North Atlantic Craton architecture revealed by kimberlite-hosted crustal zircons

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A B S T R A C T

Archean cratons are composites of terranes formed at different times, juxtaposed during craton assembly. Cratons are underpinned by a deep lithospheric root, and models for the development of this cratonic lithosphere include both vertical and horizontal accretion. How different Archean terranes at the surface are reflected vertically within the lithosphere, which might inform on modes of formation, is poorly constrained. Kimberlites, which originate from significant depths within the upper mantle, sample cratonic interiors. The North Atlantic Craton, West Greenland, comprises Eoarchean and Mesoarchean gneiss terranes – the latter including the Akia Terrane – assembled during the late Archean. We report U–Pb and Hf isotopic, and trace element, data measured in zircon xenocrysts from a Neoproterozoic (557 Ma) kimberlite which intruded the Mesoarchean Akia Terrane. The zircon trace element profiles suggest they crystallized from evolved magmas, and their Eo- to Neoarchean U–Pb ages match the surrounding gneiss terranes, and highlight that magmatism was episodic. Zircon Hf isotope values lie within two crustal evolution trends: a Mesoarchean trend and an Eoarchean trend. The Eoarchean trend is anchored on 3.8 Ga orthogneiss, and includes 3.6–3.5 Ga, 2.7 and 2.5–2.4 Ga aged zircons. The Mesoarchean Akia Terrane may have been built upon mafic crust, in which case all zircons whose Hf isotopes lie within the Eoarchean trend were derived from the surrounding Eoarchean gneiss terranes, emplaced under the Akia Terrane after ca. 2.97 or 2.7 Ga, perhaps during late Archean terrane assembly. Kimberlite-hosted peridotite rhenium depletion model ages suggest a late Archean stabilization for the lithospheric mantle. The zircon data support a model of lithospheric growth via tectonic stacking for the North Atlantic Craton.

1. Introduction

The Archean cratons, the nuclei of modern continents, are composites of terranes formed at different times, possibly in distinct geodynamic settings, resulting in a juxtaposition of heterogeneous crustal blocks (e.g., Bleeker, 2003; Friend et al., 1988; Percival et al., 2006). Many Archean cratons are underpinned by a thick (>250 km), refractory, sub-continental lithospheric mantle (Griffin et al., 2004; Kamber and Tomlinson, 2019; Michaut et al., 2009; Pearson,

1999; Wang et al., 2018). However, the mode of development of this deep lithospheric root is of debate, with contrasting models of vertical growth versus horizontal accretion of different terranes (e.g., Arndt et al., 2009; Griffin and O'Reilly, 2007; Rollinson, 2010). Further, how the documented across-strike differences in Archean terranes are reflected at depth, both within the lower crust and the lithospheric mantle, is poorly constrained, primarily due to the difficulties in establishing vertical profiles through the cratonic lithosphere.

One means to sample the interior of cratons is via kimberlites. Kimberlites are rare, volumetrically minor, enriched ultramafic igneous intrusions, which originate from significant depths (>150 km) within the deep upper mantle (Mitchell, 1986). These mag-
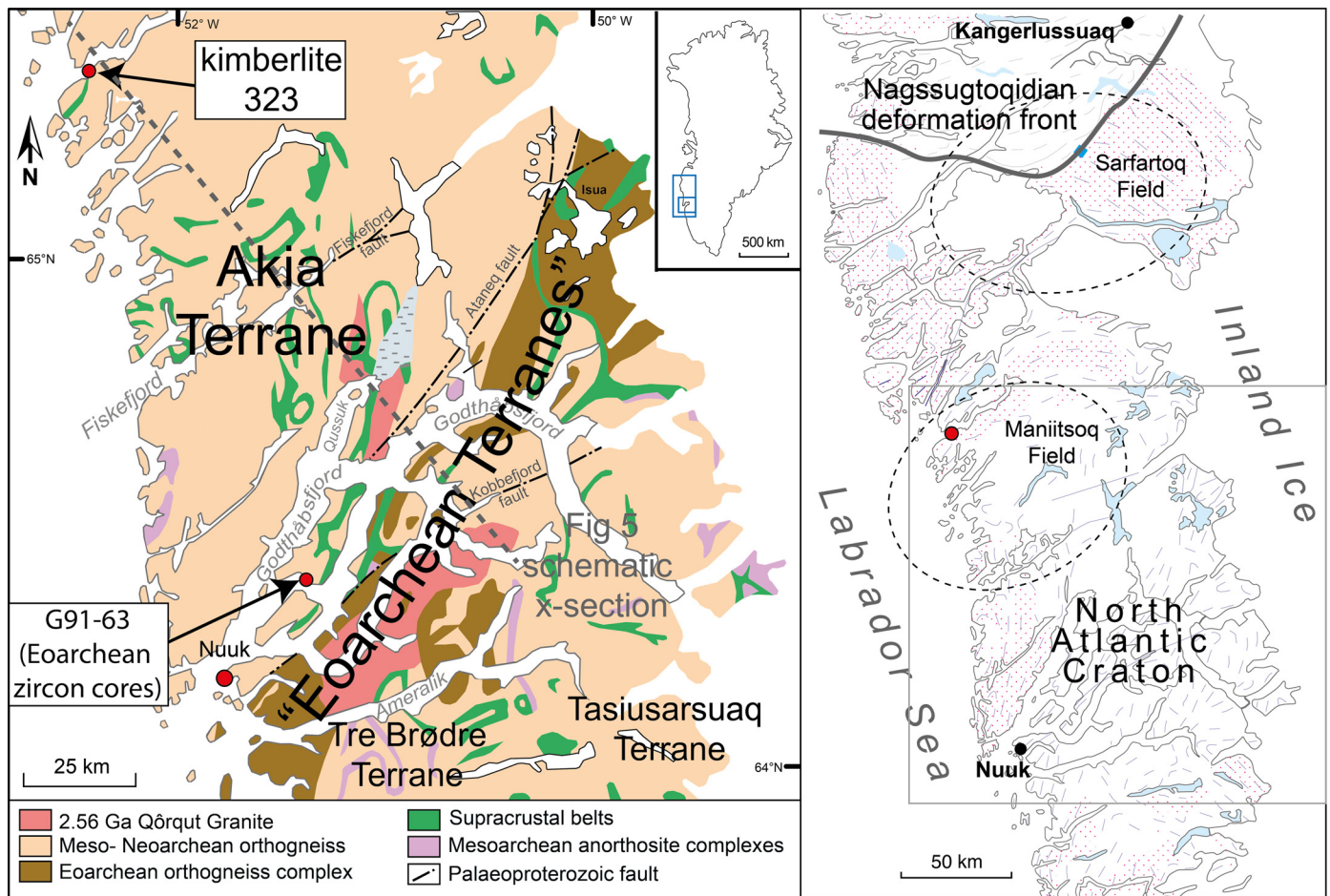
Fig. 1. Left panel: Simplified geological map of the Nuuk area, with kimberlite 323 locality highlighted. The "Eoarchean terranes" contain Eo- to Neoarchean orthogneiss assemblages and granitic derivatives. The locality of sample G91-63 of Friend et al. (1996) at the southern margin of the Akia Terrane, a ca. 2.7 Ga granite dyke containing inherited Eoarchean zircon cores, is also shown. The dotted line represents the trace of the cross-section in Fig. 5. Right panel: Regional map of West Greenland, showing the location of the Sarfartoq and Maniitsoq kimberlite fields, and the Nagssugtoqidian deformation front. Maps modified from Næraa et al. (2014) (left panel) and Windley and Garde (2009) (right panel). (For interpretation of the colours in the figure(s), the reader is referred to the web version of this article.)

mas may carry exotic cargo, entrained during ascent, commonly in the form of peridotite or eclogite xenoliths (Pearson, 1999; Schmitz and Bowring, 2001; Tappe et al., 2011b). However, kimberlites also carry zircon, commonly mantle-derived megacrysts (Sun et al., 2018; Valley et al., 1998), but also xenocrystic zircon that crystallized from evolved crustal magmas. Kimberlites thus offer a probe into craton interiors by sampling their lithosphere, providing insight into its age, and chemical history (e.g., Bernstein et al., 2013; Griffin et al., 2004; Wittig et al., 2008).

Here, we present U–Pb and Hf isotopes, and trace element data, measured in xenocrystic zircon crystals hosted by a Neoproterozoic (557 Ma) kimberlite intrusion located in the North Atlantic Craton of West Greenland. Eo- to Neoarchean U–Pb ages coupled with Hf isotope data from these zircons are similar to that recorded in exposed adjacent tonalite-trondhjemite-granodiorite (TTG) gneiss terranes. Data from the xenocrystic zircons reproduce the regional pattern of Archean continental crust formation and evolution, and highlight that in the North Atlantic Craton this magmatism was episodic and followed at least two distinct crustal evolution trends. The kimberlite zircon cargo thus sampled vertically the regional pattern of evolved crust outcropping laterally, implying the presence of evolved crust buried within the cratonic lithosphere. A tectonic stacking model has previously been invoked for the formation of the North Atlantic Craton in West Greenland (e.g., Tappe et al., 2011b; Wittig et al., 2008) and we discuss this model in the context of our new zircon data.

2. Archean West Greenland

The North Atlantic Craton (NAC) in West Greenland provides one of the key examples of early Archean cratons, and there is much speculation on the tectonic mode(s) of its formation (Bridgwater et al., 1974; Friend et al., 1988; Friend and Nutman, 2019). In the Nuuk region, the NAC is largely composed of Eo- to Neoarchean orthogneiss and their granitic derivatives, including Earth's most extensive tract of Eoarchean crust, the Itsaq Gneiss Complex (Nutman et al., 1996). The NAC continental crust has been broadly subdivided into Eoarchean and Mesoarchean gneiss terranes (Fig. 1) on the basis of structural associations, metamorphic grade, and protolith age (Friend and Nutman, 2005, 2019). These terranes are interpreted to have had their final assembly via horizontal accretion during the Neoarchean (Friend et al., 1996).

The "Eoarchean terranes" form a narrow 200 km-long belt exposed from the mouth of Nuuk Fjord (Godthåbsfjord) northeast (Fig. 1), and are made up of 3.89–3.60 Ga orthogneiss (Hiess et al., 2011; Nutman et al., 1999b), with later Meso- to Neoarchean orthogneiss assemblages and granitic derivatives. The Eoarchean terranes are bordered to the north and south by Mesoarchean terranes (Friend and Nutman, 2019), and the Mesoarchean terrane immediately to the north is the Akia Terrane (Fig. 1). The Akia Terrane is formed of two major orthogneiss components: ca. 3.2 Ga diorite mainly cropping out in the southern part of the Akia Terrane, and ca. 3.0 Ga tonalite, which volumetrically dominates the northern part of the terrane (Garde, 1997; Gardiner et al., 2019).
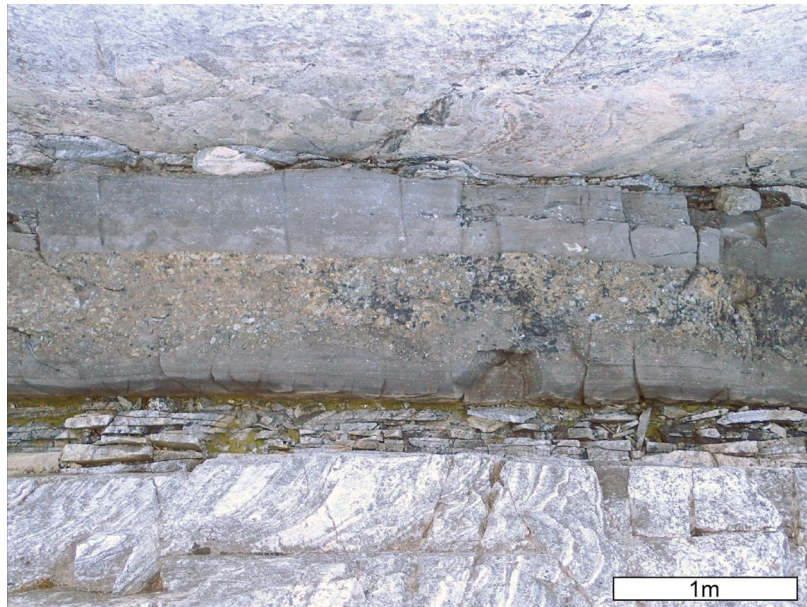
Fig. 2. Outcrop photograph of kimberlite 323. The xenocryst- and xenolith-rich sheet from where the zircon crystals were extracted is clearly observed. Dyke thickness is approximately 120 cm.

The protracted assembly of the Eoarchean and Mesoarchean terranes, beginning in the Mesoarchean and culminating during the Neoarchean, led to extensive crustal reworking, and is recorded by two regional magmatic events: ca. 2.7 Ga intrusion of granitic (*s.s.*) sheets and pegmatites (Friend et al., 1996; Kirkland et al., 2018), and ca. 2.5 Ga granitic magmatism. This latter magmatism includes the extensive 2.56 Ga Qôrqut Granite Complex (Fig. 1) (Friend et al., 1985) interpreted as marking the final assembly of the NAC (Næraa et al., 2014).

2.1. Kimberlite sample 323

Widespread kimberlitic dyke intrusions are found throughout West Greenland (Larsen and Rex, 1992; Nielsen et al., 2009; Tappe et al., 2018). Whereas those ultrapotassic dykes occurring within the northern Sarfartoq field at the NAC margin (Fig. 1) have lamprophyric to aillikitic affinities, the intrusions located in the Maniitsoq field within the core of the craton are *bona fide* kimberlites (Nielsen et al., 2009).

Kimberlite sample 323 crops out in the north of the Akia Terrane, on the shore of Isortoq fjord (65.38785N, −52.4014W), and is located within the Maniitsoq kimberlite field (Fig. 1). In outcrop, it intrudes the 3.0 Ga tonalitic orthogneiss as a dyke ∼120 cm wide. The kimberlite was emplaced as discrete sheets, with a fine-grained margin hosting a well-developed coarse-grained central sheet which contains xenocrysts of zircon, olivine, garnet and ilmenite, and rounded xenoliths of tonalite (Fig. 2).

Kimberlite sample 323 is the same locality as the kimberlite sample 483862 of Tappe et al. (2011a), and we interpret it to be the same intrusion. These authors dated the crystallization of the dyke to 556.5 ± 3.6 Ma (2σ) through Rb/Sr geochronology and, on the basis of its trace element and moderately depleted Sr-Nd-Hf isotopic compositions, interpreted its source as the top of the asthenosphere. Thus, during the end of the Neoproterozoic, the kimberlite may have ascended through the entire cratonic lithosphere, which in the central NAC may be up to 250 km thick (Wittig et al., 2010).

For this study, zircon crystals were extracted from a sample of the xenocryst- and xenolith-rich core of kimberlite sample 323, mounted in epoxy, and imaged using SEM cathodoluminescence (CL). Zircons were analyzed at the John de Laeter Centre for Mass Spectrometry, Curtin University, Perth, for U–Pb and Hf isotopes, and trace elements, via split-stream LA-(MC)-ICPMS. See supplementary data for methods and full tabulated results.

3. Results

The zircon crystals are variable in shape, ∼100 μm in length, and range from stubby to equant, but all have highly rounded terminations. Under CL imaging the grains reveal an array of internal textures including idiomorphic and contorted zoning and homogeneous domains (Fig. S2). Many grains are overgrown by a high-CL response overgrowth, which have low concentrations of uranium (∼33 ppm). The cores of other grains record higher uranium contents, up to 1200 ppm. Core domains were the primary analytical targets (Supplementary Table S1). Twenty-nine U–Pb analyses were undertaken on a range of zircon grains, of which 26 were within our discordance thresholds (<10% difference between ^{207}Pb/^{206}Pb and ^{238}U/^{206}Pb ages; red ellipses, Fig. 3A). Three analyses outside discordance thresholds are interpreted to have lost various amounts of radiogenic Pb (grey ellipses, Fig. 3A). ^{207}Pb/^{206}Pb ages for concordant analyses range from 3.6 to 2.4 Ga. Zircon U–Pb results are detailed in Supplementary Table S1.

Twenty-six Hf isotope analyses were matched with concordant ^{207}Pb/^{206}Pb ages; full results are detailed in Supplementary Table S2. Zircon εHf(t) (initial ^{176}Hf/^{177}Hf ratio normalized to chondrite) ranges from chondritic to highly sub-chondritic values (0 to −23 epsilon units). Plotting εHf(t) versus ^{207}Pb/^{206}Pb ages (evolution plot, Fig. 3B) highlights a general trend in εHf(t) with age, where older chondritic Hf isotope values trend towards younger more evolved (less radiogenic) values.

Zircon rare earth element (REE) compositions are detailed in Supplementary Table S3, and chondrite-normalized values are plotted in Fig. 4. We find enrichment in the heavy REE for all zircons, with a pronounced positive Ce anomaly, and a minor negative Eu anomaly. Older and younger zircon analyses are indistinguishable in terms of their REE profiles.
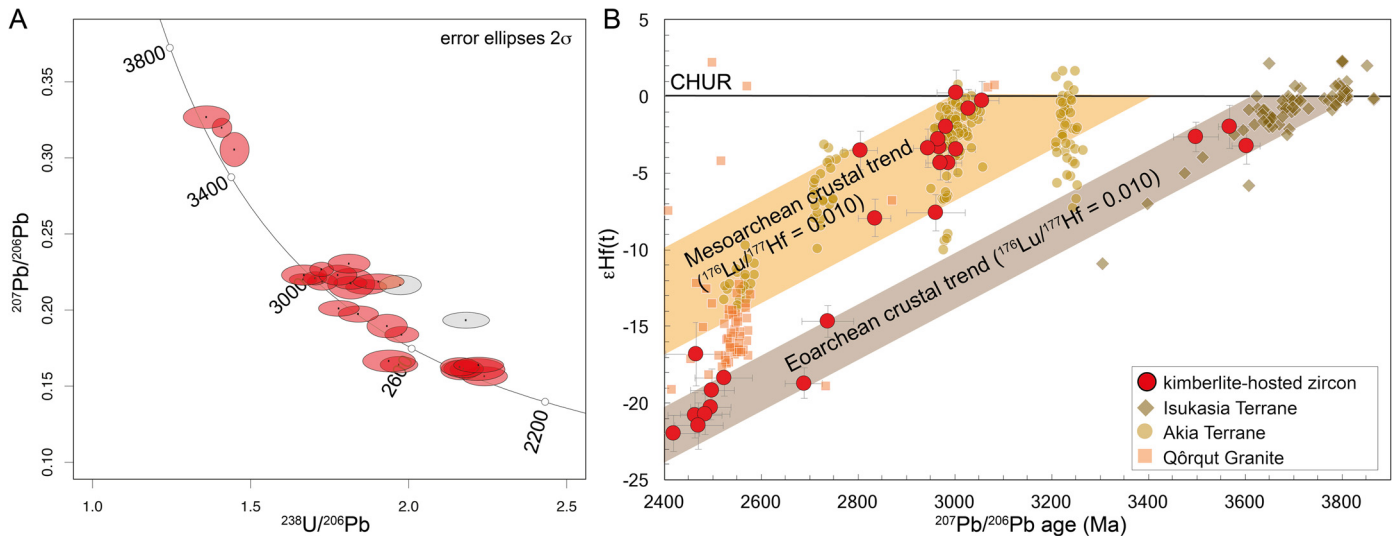
Fig. 3. A. Tera-Waserburg U–Pb Concordia plot for the kimberlite zircon data. Discordant analyses are coloured in grey. **B.** Hf isotope evolution plot for the kimberlite zircon data, red circles. Highlighted are the Eoarchean and Mesoarchean crustal evolution trends calculated using a $^{176}Lu/^{177}Hf = 0.010$ for evolved Archean crust (Gardiner et al., 2018). Also plotted are published Hf data from Eo- to Neoarchean TTG and dioritic gneisses from the northern Nuuk region from published sources (Gardiner et al., 2019; Hiess et al., 2011; Hoffmann et al., 2011, 2014; Kemp et al., 2009; Næraa et al., 2014, 2012). Where necessary, recalculation of the isotope data used the chondritic uniform reservoir (CHUR) values of Bouvier et al. (2008).
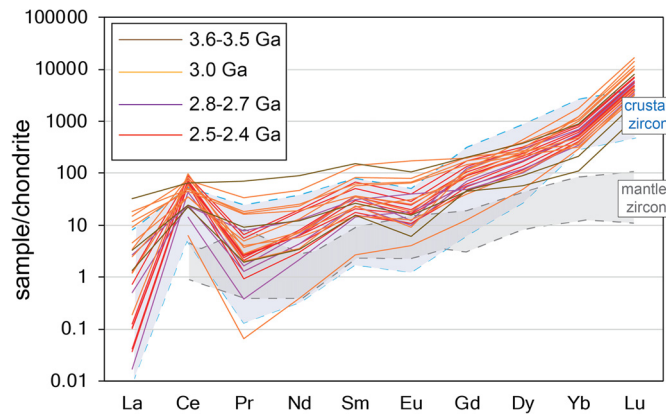

Fig. 4. Chondrite-normalized rare earth element (REE) plot for the xenocrystic zircons, coloured by $^{207}Pb/^{206}Pb$ age grouping. Also plotted are representative REE data from Eoarchean crustal zircons from West Greenland (Whitehouse and Kamber, 2003) and mantle-derived zircon megacrysts of Belousova et al. (1998). Chondrite composition of Palme and O'Neill (2003).

4. Discussion

4.1. Origin of the zircon xenocrysts

Although kimberlites are known to contain zircon megacrysts that are ultimately derived from the upper mantle (Sun et al., 2018; Valley et al., 1998), these zircons are mostly Phanerozoic in age with only a few dated to the Paleoproterozoic (Griffin et al., 2000). Further, such mantle-derived zircon crystals tend to be of a larger size than the xenocrystic zircons from the kimberlite studied here, and are absent any observed internal zonation patterns. The chondrite-normalized REE profiles measured in the analyzed xenocrystic zircons (Fig. 4) show pronounced enrichment in the heavy REE, typical of zircons grown within evolved crust (Hoskin and Ireland, 2000) and are a good match for that measured in zircons sourced from the surrounding TTGs (Fig. 4). These REE trends stand in contrast to the flatter profiles typically measured in rare mantle-derived zircons (Belousova et al., 1998), whose average values are also highlighted on Fig. 4. Hence, the separated zircon cargo of kimberlite sample 323 appears to lack any crystals that are mantle-derived.

A feature of Archean magmatic rocks cropping out in West Greenland is that they record discrete pulses of magmatism (Gardiner et al., 2019; Næraa et al., 2012; Nutman et al., 2004). We interpret the xenocrystic zircon $^{207}Pb/^{206}Pb$ ages to be magmatic on the basis of Th/U ratios being on average > 1.0 and the analyses targeted within zircon core domains with magmatic growth textures. These ages are striking in that they record the majority of the documented regional magmatic events, with groupings at: 3.6–3.5, 3.0, 2.8–2.7 and 2.5–2.4 Ga (Fig. 3). They thus provide a good match for those ages recorded from the surrounding gneiss terranes. The oldest xenocrystic zircon components (3.6–3.5 Ga) we interpret as sampling Eoarchean evolved crust. Rocks of this age in West Greenland are not present within the Akia Terrane, but primarily crop out within the Eoarchean terranes (e.g., Nutman et al., 2004) which have their surface expression ∼150 km south east of the kimberlite locality (Fig. 1), although rare Eoarchean rocks have also been documented some 200 km northeast of the Akia Terrane (Rosing et al., 2001).

The xenocrystic zircon population includes those with ages matching the 3.0 Ga tonalite of the Akia Terrane, but not the 3.2 Ga diorite (Fig. 3). This absence may either reflect the kimberlite dyke emplacement 80 km to the north of the main outcrop area of this dioritic component, or it could simply reflect a sampling bias. The 2.8 Ga xenocrystic zircons have ages similar to that recorded in the Mesoarchean terranes to the south of the Eoarchean terranes – the Tasiusarsuaq (Næraa and Scherstén, 2008) or Tre Brødre (Friend and Nutman, 2005) terranes (Fig. 1). The kimberlite also samples zircons similar in age to the 2.7 Ga and 2.5 Ga granitic magmatism linked to the final assembly of the NAC. We measure no $^{207}Pb/^{206}Pb$ ages in the xenocrystic zircons outside those ages recorded in the regional gneiss terranes.

Whole-rock Sr-Nd-Hf isotopes measured on the kimberlite dyke imply little crustal assimilation (Tappe et al., 2011a), which needs to be reconciled with the presence of xenocrystic zircons that imply some digestion of crustal material during ascent. In outcrop, the kimberlite dyke is sheeted, where discrete phases of magma both poor and rich in xenocrysts and xenoliths were sequentially emplaced, the latter forming a bifurcating central sheet within the dyke (Fig. 2). In this study, we specifically targeted this coarse-grained core sheet with the aim of extracting xenocrystic zircons,

and it may be that for whole-rock analysis the less contaminated margins of the dyke were sampled.

On the basis of their similar REE profiles and $^{207}Pb/^{206}Pb$ ages, it seems highly probable that the xenocrystic zircons were ultimately derived from tracts of local gneiss, which were entrained into the kimberlite magma as it passed through the lithospheric column in the latest Neoproterozoic (557 Ma). Thus, the kimberlite has effectively sampled vertically much of the regional Archean gneiss terranes that are found outcropping laterally.

4.2. Evidence for exotic evolved crust beneath the northern Akia Terrane

Hafnium isotope data measured in Eoarchean TTGs from the NAC are (sub)chondritic (Fig. 3B) (Hiess et al., 2011; Hoffmann et al., 2011, 2014; Kemp et al., 2009; Næraa et al., 2014, 2012). Within the Akia Terrane, less radiogenic (more evolved) Hf isotope values are measured in the Mesoarchean tonalites (0 to −10 epsilon units) (Gardiner et al., 2019) and interpreted as the tonalites having their origin through the partial melting of Eoarchean mafic crust. There is no evidence of Eoarchean felsic magmatism within the Akia Terrane. Later Neoarchean granitic magmatism across the Nuuk region exhibits a further shift towards highly unradiogenic Hf isotope values, as low as −20 epsilon units (e.g., Næraa et al., 2014).

At the surface, the kimberlite is emplaced into the ca. 3.0 Ga tonalites of the Akia Terrane, and that this crust is convincingly sampled is reflected in the similar $^{207}Pb/^{206}Pb$ ages and $\varepsilon Hf(t)$ recorded in the xenocrystic zircons (Fig. 3B) (Gardiner et al., 2019). However, a question remains whether the older, and younger, xenocrystic zircons were also sourced from within the surrounding Akia crust.

The tonalitic precursors of both the Eoarchean and Mesoarchean orthogneisses were derived from the partial melting of amphibolites (Gardiner et al., 2019; Hoffmann et al., 2014; Kemp et al., 2019; Nutman et al., 1999b). These tonalitic components represent juvenile addition of continental crust, and the Hf isotopic values of these new crustal additions can be used to anchor evolution trends, whose trajectory is defined by the Lu/Hf composition of the crustal reservoir. Taking evolved Archean crust as having an average $^{176}Lu/^{177}Hf$ value of 0.010 (e.g., Gardiner et al., 2018), two distinct crustal evolution trends can be identified within the NAC Hf isotope data: (i) Eoarchean, anchored at the 3.89–3.65 Ga gneisses; and (ii) Mesoarchean, anchored at the 3.0 Ga Akia tonalites (Fig. 3B).

It is notable that the 3.6–3.5 Ga xenocrystic zircon Hf data lie within the Eoarchean trend, plotting at subchondritic values, similar in $^{207}Pb/^{206}Pb$ age and $\varepsilon Hf(t)$ to that recorded from granitic augen gneisses and monzonites of the Eoarchean terranes (Hiess et al., 2011; Nutman et al., 2013). These granitic augen gneisses are only exposed at the present-day surface some 100–150 km southeast of the kimberlite locality, and have been linked to either crustally-derived magmatism associated with TTG reworking during the 3.65–3.60 Ga Isukasian Orogeny (Baadsgaard et al., 1986; Nutman et al., 2013), or the product of deep crustal melting (Hiess et al., 2011). While it is possible that these zircon data have experienced the Pb-loss which commonly affects Archean zircons, skewing the data towards younger ages and less radiogenic Hf (Kemp et al., 2019), these analyses would still reflect derivation from Eoarchean crust.

2.7 Ga granitic pegmatites outcropping within the Akia Terrane are interpreted on the basis of their Hf isotope signatures to be derived from the surrounding Mesoarchean tonalite (Gardiner et al., 2019). However, other regional 2.7 Ga magmatism is thought to represent the reworking of older Eoarchean TTG, with granite sheets cropping out on the southern margin of the Akia Terrane adjacent to the Eoarchean terranes documented as containing in-

herited Eoarchean zircon cores (Friend et al., 1996 sample G91-63; Fig. 1). The 2.7 Ga xenocrystic zircons have highly unradiogenic $\varepsilon Hf(t)$ (∼−19) which lie within the Eoarchean trend, suggesting they were derived from Eoarchean crust, and thus these zircons do not appear to reflect any known crust of the Akia Terrane.

The youngest 2.5–2.4 Ga xenocrystic zircons are similar in age to the 2.56 Ga Qôrqut Granite (Fig. 3B). This granite has a highly unradiogenic Hf isotope composition, interpreted as originating via partial melting of Eoarchean mafic crust (Næraa et al., 2014). The xenocrystic zircons of this age record even more unradiogenic Hf isotope compositions, and lie within the Eoarchean crustal trend. Thus, we interpret them as also being derived from reworking Eoarchean TTG, and not from the crust which forms the surface expression of the northern part of the Akia Terrane.

In summary, many of the kimberlite-hosted xenocrystic zircons fall outside the 3.0 Ga population (interpreted as reflecting the hosting Akia Terrane tonalite), and record Hf values implying that they were derived from crust formed through the reworking of Eoarchean TTG. Such Eoarchean crust is mainly found cropping out within the Eoarchean terranes to the south of the Akia Terrane, and thus the xenocrystic zircons with Eoarchean affinity pose the question of their origin.

In a geochronological campaign, over fifty tonalitic orthogneiss samples taken from across the northern Akia Terrane were analyzed by SIMS zircon U–Pb, and neither a single inherited nor xenocrystic zircon older than ca. 3.2 Ga was discovered (Kirkland et al., 2016). Further, the Mesoarchean and Eoarchean gneiss terranes have not previously been shown to be juxtaposed in a single crustal column during the major phases of crustal growth at 3.0 Ga, prior to craton assembly (Friend and Nutman, 2005). Thus, there is arguably no compelling evidence for any component of older (Eoarchean) felsic crust within the source of the 3.0 Ga tonalities, nor by extension any evidence for the Akia Terrane to have been built upon a crustal substrate that was anything other than dominantly mafic in composition. There is thus a lack of genetic relationship between the Akia Terrane and Eoarchean evolved crust, hence an exotic origin for the xenocrystic zircons with Eoarchean affinity appears a viable alternative.

It is suggested that kimberlite sample 323 had an opportunity to sample the entire lithospheric column that now underlies the NAC (Tappe et al., 2011a). We interpret all the exotic zircons to have their origin in the surrounding Eoarchean gneiss terranes, which predominantly lie to the south of the Akia Terrane. This would imply a relationship between these Eoarchean terranes and the Akia Terrane at depth, which must have developed after 3.0 Ga, the last phase of crustal growth of Akia. Such interpretation has fundamental implications for the mode of formation and architecture of the NAC.

4.3. Implications for craton development

A feature of the NAC sub-continental lithospheric mantle (SCLM) under West Greenland is the highly refractory nature of the mantle residues. It has an average olivine composition of Fo$_{92.6}$ (Bernstein et al., 2007; Wittig et al., 2008), interpreted as reflecting high degrees of melt extraction from the mantle. However, the geodynamic setting and timing of melt depletion is debated. Bernstein et al. (2007) argued for the formation of the NAC SCLM in a plume setting. The plume model implies continued melt extraction during terrane formation, leading to vertical growth of a deep refractory lithospheric root, and is similar to that invoked for the Paleoarchean East Pilbara Terrane of Western Australia (e.g., Smithies et al., 2005). Alternatively, Wittig et al. (2008) proposed terrane growth via shallow melting in a subduction zone, resulting in relatively thin (∼100 km) melt-depleted SCLM. In the model of Wittig et al. (2008), these thin tracts of crust and associated re-

fractory mantle residue were then tectonically imbricated through horizontal accretion to ultimately form the deep SCLM root that today underlies the NAC – so-called "lithospheric stacking" (e.g., Helmstaedt and Schulze, 1989; Wang et al., 2018).

One interpretation for the origin of the exotic xenocrystic zircons in kimberlite sample 323 is that they reflect the emplacement of separate tracts of evolved Eoarchean crust underneath the Akia Terrane, perhaps as slices within the lithospheric column. The kimberlite locality is ~100–150 km northwest of the Eoarchean terranes (Fig. 1), which we consider to be the most likely source of the exotic zircons, implying a significant horizontal displacement of this Eoarchean crust. Given the interpretation of the northern Akia Terrane being built upon older mafic crust, any emplacement of Eoarchean evolved crust under northern Akia must have occurred after 3.0 Ga.

It may be that the Akia Terrane was thrust over the Eoarchean Terrane assemblage during the interpreted ca. 2.97 Ga collisional event between the Eoarchean Terranes and the Mesoarchean Kapisilik Terrane, a probable equivalent of the Akia Terrane (Nutman et al., 2015). Alternatively, or in addition, a Neoarchean timing of emplacement may have occurred. Granite sheets with crystallization ages of ca. 2.7 Ga are widely found cropping out across the Akia Terrane (Friend et al., 1996; Gardiner et al., 2019; Kirkland et al., 2018). However, it is only where these granites intrude the southern margin of the Akia Terrane, adjacent to the Eoarchean terranes, that they contain reported Eoarchean zircon cores (Fig. 1). The absence of granite-hosted Eoarchean zircon xenocrysts further north potentially implies an absence of evolved Eoarchean crust under the northern Akia Terrane at the time of granite intrusion (although granite sheets may not sample at the same depths as a kimberlite intrusion). A post 2.7 Ga timing of tectonic overthrusting would fit well with the interpreted late Archean assembly of the NAC (Friend et al., 1996). We feel it unlikely that the overthrusting of terranes occurred later than the end of the Archean. NAC assembly was followed by a period of tectonic quiescence in West Greenland, terminated by the ca. 1.8 Ga Nagssugtoqidian orogen, which reworked the cratonic margin some 150 km to the north of the study area (Fig. 1). The Nagssugtoqidian orogen was immediately preceded by the emplacement of ca. 2.0 Ga NE-trending Kangâmiut dykes (Nutman et al., 1999a), now found to extend north from Maniitsoq to the cratonic margin. Although within the Nagssugtoqidian orogenic zone itself these dykes have been deformed and recrystallized, south of the Nagssugtoqidian deformation front (Fig. 1) they retain primary igneous textures (Mayborn and Lesher, 2006), which implies the craton had stabilized prior to the Nagssugtoqidian orogen.

The lithospheric stacking model invoked for the NAC (Wittig et al., 2008) has not only slices of crust, but also that of associated lithospheric mantle, being tectonically imbricated and accreted together. We suggest that the kimberlite-hosted xenocrystic zircons provide evidence of emplacement of Eoarchean crust underneath the Akia Terrane during the Mesoarchean (2.97 Ga) at the earliest. Kimberlite-hosted peridotite xenoliths from across the northern North Atlantic Craton, including from the Maniitsoq kimberlite field in the northern Akia Terrane, show a pronounced lack of Eoarchean rhenium depletion model ages, instead mostly recording Meso- to Neoarchean model ages (Wittig et al., 2010). These model ages imply a late Archean timing of stabilization for the central NAC lithospheric mantle, which is also the timing for the protracted assembly of the discrete terranes that today comprise the NAC (Friend and Nutman, 2019). Thus, it may be that NAC terrane assembly involved the stacking of tracts of evolved crust with some associated lithospheric mantle (Pearson and Wittig, 2008). The assembly may well have also entrained and buried oceanic lithosphere, as implied by the ca. 2.7 ± 0.29 Ga (2σ) Pb–Pb model ages determined from clinopyroxenes extracted from kimberlite-
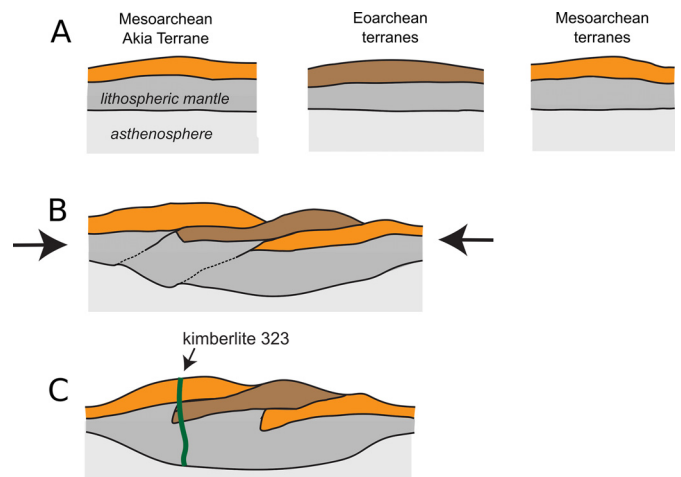

Fig. 5. Cartoon showing conceptual development of North Atlantic Craton lithosphere via tectonic stacking. **A.** Discrete Archean terranes after the last phase of crust production at 3.0 Ga, highlighting the different ages for these blocks of crust, which may have been formed via different geodynamic processes. **B.** Terrane assembly via tectonic stacking to yield a proto-craton, where horizontal shortening causes over-thrusting and vertical juxtaposition of the different aged gneiss terranes, with associated thickening of the lithospheric root. For the North Atlantic Craton this likely occurred during 2.7–2.5 Ga. **C.** The craton post-maturation and stabilization. This is the assumed state of the North Atlantic Craton when kimberlite sample 323 traversed the cratonic lithosphere to intrude into the Mesoarchean Akia Terrane at 557 Ma. Our model suggests it sampled zircons from the different tracts of crust during emplacement.

hosted eclogite xenoliths (Tappe et al., 2011b). This tectonic stacking marked the construction of the deep lithospheric root, and the onset of stabilization of the North Atlantic Craton (Fig. 5).

5. Conclusions

Xenocrystic zircons entrained in a kimberlite from the Akia Terrane can be linked on the basis of $^{207}Pb/^{206}Pb$ ages and Hf isotope signatures to the surrounding gneiss terranes. The Hf isotope trends highlight that in the Nuuk region there were two main Archean crust-forming events. The Eoarchean zircons are a match in age and $\varepsilon Hf(t)$ for reported components of the Eoarchean gneisses, and the 2.7 and 2.5 Ga zircons were likely sourced from rocks derived from reworking of Eoarchean evolved crust during the protracted assembly of the North Atlantic Craton. The Akia Terrane presents no compelling evidence for the incorporation of Eoarchean evolved crust in its genesis, thus we interpret the exotic zircons to reflect tracts of evolved crust emplaced within the NAC lithosphere after at least 2.97 Ga or possibly later at 2.7 Ga. If the North Atlantic Craton SCLM was built through "lithospheric stacking", involving the tectonic imbrication of tracts of evolved crust as well as burial of mafic (oceanic) lithosphere, then this mechanism would provide a process to under-thrust slivers of older continental crust during Meso- to Neoarchean terrane assembly, and which could be later sampled by the kimberlite.

If these Eoarchean crustal tracts were indeed derived from the Eoarchean terranes as is consistent with the existing geochronology, then this would imply northwards-thrusting (in present-day orientation) of the Eoarchean terranes under the Akia Terrane after 3.0 Ga, or alternatively southwards over-riding of the Eoarchean terranes by the Akia Terrane. Significant horizontal forces driving the convergence of these terranes are likely to be linked to the final assembly of the NAC, which occurred during the Neoarchean, a key period in Earth history marked globally by changes in chemical proxies interpreted as representing the onset of widespread plate tectonics (e.g., Cawood et al., 2018; Dhuime et al., 2012; Næraa et al., 2012).

Craton assembly brings together different aged Archean terranes (e.g., Fig. 5), which may have been formed in different geodynamic settings. A lithospheric stacking model implies a late-stage formation for cratonic lithosphere during the process of craton assembly, which then matures and stabilizes over time (e.g., Pearson and Wittig, 2008). Surface exposures of Archean crust may not be solely representative of the cratonic lithosphere composition at depth, and elucidating the geodynamic processes that operated in the Archean requires sampling deep portions of Archean lithosphere to obtain a more complete record of craton evolution.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests.

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Appendix A. Supplementary material

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.epsl.2020.116091.

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