fig. 8) have been age determined to span an age interval of 2050–2030 Ma (Nilsson et al., 2010; 2013). Although the principal direction of dykes seems WNW-ESE, they can, at least locally, display northerly trends. The MD3 dykes are coeval to the Kangâmiut dykes, but occur up to 500 km south of the Kangâmiut area.

2045–2020 Ma Kangâmiut dykes

The Kangâmiut dykes (black lines in the north of the craton in Fig. 8) was early described by Ramberg (1949), who assigned all the dykes in the southern Nagssugtoqidian orogen to belong to the Kangâmiut swarm. The most prominent dykes of the Kangâmiut swarm have a NNE trend, with a lesser amount of coexisting E-trending dykes. The swarm as a whole is deflected and curved into an ENE-trend closer to the orogenic front (Escher et al., 1975; Ramberg, 1949). The Kangâmiut dykes are gradually more deformed and metamorphosed closer to the orogenic front, whereas they are fresh dolerites south of Maniitsoq (Willigers et al., 1999). Age determinations of Kangâmiut dykes have yielded ages within the 2045-2020 Ma age span (Nutman et al., 1999; Connelly et al., 2000). In addition, a ca. 2015 Ma age from the Ammasalik area in SE Greenland suggest that the Kangâmiut dykes are continuous under the inland ice (Nutman et al., 2008).

6. Discussion

6.1. Timing and duration of mafic intrusions with implications for paleoreconstructions

Present day volcanism occurs at various locations around the globe, without any relation or common origin. Since this observation should also be valid through Earth history, and a single age match between cratons therefore does not imply any common ancestry. Mafic dykes are emplaced in a variety of geological settings, with linear swarms commonly being associated with break-up of continental margins, back-arc basins or failed rifts. Supercontinent cycles infer that Earth history has been punctuated by periods of global enhanced rift-related magmatism.

The probability of finding age matches of events of mafic magmatism between cratons increases with increased duration of events, i.e. wide barcode lines. On the other side, a low number of age determinations with small margin of errors may create near-matches that do not statistically overlap. Nevertheless, such events could still have a common source due to small real age differences locally and/or an insufficient amount of dykes dated. Wide barcode lines are controlled by either multiple, partially overlapping ages of longer-lived events or by a large age uncertainty in a single age. In the case of Skjøldungen and Ruinæsset dykes, the scarce amount of baddeleyite recovered is the controlling factor on the magnitude of error (± 8 and 11 Myr).

As the result of an increase in number of precisely dated mafic dykes and sill complexes, it has become evident that short to moderate duration events (1–10 Myr) are perhaps not so common as previously thought. Many dyke swarms represents relatively long duration events, with emplacement ages spanning several tens of Myr, which in turn increases the probability of global age matches. A few dyke swarms stand the test of multiple age determinations with their short duration intact, such as the 780 Ma Gunbarrel event (eight U–Pb age determinations) or the 2370 Ma Dharwar giant dyke swarm (nine U–Pb age determinations), with all ages statistically indistinguishable from each other (Harlan et al., 2003; Halls et al., 2007; French and Heaman, 2010; Kumar et al., 2012; Demirer, 2012). A famous example of a moderate duration event is the 1267 Ma Mackenzie dyke swarm, which represents the largest continental dyke swarm in the world. All the magmatic activity, represented by both dykes and sills, is considered to have occurred within a few million years (LeCheminant and Heaman, 1989).

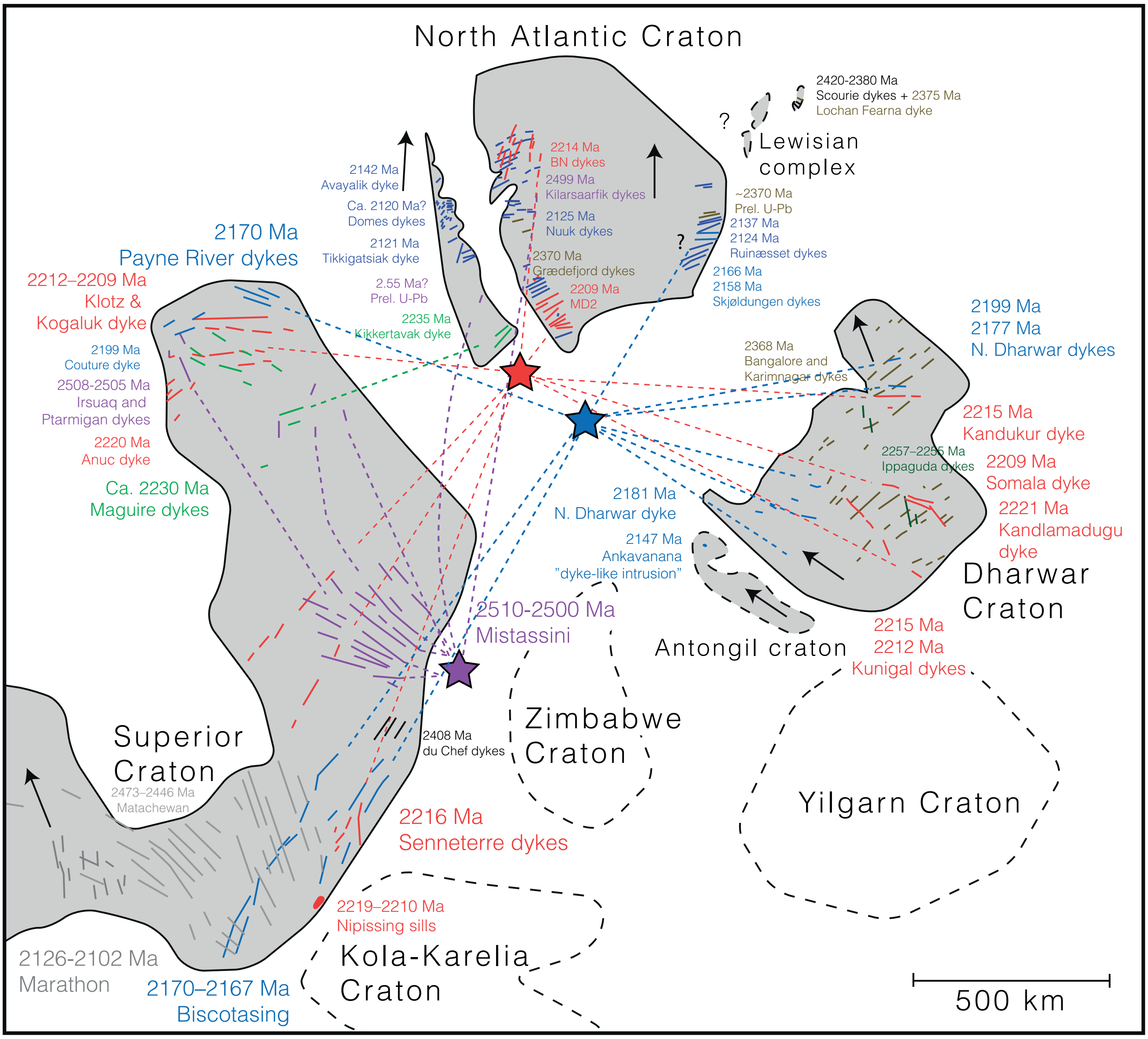

Fig. 9. Sketch map of proposed Superia configuration during the early Paleoproterozoic (2.37–2.17 Ga). Note that the northern Dharwar Craton is rotated relative to the southern part of the craton, in accordance with Kumar et al. (2012) and Belica et al. (2014). Zimbabwe, Yilgarn and the Kola-Karelia cratons are placed after a paleomagnetically permissive reconstruction by Pisarevsky et al. (2015). The opening of Labrador Sea is corrected for as suggested by Nilsson et al. (2010). The Lewisian complex and Antongil Craton are tentatively located in placeholder positions. Age references are found in Table 2, Paper IV in this thesis. Superior craton is modified from Buchan et al. (2007) and Maurice et al. (2009) and Dharwar Craton after French and Heaman (2010).

The short duration of dyke and sill emplacement together with the large magma volume and radiating geometry of this swarm, makes a mantle plume origin probable (LeCheminant and Heaman, 1989; Ernst and Baragar, 1992). Mantle plume origins have also been suggested for dyke swarms with longer duration, for example the Marathon Large Igneous Province with a total duration ~60 Myr between 2126–2067 Ma (Halls et al., 2008). Dyke swarms postulated to belong to this single, but periodic, plume event converges towards a common focal point, which implies a stationary plume in respect to the overlying continental block.

A wide barcode line for one craton can result from multiple age determinations of a single swarm, whereas in another craton only a single unit of a correlative unit might have been analysed. The take-home message is that caution needs to be taken even in the case of multiple individual age matches, and for each event we need to assess the probability of the magmatic units being genetically related to each other. The use of barcodes and geometries of dyke swarms can be a powerful tool not only to make first order assessments of probable cratonic configurations, but might also aid in evaluating the robustness of barcode correlations. There are several challenges in the proposed reconstruction of Superia (Fig. 9), discussed below.

6.2. Was North Atlantic Craton adjacent to Superior Craton from 2.5 Ga?

The 2.5 Ga Kilaarsarfik dyke (purple), is tentatively speculated to be distally related to the Mistassini plume center, but provide little constraints on the North Atlantic-Superior cratons reconstruction. Coeval and conjecturally related Irsuaq and Ptarmigan dykes in Superior Craton display a significant curvature in their geometry. The 1267 Ma Mackenzie dyke swarm (LeCheminant and Heaman, 1989) display a similar reorientation with increased distance from the focal point, attributed to regional stresses that begin to dominate over central radial stresses caused by plume uplift (Ernst, 2014). The single Kilaarsarfik dyke cannot be attributed to any overall swarm trend as the extension of dykes of this generation in southern West Greenland is unknown. Coupled with an overall curvature of dykes >1000 km away from the plume center (Ernst, 2014), there are too many degrees of freedom for the Kilaarsarfik dyke to provide strong constraints on the position of North Atlantic Craton relative Superior Craton at this time.

6.3. Was North Atlantic and Superior cratons adjacent to Dharwar Craton from 2.37 Ga?

The 2375–2365 Ga Graedefjord dykes (brown in Fig. 9) are a unique barcode event globally, only found in North Atlantic and Dharwar cratons. In the Dharwar Craton, the Bangalore-Karimnagar (hereafter Dharwar Giant dyke swarm, after Kumar et al., 2012) dykes have ages that are statistically undistinguishable from each other (Halls et al., 2007; French and Heaman, 2010; Kumar et al., 2012; Demirer, 2012). Dharwar Giant dyke swarm converges onto a point ca. 300 km west of the craton, and this focal point has been suggested to mark a mantle plume (French and Heaman, 2010; Kumar et al., 2012). The areal extent of 140,000 km^2, high abundance of dykes and a short duration of emplacement also speak in favour of a mantle plume origin. However, Kumar et al. (2012) noted the possibility of intracratonic counter-clockwise rotation of the northern part of Dharwar Craton with respect to the southern part. The suggestion was based on a curvature in the structural grain in the Archaean basement, fanning pattern of dykes as well as paleomagnetic data from a 250 km long ca. 2.2 Ga dyke in the central craton (probably the same dyke age determined to 2215 ± 2 Ma by Srivastava et al. 2011; 2014). This dyke was sampled in both its northern and southern parts and show significant difference in declination in accordance of rotation of northern relative southern Dharwar. Belica et al. (2015) presented further paleomagnetic data that supports an intracratonic rotation of Dharwar. Assuming that the rotation occurred after intrusion of 2220–2210 Ma Kunigal dykes (French and Heaman, 2010; Demirer, 2012; Srivastava et al., 2011; 2014), a tentative restorative rotation of Dharwar Craton instead allows the Dharwar Giant dyke swarm to be roughly linear. If a greater amount of restorative rotation is needed, the focal point of a tentative mantle plume center would be located to the east of the craton instead of to the west as suggested by French and Heaman (2010) and Kumar et al. (2012). In the presented paleoreconstruction, the Grædefjord and Dharwar giant dyke swarm would then converge to a point to the right of North Atlantic Craton in the diagram. An eastern focal point of the Dharwar giant dyke swarm would be compatible with the greater density of 2.37 Ga dykes in the eastern compared to the western Dharwar Craton. The age match between the Dharwar giant dyke swarm and the Grædefjord dykes are unique, but provides many degrees of freedom in the reconstruction.

The rotational restoration also allows the trends of 2255 Ma Iggapuda dykes (Fig. 9, dark green lines) in northern and southern Dharwar Craton to be parallel to each other, while both 2220–2210 Kunigal dykes (red lines, Fig. 9) and 2199–2177 Ma Northern Dharwar dyke swarm (blue lines in Fig. 9; French and Heaman, 2010; Demirer, 2012) both have radiating geometries.

In Figure 9, ca. 2220–2210 Ma dykes are allowed to converge towards the proposed Ungava plume center (red star). In North Atlantic Craton, only two dykes have been age determined within this time span, a 2209 ± 5 Ma MD2 dyke and a 2214 ± 10 Ma BN dyke (Nilsson et al., 2013; Nutman et al., 1995). The BN dyke has a noritic composition, as has the 2209 ± 3 Ma Somala dyke dated by French and Heaman (2010). Note that inferred MD2 dykes in Figure 8 are based on trend and relative ages, but some of these might instead be correlative of 2235 Ma Kikkertavak dykes in Nain province (green in Fig. 9; Cadman et al., 1993).

The ca. 2170 Ma Biscotasing plume centre (blue star in Fig. 9) allows dykes in the Superior Craton and the Northern Dharwar dyke swarm to converge onto a common focal point. The Northern Dharwar dyke swarm has shown to have older components and thus a longer duration than previously thought (2199–2177 Ma as opposed to 2181–2177 Ma, Demirer, 2012; French and Heaman, 2010). In the North Atlantic Craton, the Skjøldungen dykes are somewhat younger (2166–2158 Ma). The E-W trend of the Skjøldungen dykes do not perfectly line up with the Biscotasing plume centre. This might infer that the Skjøldungen and Northern Dharwar dykes are not genetically linked, which is corroborated by their just barely overlapping ages.

6.4. Additional remarks

As discussed, many assumptions are inherent in paleoreconstructions based on dyke swarm geometry alone. In addition, although dyke swarm orientations may indicate the regional tectonic stress direction, the trends of individual dykes might be local and related to pre-existing structural lineaments in the basement rocks. Dyke trends recorded at the sampling site might not always reflect the overall trend of the dyke or the swarm. Satellite and aerial photographs can be useful in solving these issues, given that the resolution is sufficient. What we are interested in, in the end, is to ascertain the main orientation of the swarm instead of that of individual dykes. The subdivision of dykes into distinct suites is commonly based on region of occurrence, trends, relative or absolute ages, petrography or geochemistry. In some locations, dyke generations are intermixed and indistinguishable from each other based solely on these criteria. Geochemistry is often used in complement to geochronology in attempt to distinguish between subswarms. However, in many cases crustal contamination dominate the geochemical signatures over source magma, as exemplified in e.g. Gumsley et al. (2015). In their paper geochemistry of dykes have unique signatures that can be correlated to three distinct cratonic areas, not to ages or trends. Paleomagnetic studies of the dyke generations dated herein would test the proposed reconstruction, and strongly constrain the position of North Atlantic Craton during the Palaeoproterozoic.

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Svensk sammanfattning

Ett antal superkontinenter har existerat under jordens 4.6 Ga (miljarder år gamla) historia. Utav dessa är superkontinenten Pangea, som betyder ”allt land”, den senaste och mest väldefinierade. Bildning och uppsprickning av superkontinenter drivs av plattektoniska processer som i sin tur beror på strömningar (konvektion) i jordens mantel. Förutom dessa processer så anses numera mantelplymer ha haft betydelse för uppsprickning av superkontinenter. Dessa kan ses som uppvälvning av varmt material från jordens inre som rör sig uppåt tills de kommer i kontakt med jordens yttre hårda skal – litosfären. Då detta sker kommer sprickor bildas i litosfären längs vilka magmor kan röra sig mot ytan och där orsaka omfattande vulkanism. Det är idag allmänt accepterat att ett antal mantelplymer var involverade i Pangeas uppsprickning.

Magma från jordens inre kan tränga upp genom berggrunden och kristallisera som diabasgångar med olika geometrier, såsom parallella eller radierande svärmar. Större magmatiska händelser som leder till uppsprickning av kontinenter är ofta relaterade till s.k. mantelplymer och ger upphov till radierande gånggeometrier. Det finns ett antal superkontinenter före Pangea som idag är mer eller mindre vedertagna: 0.6–1.1 Ga Rodinia och 1.3–1.8 Ga Columbia. Mycket tyder på att det också funnits en äldre superkontinent. Fragment från denna äldsta kontinentala landmassa återfinns idag som ca. 35 lithosfärfragment utspridda över jordens yta. Ett av dessa fragment utgörs av södra Grönlands berggrund tillsammans med en del av nordöstra Kanada (Nain province) samt Lewisian Complex i nuvarande Skottland. Förekomsten av diabasgångar utgör spår av yngre episoder av magmatiska händelser. Diabas innehåller ofta små mängder av mineralet baddeleyit, som går att åldersbestämma med U–Pb metoden, genom att uran sönderfaller till bly med känd hastighet. Genom att mäta halterna av olika uran- och blyisotoper kan man beräkna åldern för dessa episoder av magmatism. Varje kontinentalt fragment har således en egen ”magmatisk historia”, som går att visualisera i ett så kallat streckkodsdiagram. Streckkodsdiagrammet tillåter oss att jämföra tidpunkterna för dessa magmatiska händelser och utifrån dessa jämförelser kunna utvärdera vilka kontinentala fragment som en gång satt ihop i en större landmassa.

I mitt doktorandarbete har jag åldersbestämt diabasgångar från sydvästra och sydöstra Grönland (arkeiska provinsen North Atlantic Craton). Ett stort antal generationer av diabasgångar har identifierats tack vare dessa nya åldersbestämningar och deras åldrar är ca. 2.5 Ga, 2.37 Ga, 2.21 Ga, 2.17 Ga, 2.13 Ga och 2.04 Ga. Streckkodsdiagram för Grönland visar att flera likåldriga diabasgenerationer också finns i Dharwar craton i nutida södra Indien samt i Superior Craton i Kanada. I denna avhandling presenterar jag en rekonstruktion över dessa kontinenters möjliga lägen relativt varandra. Min hypotes utifrån dessa resultat är att dessa tre landmassor kan ha suttit i en större landmassa kallad Superia.

Appendix A

Papers not included in this thesis.

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