A record of Neoarchaean cratonisation from the Storø Supracrustal Belt, West Greenland

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ABSTRACT

During the late Archaean, exotic juvenile continental (TTG) terranes assembled into stable cratons leading to continental emergence and deposition of shallow-marine sedimentary sequences. This period of cratonisation coincided with crustal reworking and maturation driving the production of granites *sensu stricto* on most cratons, and may mark a final transition to mobile-lid tectonics. We investigate the relative timing of continental assembly, stabilization, emergence, and maturation, during the formation of the North Atlantic Craton (NAC) in West Greenland from its constituent terranes, using geochemical data from zircon and monazite extracted from its oldest mature metasedimentary unit, the Storø quartzite. Zircons form two U-Pb age groups: (i) an older >2820 Ma group with juvenile (elevated) εHf(t) and $\delta^{18}O$, derived from weathering surrounding Mesoarchaean terranes; and (ii) a younger <2700 Ma group with less radiogenic (lower) εHf(t) and elevated $\delta^{18}O$ that record post-burial metamorphism peaking ca. 2620 Ma. The quartzite protolith has a maximum depositional age of ca. 2830 Ma, and was deposited after final TTG formation but prior to granite magmatism at ca. 2715 Ma, during which time terranes had sufficiently assembled, stabilized, and emerged to form a common watershed. Cratons form via lateral accretion which requires strong continental lithosphere, for which one agent is crustal reworking and maturation. However, for the NAC, terrane assembly and emergence commenced prior to granite formation, and crustal reworking may be a response to lithospheric thickening. Cratonisation involves a series of complex, intertwined processes operating over 100’s of millions of years, which together lead to the development of thick, stable, continental lithosphere. Studies of ancient mature metasediments such as the Storø quartzite can help build timelines for these processes to ultimately better understand their choreography and co-dependencies, that together produced Earth’s enduring cratons.

1. INTRODUCTION

The late Archaean (3.0–2.5 Ga) was a fundamental period in Earth's evolution, during which early Archaean (4.0–3.0 Ga) juvenile continental terranes were assembled and ultimately stabilized to form cratons (e.g., Bleeker, 2003; Gardiner et al., 2020). This process of cratonisation was manifest in the widespread emergence above sea level of continental crust, consistent with the appearance of shallow-marine sedimentary sequences on many cratons (e.g., Chowdhury et al., 2021 and refs therein). Notably, the period of cratonisation also coincided with what many argue to be a fundamental transition in planetary geodynamics, the onset of subduction-driven mobile lid (plate) tectonics (Brown et al., 2020; Cawood et al., 2018).

The Archaean rock record is our archive of cratonisation. Whereas early Archaean crustal rocks mostly comprise sodic granitoids of the tonalite-trondhjemite-granodiorite series (TTGs) that represent primitive, juvenile, continental crust (Moyen and Martin, 2012), the late Archaean is characterized by more evolved rocks in the form of potassic granitoids (Laurent et al., 2014; Nebel et al., 2018). The widespread and sudden appearance of granites *sensu stricto* marks a key magmatic shift from the generation of new continental crust to the onset of significant crustal reworking, and a fundamental question is how intrinsically linked this process of crustal maturation is to cratonisation (Cawood et al., 2018; Moyen and Laurent, 2018).

Here, we investigate the relative timing of crust formation, emergence, stabilization, and maturation, during assembly of the North Atlantic Craton (NAC) in West Greenland, using the detrital record of a mature sediment. The NAC consists of several Eoarchaean to Mesoarchaean crustal terranes with discrete formation histories and isotopic signatures, which are argued to have been assembled by a process of subduction-accretion during the Neoarchaean (Friend et al., 1988). We present new geochronological and geochemical data to characterize zircon and monazite grains from a quartzite within the Storø Supracrustal Belt. The Storø quartzite represents the metamorphosed product of the oldest known mature sediment from the cratonic heart of the NAC (Szilas et al., 2014), and was derived from the weathering of proximal TTG. We use these data to investigate the timing of uplift, exposure, and weathering of local continental rocks, and the orogenic processes leading to their burial and metamorphism, and integrate our data with existing constraints to build a timeline for the cratonisation of the NAC.

2. GEOLOGICAL BACKGROUND

The Nuuk region of West Greenland consists of a number of crustal (orthogneiss) terranes (Fig. 1), defined on the basis of U-Pb ages, structural relations, and metamorphic grade (Friend et al., 1988). South of Nuuk Fjord (Godthåbsfjord) lies a central band of Eoarchaean orthogneiss terranes (collectively the Itsaq Gneiss Complex), bounded to the north and south by younger Mesoarchaean terranes – notably the Akia, Tasiusarsuaq, and Kapisilik terranes. These terranes are interpreted to have evolved separately during the Eo- to Mesoarchaean (Friend et al., 1988; Friend and Nutman, 2019) and represent distinct phases of Archaean crustal growth. The terranes then diachronously amalgamated via subduction-accretion processes between 2.96 and 2.6 Ga to form larger crustal blocks: the assembly of the Kapisilik and Tasiusarsuaq terranes ca. 2790 Ma, with the final suturing of Akia onto these crustal nuclei ca. 2550 Ma (Friend and Nutman, 2019; Hollis et al., 2006). Terrane assembly was accompanied by lithospheric thickening and stabilization, perhaps accomplished via “lithospheric stacking”, to form the core of the present-day NAC (Bridgwater et al., 1974; Friend et al., 1996; Gardiner et al., 2020; Wittig et al., 2010).

The island of Storø ("big island") lies within the central Nuuk Fjord, 45 km northeast of the city of Nuuk (Fig. 1). The island exposes the late Archaean Storø Supracrustal Belt (SSB; Fig. 1), a >1 km-thick tectonic slice now sandwiched between the Mesoarchaean Akia Terrane and the Eoarchaean Isukasia Terrane, and is bounded by major shear zones (Nutman et al., 2007). The SSB is notable for its gold mineralization (Szilas et al., 2020), and comprises mafic to ultramafic metavolcanic and metasedimentary (garnet-sillimanite mica schist and quartzite) rock associations that experienced peak amphibolite-facies metamorphism (Szilas et al., 2014). The SSB lies adjacent to the Storø Anorthosite Complex, interpreted as a relict ca. 3050 Ma juvenile island arc complex (Szilas et al., 2014), with the contact between the two representing both a structural and temporal break (Scherstén et al., 2012).

The Storø quartzite is a unit of the SSB, and is arguably the oldest (metamorphosed) mature (>82 wt.% SiO_2, see Supplementary Data) sedimentary rock known from the Nuuk region (Szilas et al., 2014). The maturity of the quartzite, and its compositional similarity to proximal TTGs, suggests it was derived from the sub-aerial weathering of continental crust at a continental margin (Ordónez-Calderón et al., 2011; Szilas et al., 2014).

3. METHODS AND RESULTS

Ten samples were selected from a 50 m-long core drilled through the Storø quartzite (locality 64.43724 N, 51.06272 W, Drill hole ID 'STO-DH-12' Fig. 1; intersection depth 388 m; see Supplementary Data for sample details and petrography). From each sample we separated out zircon and monazite grains for detailed analysis, choosing a range of crystal sizes, colours, and morphologies, to prepare a representative sample set. The grains were cast into epoxy mounts and then polished. The mounts were then imaged using cathodoluminescence (CL; Appendix

Figure) to characterize zircon morphology and select targets for analysis of a representative range of zircon grains with various morphologies, and variably complex internal domains such as cores and rims. The zircons were analyzed *in situ* for O isotopes via secondary ionization mass spectrometry (SIMS) at the NordSIMS facility, Museum of Natural History, Stockholm. The same spot locations as analyzed by SIMS were then targeted for both U-Pb and Hf isotopes, and for trace element contents, via laser ablation split-stream (multi-collector) inductively-coupled plasma mass spectrometry (LA-SS-(MC)-ICPMS) at the Isotopia Laboratory, School of Earth Atmosphere and Environment, Monash University, Melbourne. Mounted monazite separates were analyzed for U-Pb geochronology by LA–ICPMS also at the Isotopia Laboratory. Full analytical methods and tabulated results are provided in the Supplementary Data.

3.1. Results

Zircon and monazite U-Pb data

Zircon grains are ~100 μm in length and range in shape from strongly prismatic to more equant. Most grains show oscillatory zoning under CL (Appendix Figure), and many have well-defined cores that are variably truncated by distinct overgrowths. Most grains commonly have a thin (10–20 μm) outer rim with uniform, dark CL response. We apply a strict concordance threshold by only considering those analysis with calculated $^{235}U/^{207}Pb$ and $^{238}U/^{206}Pb$ ages that are 98-102 % concordant.

There are no significant differences in the distribution of calculated ages measured between the different core samples (Supplementary Figure S6) and we therefore treat all samples as a single coherent dataset. A Wetherill concordia plot of zircon analyses that satisfy our concordance threshold shows they range from 3760 to 2590 Ma (Fig. 2A and Supplementary

Figure S7), and have a complex age structure, with a major cluster at 2840–2820 Ma, a subsidiary cluster at 2890 Ma, plus smaller clusters at 3220 and 2640–2620 Ma. In addition, there are minor components at > 3600 Ma (Fig. 2A).

Monazite U-Pb ages are also shown in a concordia plot (Fig. 2B). Many ages calculated for these monazite grains are compromised by excess ^{206}Pb resulting in reverse discordance. The most concordant monazite analyses (98–102 % concordant) have ages between ca. 2600 Ma and 2630 Ma and yield an overdispersed concordia age of 2619 ± 8 Ma (MSWD = 4; n = 18). Acknowledging the overdispersion of this population implied by the high MSWD, we estimate peak timing of monazite crystallization in our samples to be ca. 2620 Ma.

Zircon Hf and O isotope data

Only Hf and O isotope data paired with ^{207}Pb/^{206}Pb ages passing our concordance threshold are considered. Zircon εHf(t) (initial ^{176}Hf/^{177}Hf ratio normalized to chondrite) range from +8.8 to -14.3, with most points lying between +5 and -5 epsilon units. We classify analyses as being on zircon cores versus rims on the basis of CL imaging. Figure 3A shows a plot of zircon εHf(t) versus ^{207}Pb/^{206}Pb age and Figure 3B plots δ^{18}O data versus ^{207}Pb/^{206}Pb age. Most > 2820 Ma zircons are measured on cores, and typically have juvenile isotopic characteristics with radiogenic (suprachondritic) εHf(t), with the majority of data points lying on or above the chondritic uniform reservoir baseline (CHUR; εHf = 0), and δ^{18}O between 5.3–6.1 ‰, i.e. plotting towards the upper end of the range for zircon crystallized from mantle-derived magmas (Valley et al., 2005). In contrast, grains younger than 2700 Ma, typically measured on rims, have a more evolved Hf isotopic character, with less radiogenic (subchondritic) εHf(t) and preserve heavier δ^{18}O values up to 10.5 ‰.

Zircon trace element data

Zircon trace element data show enrichment in the heavy rare earth elements (Supplementary Figure S4), with a variable-positive Ce anomaly, and a small negative Eu anomaly, typical of zircons grown within evolved (TTG) melts (Whitehouse and Kamber, 2003). A secular trend is seen whereby the Eu anomaly decreases (Eu/Eu* increases), and $U_{(t)}$/Yb ratios show a marked increase with decreasing age, reflecting U increase (Figs. 3C, D).

4. DISCUSSION

4.1. Zircon U-Pb ages

Zircon grains from ancient terranes with polyphase tectono-thermal histories, like the NAC, are susceptible to Pb-loss, which drives calculated ages towards younger values. Of interest in constraining the maximum timing of deposition of the SSB is the robustness of the small population of zircon grains yielding U–Pb ages which spread from the main 2840–2820 Ma cluster towards younger (2820–2700 Ma) ages. In this regard, considering the Hf isotopic systematics of zircon grains is useful for identifying Pb-loss as the Lu-Hf isotopic system is less-likely to be disturbed by post-crystallization thermal events (Gerdes and Zeh, 2009).

Figure 2C is a plot of zircon U-Pb age versus ^{176}Hf/^{177}Hf(t), and inspection shows that Hf isotope data from the 2840–2820 Ma cluster define a coherent group exhibiting a typical spread in ^{176}Hf/^{177}Hf(t). In contrast, the younger 2820–2700 Ma data define a broad horizontal array of relatively constant ^{176}Hf/^{177}Hf(t). Further, some of these younger ages were measured in the same zircon domain as concordant older > 2820 Ma ages (see Supplementary Figure S5), which also raises concern over their robustness.

We interpret the horizontal trend in $^{176}Hf/^{177}Hf(t)$ as representing Pb-loss causing a spread towards artificially young ages while maintaining original $^{176}Hf/^{177}Hf$ compositions, and in summary conclude that those ages lying between 2820 and 2700 Ma most likely represent analyses of zircon grains from the 2840–2820 Ma age cluster, which have experienced Pb-loss, driving them towards younger ages. These younger analyses and their paired Hf, O, and trace element data are therefore discarded from further discussion.

4.2. Timing of Storø Supracrustal Belt deposition and metamorphism

Based on their textures, U-Pb ages, $\varepsilon Hf(t)$ and $\delta^{18}O$ compositions, we subdivide the zircon population into two groups: (i) those with ages >2820 Ma, which have juvenile isotopic affinities; and (ii) those with ages <2700 Ma, typically measured on rims, which record more evolved $\varepsilon Hf(t)$ and heavier $\delta^{18}O$.

Szilas et al. (2014) argued on the basis of its mineralogical maturity, trace element composition, and the U-Pb age profile of its detrital zircon cargo, that the Storø quartzite was derived from weathering of proximal orthogneiss terranes. We concur, and interpret the >2820 Ma zircons from the quartzite as being of detrital origin given their diverse U-Pb age profile. We estimate a conservative maximum depositional age for the quartzite of ca. 2830 based on the median of the youngest 2840–2820 Ma cluster (n=20). Although our age is in line with previous estimates (Szilas et al., 2014), we argue that our careful consideration of Pb-loss effects in the context of paired Hf isotope systematics yields a more robust maximum depositional age.

In contrast to the older >2820 Ma population, the majority of the young <2700 Ma ages were measured on zircon rims, which typically occur as overgrowths that variably truncate or grew conformably on zircon cores (Appendix Figure). These rims have less radiogenic $\varepsilon Hf(t)$, which mostly lie on a “crustal” Hf evolutionary trend of $^{176}Lu/^{177}Hf = 0.01$ extending from the older 3000–2800 Ma population (Fig. 3A), which may represent the age of the source material. These rims also have elevated $\delta^{18}O$ signatures implying the incorporation of material that had experienced low-temperature (< 200 °C; Valley et al. (2005)) surficial (or near-surface) alteration. Similar-old zircons within the SSB have low Th/U ratios typical of metamorphic zircon (Szilas et al., 2014). We attribute the < 2700 Ma population, which has a dominant age peak at ca. 2630 Ma, as recording zircon rim growth during metamorphism.

Early gold mineralization within the SSB has been dated to 2707 ± 8 Ma (Re-Os on arsenopyrite; Scherstén et al., 2012), while a garnet Lu-Hf isochron from an aluminous sillimanite-biotite gneiss from within the supracrustal belt has yielded an age of 2697 ± 8 Ma (Szilas et al., 2020). Deposition of the supracrustal packages must have pre-dated these events, after which the SSB was buried and metamorphosed to ≥ 650 °C and ~7 kbar (Szilas et al., 2020; Yakymchuk and Szilas, 2018), equating to depths of ~20–25 km assuming a normal crustal density and no significant tectonic overpressure. Assuming garnet grew at or before 2697 Ma, and taking Archaean burial rates of 1.0–1.5 km Ma^{-1} (e.g., Nicoli et al., 2016), we estimate a minimum age for the onset of burial of the supracrustal package of ca. 2715 Ma. This age is similar to that of the ca. 2720 Ma granite sheets that intrude TTGs in both the Akia and Tasiusarsuaq terranes (Friend and Nutman, 2019; Gardiner et al., 2019; Nutman and Friend, 2007).

After burial, the SSB experienced protracted metamorphism that reached a thermal peak at ca. 2635–2630 Ma (Nutman et al., 2007; Szilas et al., 2020; our zircon and monazite data) which then waned prior to intrusion of the 2550 Ma Qôrqut Granite (Nutman et al., 2011). The measured range of monazite ages (2630–2600 Ma) suggest protracted monazite growth during cooling from the metamorphic peak, which may have been at or slightly before 2630–2620 Ma, and we note the peak in metamorphic zircon ages pre-dates that of monazite growth.

In summary, our data from the Storø quartzite suggest: (i) deposition of the SSB between 2830–2715 Ma; (ii) its subsequent burial to ca. 25–20 km between 2715–2697 Ma; and (iii) peak metamorphism at ca. 2630–2620 Ma. Docking of the Akia Terrane to the north and intrusion of the 2550 Ma Qôrqut Granite mark the final assembly of the NAC (Hollis et al., 2006).

4.3. Provenance of Storø detrital zircons

The Storø zircons are likely to have a dominant source in the regional TTG orthogneiss. The quartzite bulk rare earth element compositions are a good match for regional TTG (e.g., the Mesoarchaean TTG of the Tasiusarsuaq Terrane; Supplementary Figure S3), and both the juvenile isotopic affinities and trace element data recorded in the older zircon population are typical of TTG (Supplementary Figure S4).

A comparison of our zircon U-Pb ages with a compilation from regional Eo- to Mesoarchaean orthogneiss terranes (Fig. 4) shows that the >2820 Ma age peaks are a good match for the U-Pb crystallization ages of magmatic rocks from these TTG-dominated sources. The 2950, 2890, and 2840 Ma peaks are similar to ages recorded in TTG from the 2920–2820 Ma Tasiusarsuaq Terrane (and the underlying 2840–2820 Ma Tre Brødre Ikkattoq Gneisses), and from the 3075–2980 Ma Kapisilik Terrane to the south (Kolb et al., 2012; Nutman et al., 2015). There is some overlap in age with the ca. 3000 Ma tonalites of the Akia Terrane to the north (Gardiner et al., 2019), whereas the 3220 Ma age peak is similar to that recorded in dioritic rocks also from Akia (Garde et al., 2000). The presence of rare > 3600 Ma zircons in the quartzite is consistent with derivation from the Tasiusarsuaq Terrane, at least in part, which contains minor >

3600 Ma gneiss components (e.g., Næraa et al., 2012). The SSB may have been deposited upon a ca. 3050 Ma juvenile island arc (Szilas et al., 2014), and minor zircon grains of this age within the quartzite likely reflect weathering of this substrate, as does the presence of small quantities of fuchsite.

There is some discrepancy between the zircon Hf isotope values reported here and that measured in similarly-aged proximal TTG, although it must be borne in mind that the regional zircon U-Pb dataset plotted in Figure 4 is somewhat larger and thus arguably more complete than that available for zircon Hf (Fig. 3A). In particular, the large cluster of detrital zircon Hf data between 2940 and 2820 Ma is more radiogenic (juvenile) than limited data available from the similarly-aged Tasiusarsuaq terrane. This difference may represent the weathering of now missing crust, either unroofed components of the Tasiusarsuaq terrane or of another crustal source entirely. Regardless, given the general good agreement between both U-Pb ages and Hf isotopes from regional orthogneiss terranes, we conclude that our data suggest that the principal origin of the > 2820 Ma Storø zircon grains was weathering of juvenile TTG of the Tasiusarsuaq and Akia terranes.

Assuming equilibrium, the trace element compositions of zircon reflect the melt from which they grew, and by extension the conditions of melt generation and of fractional crystallization. A secular change in the TTG-derived (> 2820 Ma) Storø zircon trace element dataset is observed, with the youngest (2850–2820 Ma) recording a sharp increase in both Eu/Eu* (i.e. a decrease in the Eu anomaly), and $U_{(t)}$/Yb, compared to older TTG (Fig. 3C, D). Eu/Eu* has typically been used as a monitor of the involvement of plagioclase during partial melting and, by extension, a proxy for melting depth. However, recent studies have shown that during TTG crystallization, zircon may saturate late in near-solidus conditions from highly evolved residual melts (Laurent et al., 2020; Laurent et al., 2021). Such residual melts would display a decreased Eu/Eu* (increased Eu anomaly) paired with an increased U compared to the original (bulk) TTG melt. Therefore, if our observed secular trend in TTG-derived zircon trace elements reflected that the youngest 2850–2820 Ma zircons recorded late near-solidus crystallization compared to earlier saturation of older zircon, then we would expect the observed $U_{(t)}$/Yb increase to be accompanied by an Eu/Eu* decrease. In contrast, we see an increase in both these ratios, suggesting that the recorded change in Eu/Eu* may indeed be controlled by melting depth, i.e. that the younger TTG magmas may have been produced via partial melting at greater depth compared to the older magmas. An increase in melting depth might be related either to crustal thickening over time and/or waning ambient geothermal gradients since the Mesoarchaean (Herzberg et al., 2010). The elevated $U_{(t)}$/Yb ratios compared to older samples (Fig. 3D) might reflect a higher degree of assimilation of juvenile crust (given the εHf(t) and $\delta^{18}O$ signatures), and/or fluid derived therefrom (Grimes et al., 2015) in the younger magmas, and/or melt generation in the presence of garnet, again suggestive of deeper levels of melting.

4.4. Late Archaean geodynamics

West Greenland terrane assembly and orogeny

The SSB lies in the heart of the Archaean rocks of West Greenland. Within this sequence, the Storø quartzite is a metamorphosed mature sediment deposited between ca. 2830 and 2715 Ma on or adjacent to a continental margin, a sediment which we interpret as being largely derived from sub-aerially weathered juvenile continental (TTG) crust. The Nuuk region records at least five pulses of crust (TTG)-forming events from ca. 3800 Ma to ca. 2820 Ma, reflected in the various Eo- Mesoarchaean terranes, and the quartzite contains material derived from weathering most of these surrounding Mesoarchaean terranes, recording a dominance of 2840–2820 Ma ages (Fig. 4), similar to the detrital record of other metasedimentary units in the region (Friend and Nutman, 2019). There is no requirement for any significant material derived from the Eoarchaean terranes; preferential weathering of Mesoarchaean crust might be expected, since during continental convergence and orogenesis these rocks may have been thrust over the older terranes (e.g., Nutman et al., 2015), thereby being favourably eroded compared to the older crust which was probably mostly unexhumed at that time.

By 2790 Ma, the Tasiusarsuaq, Tre Brødre, and Kapisilik terranes had begun to assemble (Crowley, 2002; Dziggel et al., 2019; Friend et al., 1987; Friend and Nutman, 2019), together forming a proto-cratonic continental hinterland, in proximity to which the SSB was deposited. We interpret the quartzite as containing material weathered from all these terranes, as well as from the Akia Terrane to the north, implying that Akia was proximal to the deposition site, exhumed, and being weathered some considerable time before its suturing onto the proto-craton at 2550 Ma marked the final assembly of the NAC (Hollis et al., 2006). Together, all these Mesoarchaean terranes must have emersed from the ocean, had sufficient topographic relief to allow for subaerial weathering – implying relatively stiff crust able to support orogenic processes – and formed a common watershed between 2830 and 2715 Ma, some 280–165 Ma before final craton assembly, from which detrital material could be transported and eventually deposited as a mature sediment. Although it is difficult to fully constrain the nature of basement upon which the SSB was deposited, we agree with Szilas et al. (2014) that it is likely to have been structurally underlain by the 3050 Ma juvenile island arc complex, given the presence of appropriately-aged zircons, and that this complex must have been proximal to the proto-cratonic margin.

The youngest juvenile crust known from the Nuuk region is the ca. 2840–2820 Ma TTGs of the Tasiusarsuaq and Kapisilik terranes, and the similarly-aged Ikkattoq Gneisses of the Tre Brødre Terrane (Friend and Nutman, 2019). Incorporation of this material into the Storø quartzite requires that this crust had been exhumed and subjected to sub-aerial weathering prior to SSB deposition. We have argued that this younger crust may have formed at deeper levels than older TTG, perhaps reflecting thicker crust (and possibly waning ambient geothermal gradients). If these TTG were subaerially exposed between 2820–2715 Ma, then their uplift and exhumation must have occurred within a timespan of 20–100 Ma.

Younger intrusive rocks in the Nuuk region are granite, notably the ca. 2720 Ma sheets that intrude into TTG of both the Akia and Tasiusarsuaq terranes (Friend and Nutman, 2019; Gardiner et al., 2019; Nutman and Friend, 2007). In contrast to the protracted formation of TTG terranes, the intrusion of late Archaean granites across the NAC occurred over a much shorter timescale and simultaneously within multiple terranes (Friend et al., 1996). These rocks record a regional switch from protracted juvenile magmatism to crustal-dominated evolved melts, reflected in a transition from chondritic to subchondritic εHf(t) (Gardiner et al., 2019; Næraa and Scherstén, 2008; and Næraa pers comm (2020), their sample 499227) (Fig. 3A). We find no representation of these granites in the detrital zircons from the Storø quartzite, suggesting deposition and burial of the quartzite pre-dated formation and/or unroofing of the granites.

We calculate that the onset of burial of the SSB occurred on or before 2715 Ma, and that the package of supracrustal rocks reached depths of ca. 25–20 km by 2697 Ma, implying that by this time, orogenic processes were sufficiently well-developed to allow material to be buried to amphibolite-facies depths, perhaps within 20 Ma. Peak metamorphism likely occurred between 2630–2620 Ma and our monazite ages suggest the rocks remained at depth up to at least 2600

Ma, perhaps even longer given the regional context of ongoing terrane convergence until 2550 Ma.

Continental stabilisation and cratonisation

Cratonisation broadly encompasses a series of processes together leading to thick, stable, continental lithosphere. The Storø quartzite is the oldest documented mature sediment in West Greenland (Szilas et al., 2014), and we take its deposition to mark the onset of NAC cratonisation (sensu Campbell and Davies, 2017; Flament et al., 2008), i.e. on or after 2830 Ma. The predominance of material sourced from proximal Mesoarchaean terranes implies that several 100's Ma before final NAC assembly at 2550 Ma, these terranes were beginning to converge, were sufficiently stable and stiff to become emergent and support elevated topography, and that uplift and erosional processes were rapid enough that 2840–2820 Ma TTG which formed from melting at depths probably exceeding 30 km (e.g., Hoffmann et al., 2019), and emplaced within the Archaean upper crust, may have reached the surface within only a few 10's of Ma. The trace element signatures of the youngest TTG-derived zircons also suggest that the process of crustal thickening was underway by this time.

Most cratons form via lateral accretion – either modern-style accretionary orogens or shallow slab-stacking – leading to lithospheric thickening and stabilization (Jordan, 1978; McKenzie and Priestley, 2016). Lateral accretion requires continental lithosphere that is sufficiently strong to support the imposed horizontal stresses (Cawood et al., 2018). Crustal reworking via partial melting drives lithosphere differentiation, and results in the formation of a cooler, strong, refractory lower crust. Hence, a useful question is whether crustal reworking and maturation is a prerequisite for the onset of cratonisation.

We demonstrate that the deposition of the Storø quartzite pre-dates the appearance of regional granites. This implies that, at least in the context of the NAC, stabilization of a lithosphere sufficiently strong to support the onset of cratonisation appears not to require crustal reworking, and that conversely, crustal reworking may itself be a response to cratonisation. The intrusion of late Archaean granites into at least two terranes (Tasiusarsuaq and Akia) occurred at a similar time to the onset of SSB burial, and this widespread, punctuated, magmatic event was perhaps therefore triggered at a critical point in lithospheric thickening during terrane accretion (Friend et al., 1996; Jordan, 1988; Wang et al., 2018), but notably prior to the final stabilization of the sub-continental lithospheric mantle.

The period 2800–2700 Ma, i.e. the start of the Neoarchaean, marks a step-change in the formation of the NAC, during which occurred:

(i) the diachronous assembly of several juvenile TTG terranes (Friend et al., 1988);

(ii) the initial stabilization, unroofing, and emergence of continental crust, perhaps within 20 Ma of its formation, enabling sub-aerial weathering and reflecting a crustal rheology strong enough to support such processes;

(iii) the ensuing development of a pan-terrane watershed including many of the Mesoarchaean terranes, enabling the transportation and deposition of the oldest documented mature continental-derived sediment onto a stable continental margin;

(iv) orogenic processes allowing material to be buried to amphibolite-facies depths, including the first appearance of eclogites at 2.7 Ga (Tappe et al., 2011);

(v) thickening and initial stabilization of the sub-continental lithospheric mantle (Wittig et al., 2010; Yakymchuk et al., 2021), perhaps via lithospheric stacking (Gardiner et al., 2020; Lee et al., 2011; Pearson and Wittig, 2008; Tappe et al., 2011);

(vi) a regional magmatic switch from juvenile TTG to crustal reworking (partial melting and melt loss) of existing crustal rocks leading to the appearance of late Archaean granites (Friend et al., 1996) and marking the onset of crustal maturation.

Cratonisation clearly involves a number of processes, which together lead to the development of emerged, stable, continental lithosphere, but it is a complex, diachronous, and prolonged operation (Fig. 5). We show that geochemical and isotopic interrogation of detrital zircon and monazite taken from the Storø quartzite provides constraints on the timing and choreography of many of these key processes, specifically that of terrane accretion, exhumation and weathering; the rates of orogeny and burial; and the relationship of these processes to that of crustal reworking and lithospheric thickening and stabilization.

4.5. Global Significance

Mature sedimentary sequences such as the SSB are found on most cratons worldwide (Supplementary Data). Although the exact timing of their deposition varies from craton to craton, in almost all cases they appear in the late Archaean, during or after the final phases of TTG magmatism, but typically pre-dating the appearance of potassic granites (Fig. 6). Their development is a reflection of crustal stabilization (Campbell and Davies, 2017) and in the NAC they record the assembly of most if not all of its constituent terranes.

The appearance of these cover sequences in the geological record can be taken as marking a minimum age for the onset of cratonisation. They require a depositional environment on or proximal to the proto-craton, and as they variably contain clastic material sourced from surrounding weathered magmatic rocks now variously found as quartzite, conglomerate and metapelitic material (refs in Supplementary Data), require significant crustal uplift and emergence and a common watershed. In some cases these sequences even contain material deep-sourced from the cratonic sub-continental lithospheric mantle (e.g., Smart et al., 2016), which suggests that the process of lithospheric thickening was already underway at the time of their deposition. Crucially, these sequences are almost universally formed before the rapid appearance of potassic granites, rocks which commonly represent the final episode of Archaean magmatism in every craton globally (Laurent et al., 2014). These late Archaean granites mark the onset of crustal reworking, and their geochemical attributes (low Sr/Y, high K/Na and less radiogenic $\varepsilon Hf(t)$ and $\varepsilon Nd(t)$) suggest they formed at relatively shallow depths mostly via partial melting of TTG. Shallow melting of TTG requires higher geothermal gradients than might be expected within already stabilized cratonic crust (e.g., Pearson et al., 2021), hence they might be expected to form prior to final craton stabilization (Fig. 6).

The Neoarchaean era is when most cratons worldwide assembled and developed their thick, refractory, lithospheric roots (Cawood et al., 2018; Pearson et al., 2021). It is also a point in Earth history interpreted by some as marking the completion of the transition to mobile-lid plate tectonics (Brown et al., 2020; Cawood et al., 2018). Hence, a broader question is the link between the establishment of horizontal tectonics as a global geodynamic paradigm, and cratonisation. Why cratons mostly formed at a similar time, what the relationship is between cratonisation and the shift to horizontal plate tectonics, with the appearance of granites (Laurent et al., 2014), and with widespread continental emergence (Reimink et al., 2021), is not fully resolved. However, better constraints on the dependencies and timings of these processes, in part which can be yielded through interrogation of late Archaean cover sequences as demonstrated here, will help shine renewed light on a crucial point in Earth history, the late Archaean development of cratons.

5. CONCLUSIONS

We document how the oldest documented mature sediment within West Greenland may be used to help build a timeline for the processes leading to the formation of the North Atlantic Craton, and to highlight that the processes of cratonisation are complex and prolonged. We argue that the Storø quartzite originated from weathering of Archaean TTGs of proximal Mesoarchaean terranes, and using careful analysis of U-Pb integrated with Hf isotope systematics, calculate a conservative maximum age of deposition for the quartzite, and by implication the SSB, at ca. 2830 Ma, a similar timing to the final regional TTG-forming event. Such analysis of detrital zircon U-Pb data arguably provides the most robust way of filtering out Pb-loss effects and yielding a robust age profile for similar metasediments from ancient terranes. The Storø quartzite was deposited on or after ca. 2830 Ma, but before granitic magmatism ca. 2715 Ma, during which TTG terranes had stabilized and emerged to form a common watershed, providing material for weathering, transportation and deposition onto a continental margin, perhaps the proto-NAC margin, prior to final craton assembly. SSB burial commenced by 2715 Ma, a similar timing to the onset of crustal reworking, after which the units were rapidly buried and metamorphosed to amphibolite facies prior to final assembly of the NAC.

Cratonisation is the process by which (typically Archaean) juvenile lithospheric terranes, of varying ages and provenance, were assembled, stabilized, and chemically differentiated, resulting in the formation of stable and enduring cratons with deep lithospheric roots (Kamber, 2015). We highlight that cratonisation involves a series of complex, intertwined processes operating over 100's of millions of years which together lead to the development of thick stable continental lithosphere, and that mature sediments can shed new light on the respective timings of these processes. Similar mature sedimentary sequences to Storø appear on most cratons during the late Archaean, and provide unequivocal evidence for subaerial weathering of exposed TTGs and thereby continental emergence and stabilization (Campbell and Davies, 2017). Studies of these ancient mature metasediments can help build timelines for these processes to ultimately better understand their mutual choreography and co-dependencies which together lead to Earth's enduring cratons.

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Figure Captions

Figure 1. **Top:** Simplified geological map of the Nuuk area, with the major terranes annotated, and the island of Storø highlighted.

Bottom: Map of the central part of Storø Island showing the main units of the Storø Supracrustal Belt and the underlying the 3050 Ma Storø Anorthosite Complex; from Jeroen van Gool and published in Szilas et al. (2014). Location of drill hole DDH-12 is annotated.

Figure 2: Zircon and Monazite U-Pb Geochronology. A: Wetherill concordia plot of the Storø quartzite zircon U-Pb data, annotated by interpreted type: igneous (TTG-derived), metamorphic, and those analyses interpreted as suffering from Pb-loss. **Inset top:** weighted mean of 20 youngest concordant $^{207}Pb/^{206}Pb$ ages from the older population, and histogram of number of ages.

B: Monazite U-Pb data plotted as Wetherill concordia, with calculated age.

C: Zircon $^{207}Pb/^{206}Pb$ age versus $^{176}Hf/^{177}Hf(t)$ – this highlights that ages younger than 2820 Ma appear to show a Pb-loss trend at constant $^{176}Hf/^{177}Hf(t)$.

Figure 3: Zircon Hf and O isotope, and trace element data. A: Zircon Hf isotope evolution plot for the Storø quartzite, plotting $^{207}Pb/^{206}Pb$ age versus εHf(t). Zircon cores (blue circles) and rims (orange circles) are distinguished. Grey circles represent those analyses suffering Pb-loss, and discarded from the discussion. A crustal evolution trend is drawn in grey using $^{176}Lu/^{177}Hf$ = 0.010, typical of evolved Archaean crust. Also plotted are published Hf isotope data from the surrounding Archaean orthogneiss terranes (see Supplementary Data for sources). Calculated

maximum depositional age is annotated, as is the age range of deposition (yellow) and metamorphism (brown) of the SSB.

B: Zircon oxygen isotope plot, plotting $^{207}Pb/^{206}Pb$ age versus $\delta^{18}O_{V\text{-}SMOW}$. Grey box highlights the typical range of $\delta^{18}O$ for zircon crystallized from mantle-derived magmas (5.3 ± 0.6 ‰ (Valley et al., 2005)). $\delta^{18}O$ measured in cores (blue) are mainly within mantle values, whilst younger rims (orange) record elevated (heavy) $\delta^{18}O$.

C, D: Zircon trace element data, plotting the Eu anomaly (Eu/Eu*) and $U_{(t)}/Yb$ for the 3.2–2.8 Ga aged population (the subscript t reflects correction for radiogenic decay). Data is binned into 20 Ma intervals.

Figure 4: Kernel Density Estimate (KDE) plot of the Storø $^{207}Pb/^{206}Pb$ age data. This shows peaks at 2630, 2840, 2890, 2950, and 3220 Ma. In addition, there are minor >3600 Ma components. Bottom pane shows recorded zircon U-Pb ages from the surrounding orthogneiss terranes from published sources (see Supplementary Data). The multi-dimensional scaling plot (inset) highlights the similarity of the zircon U-Pb dataset to that of the Tasiusarsuaq and Akia terranes.

Figure 5: Timeline of terrane assembly in the central NAC (after Friend and Nutman (2019) and refs therein), and the age ranges of deposition, and metamorphism of the Storø quartzite. A density probability plot of published ^{187}Re-^{188}Os T_{RD} (Rhenium-depletion) model ages of peridotite xenoliths from the NAC, and which yields the approximate age of melt depletion reflecting formation of the refractory lithospheric mantle, is shown (with the X-axis showing number of analyses). This highlights a dominance of Meso-Neoarchaean ages. Also plotted are a

summary of our and others' Hf isotope data, and also Na/K ratios from granitoid whole-rock data (i.e. the trend from sodic TTG to potassic granites). These show a general trend towards crustal reworking affinities by 2.8 Ga. All data sources in Supplementary Data.

Figure 6 Time-space plot for the NAC, Superior, Dhawar, Singhbhum, Pilbara, Yilgarn, Zimbabwe and Kaapvaal cratons for the period 3.2–2.4 Ga, showing the timing of major TTG formation and that of late Archaean granites, coupled with the age constraints of major sedimentary cover sequences. Data from this study, from Cawood et al. (2018) and refs therein, and those detailed in the Supplementary Data.