1-1-2019

Tectono-stratigraphic terranes in Archaean gneiss complexes as evidence for plate tectonics: The Nuuk region, southern West Greenland

Clark R. L Friend
Gendale, UK, crlfriend@yahoo.co.uk

Allen Phillip Nutman
University of Wollongong, anutman@uow.edu.au

Publication Details Citation

Friend, C. R., & Nutman, A. P. (2019). Tectono-stratigraphic terranes in Archaean gneiss complexes as evidence for plate tectonics: The Nuuk region, southern West Greenland. Faculty of Science, Medicine and Health - Papers: Part B. Retrieved from https://ro.uow.edu.au/smhpapers1/729

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Abstract

Prior to 1970 grey gneiss complexes were interpreted as partially-melted sedimentary sequences. Once it was recognised from the Nuuk region that they comprised calc-alkaline igneous complexes, it was understood that such complexes world-wide were dominated by TTG (trondhjemite-tonalite-granodiorite) initially found to have juvenile Sr, Nd and, subsequently, Hf isotopic signatures. Between 1970 and 1985 the Nuuk region gneiss complex was interpreted by the non-uniformitarian 'super-event' model of crust formation which proposed occasional but extensive crust formation, with craton-wide correlation of granulite facies metamorphism and deformational phases. The igneous rocks formed in a late- Meso- to early Neoarchaean super-event engulfed crust formed in an Eoarchaean super-event. Mapping and reinterpretation at Færingehavn showed there are three TTG gneiss domains, each with different early accretionary, metamorphic and tectonic histories, separated by folded meta-mylonites. This established the key feature of the tectono-stratigraphic terrane model; that each terrane has an early intra-terrane history of crust formation, deformation and metamorphism, upon which is superimposed a later deformation and metamorphic history common to several terranes after they were juxtaposed. Remapping and >250 U-Pb zircon age determinations have refined the geological evolution of the entire Nuuk region, and has confirmed at least four main crust formation events and two collisional orogenies with associated transient high pressure metamorphism within clockwise P-T-t loops. Via independent corroborative studies the tectono-stratigraphic terrane model has been accepted for the Nuuk region and, through the discovery of similar relations across other gneiss complexes, its mode of evolution is found to be applicable to Archaean high-grade gneiss complexes worldwide. The TTG and mafic components that dominate each terrane have geochemistry interpreted to indicate subduction-related magmatism at convergent plate boundaries. Each terrane is thus dominated by juvenile additions to the crust. Intra-terrane sedimentary rocks show near unimodal age distributions in contrast to those near the boundaries which are more diverse and complex. The combined geochronological, metamorphic and structural evidence of convergence of these terranes leading to collisional orogeny, this indicates that plate tectonic processes operated throughout the Archaean.

Publication Details

Friend, C. R.L. & Nutman, A. P. (2019). Tectono-stratigraphic terranes in Archaean gneiss complexes as evidence for plate tectonics: The Nuuk region, southern West Greenland. Gondwana Research, 72 213-237.

Draft 31/01/2019

Tectono-stratigraphic terranes in Archaean gneiss complexes as evidence for plate tectonics: the Nuuk region, southern West Greenland

C.R.L. Friend[1], A.P. Nutman[2]

1. Glendale, Tiddington, Thame, Oxon, OX9 2LQ, U.K.

2. GeoQuEST Research Centre, School of Earth & Environmental Sciences, University of Wollongong, Wollongong, NSW 2522, Australia

Email contact: crlfriend@yahoo.co.uk

Published as: Friend, C. R.L. & Nutman, A. P. (2019). Tectono-stratigraphic terranes in Archaean gneiss complexes as evidence for plate tectonics: The Nuuk region, southern West Greenland. Gondwana Research, 72 213-237.

Dedication

We dedicate this paper to Halfdan 'Bud' Baadsgaard, Brian Chadwick (both of whom died in 2015) and Feiko Kalsbeek. Bud was a pioneer of zircon U-Pb geochronology in the Nuuk region, including producing the first Eoarchaean U-Pb zircon age determination. Brian made a major contribution to understanding the regional geology via his mapping and structural interpretations in two major projects from Exeter University under the auspices of the Geological Survey of Denmark and Greenland. Feiko was the base leader of the Survey's Midgaard base camp from 1970-1975 and it was essentially through his organisation of geological teams and his own geological research that the remarkable geology of the southern part of the region covered in this paper was first investigated. Left to right, the photographs below show Feiko Kalsbeek (in 2017), Halfdan 'Bud' Baadsgaard (in the 1990s) and Brian Chadwick (in the late 1990s) (Fig A).

Abstract

Prior to 1970 grey gneiss complexes were interpreted as partially-melted sedimentary sequences. Once it was recognised from the Nuuk region that they comprised calc-alkaline igneous complexes, it was understood that such complexes world-wide were dominated by TTG (trondhjemite-tonalite-granodiorite) initially found to have juvenile Sr, Nd and, subsequently, Hf isotopic signatures. Between 1970 - 1985 the Nuuk region gneiss complex was interpreted by the non-uniformitarian '*super-event*' model of crust formation which proposed occasional but extensive crust formation, with craton-wide correlation of granulite facies metamorphism and deformational phases. The igneous rocks formed in a late- Meso- to early Neoarchaean super-event engulfed crust formed in an Eoarchaean super-event. Mapping and reinterpretation at Færingehavn showed there are three TTG gneiss domains, each with different early accretionary, metamorphic and tectonic histories, separated by folded meta-mylonites. This established the key feature of the tectono-stratigraphic terrane model; that each terrane has an early intra-terrane history of crust formation, deformation and metamorphism, upon which is superimposed a later deformation and metamorphic history common to several terranes after they were juxtaposed. Remapping and >250 U-Pb zircon age determinations have refined the geological evolution of the entire Nuuk region, and has confirmed at least four main crust formation events and two collisional orogenies with associated transient high pressure metamorphism within clockwise P-T-t loops. Via independent corroborative studies the tectono-stratigraphic terrane model has been accepted for the Nuuk region and, through the discovery of similar relations across other gneiss complexes, its mode of evolution is found to be applicable to Archaean high-grade gneiss complexes worldwide. The TTG and mafic components that dominate each terrane have geochemistry interpreted to indicate subduction-related magmatism at convergent plate boundaries. Each terrane is thus dominated by juvenile additions to the crust. Intra-terrane sedimentary rocks show near unimodal age distributions in contrast to those near the boundaries which are more diverse and complex. The combined geochronological, metamorphic and structural evidence of convergence of these terranes leading to collisional orogeny, this indicates that plate tectonic processes operated throughout the Archaean.

Keywords: West Greenland; Nuuk region; Archaean gneiss complexes; tectono-stratigraphic terranes; tectonics; geological mapping

1. Introduction

Uniformitarianism is an established concept in geology, meaning that the rock record can be interpreted using our understanding of modern geological processes. However, there is still debate over the exact nature of its applicability to the Archaean in the far distant past. Modern plate tectonics and the oceanic lithosphere/mantle dynamics that drive it, are the key to unlocking the geological record, but how far back into the past can this modern paradigm be applied? To resolve this, there must be an understanding of the processes forming Precambrian, particularly Archaean, gneiss complexes. However, understanding these has proved to be one of the most challenging problems in basement geology. This is because large parts of the Precambrian crust comprise monotonous grey gneisses derived from plutonic igneous rocks (McGregor, 1973, 1979), which have remarkable similarity regardless of their age and they have usually undergone polyphase high-grade metamorphism and tectonic evolution. Nonetheless, it is essential that these complexes are properly interpreted to provide robust data on Earth's early evolution, for example, early tectonics and the evolution of global geochemical reservoirs. From the Nuuk region of southern West Greenland (Fig. 1), this paper presents integrated geological mapping, tectonic, metamorphic and geochronological evidence, accumulated over five decades, which indicates that a form of plate tectonics operated here throughout the Archaean.

2. Geodynamics back in time

The link back through time from the present to the start of the Alpine orogeny is relatively simple as much of the evidence is extant. For example, comparing the nature of the many different small basins and arcs in the southwest Pacific (e.g. Buys et al., 2014) and, via Uniformitarianism, understand that the processes are similar to those that produce the very large volcanic arcs and basins preserved around much of the rest of the Pacific. Similarly, the change of process from oceanic subduction and the elimination of Tethyan oceanic crust to continental crust subduction, as in the case of the Indian sub-continent, can be understood through a study of the processes happening in different parts of the Mediterranean. Here, Tethyan oceanic crust has not quite been eliminated and different parts of the end stages are represented.

Whilst it is recognised that the evidence becomes progressively reduced back in time, these modern processes can be tracked back through the Phanerozoic, for example, via the Hercynian and Caledonian orogenies into the Neoproterozoic Pan-African/Brasiliano systems

(Teixeira and da Silva., 2007; Frimmel, 2009). From here the evidence begins to be far more fragmentary and linking it together is more difficult.

2.1. Palaeoproterozoic

Despite being hotly debated (e.g. Hamilton, 2007; Stern, 2007), many researchers now accept that processes akin to modern plate tectonics were already operating in the Palaeoproterozoic, albeit somewhat modified by Earth's different thermal state (hotter) at those times. However, sufficient Palaeoproterozoic geological record is well-preserved enough in many places to document key components of the plate tectonic cycle: Palaeoproterozoic apparent polar wander paths of different continental fragments (e.g., Brito Neves et al., 1999; Meert and Torsvik, 2003); collisional orogenies with transient high pressure metamorphism (e.g., the Nagssugtoqidian orogeny in East Greenland; Willigers et al., 2002; Nutman et al., 2008); arc complexes with geochemical traits very similar to modern ones, such as those in the Nagssugtoqidian and Ketilidian orogens of Greenland (Kalsbeek et al., 1987; Chadwick and Garde, 1996; Garde et al., 2002); well-preserved 'Atlantic-margin' style passive margin sequences (e.g., Groetzinger, 1986; Ketchum et al., 2001); slices of crust that have no relation to each other (like Phanerozoic suspect terranes† of Coney et al., 1980); potential relicts of ophiolites, including sheeted dyke complexes (e.g., Kusky, 1990; Moores, 2002).

2.2. Archaean

Further back in time, into the Archaean, the extent of the geological record diminishes and evidence for unravelling the geological evolution becomes sketchier with reliance on the

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† The term terrane in this paper is used in the sense of Coney et al. (1980) who described slices of crust with completely separate origins and evolution had become tectonically juxtaposed along the Cordilleran margin. Each crustal segment preserves its own stratigraphic, structural and metamorphic characteristics and is in tectonic contact with adjacent terranes. This concept was used within the gneiss terrain of southern West Greenland to explain the juxtaposition of blocks of crust along what are now meta-mylonitic contacts of crustal slices that demonstrated completely different evolutionary histories. With the progressive accretion of slices that then share a common history, once assembled they become composite terranes (see Friend et al., 1988; Coney, 1989).

largest low-grade terrains such as the Superior Province of Canada and the Yilgarn and Pilbara Cratons of Western Australia. In early investigations there was less focus on the basement gneiss complexes due to the extremes of deformation and metamorphism, which had largely obliterated evidence for the origin of the rocks. Consequently, although for decades there have been strong arguments for plate tectonics in the Archaean (e.g., Talbot, 1973; de Wit, 1998), there have been equally vociferous cases against it (e.g., Hamilton, 1998, 2003; Stern, 2007; Bédard, 2006).

From the low-grade, Neoarchaean Superior Province granite-greenstone belts, a wide breadth of evidence (igneous geochemistry, structural geology, sedimentology, U-Pb zircon geochronology and deep seismic profiling) point to it being constructed from fragments of a convergent plate boundary with arc-like assemblages that developed and were assembled together over about 100 million years (e.g., Card, 1990; Percival et al., 2012; Bédard and Harris 2014). Similarly, the Pilbara and the Yilgarn cratons contain Neoarchaean sub-aerial arcs (e.g., De Joux et al., 2014). The life spans of these arcs has been suggested to be relatively short (Moyen and van Hunen, 2012) and can be taken to corroborate some of the earlier views regarding a plate tectonic framework for early crustal evolution (e.g., de Wit, 1998). None-the-less, whilst their origins may have conventional explanations, as exemplified by the Pilbara, their later development may be unconventional involving vertical tectonics (e.g. Collins et al. 1998).

2.3. North Atlantic Craton in southern West Greenland

A large part of the Archaean geological record, including all of the Eoarchaean, comprises strongly deformed, migmatitic gneiss complexes of high metamorphic grade (amphibolite – granulite facies). Since the plate tectonics revolution at the end of the 1960s, debate has continued whether these gneiss complexes reflect some type of early non-uniformitarian crust formation, such as dominated by vertical tectonics and plume systems, or whether they are simply deeply eroded portions of orogens formed from the lateral convergence of sialic crustal blocks (see Talbot, 1973). It has long been recognised that in these complexes there has been the general obliteration of most primary features due to poly-metamorphism and deformation associated with complicated tectonic structures (e.g., Sutton and Watson, 1951;

Berthelsen, 1960; Lauerma, 1964), and only rarely are any original structures of the rocks preserved (e.g., McGregor, 1968, 1973; Nutman et al., 2016). This means that it is extraordinarily difficult (if not impossible) to correlate rocks over any distance by appearance alone, and even from one outcrop to another; particularly given the likelihood that strain is heterogeneous and the character of the same rock unit can vary markedly over short distances (e.g., Nutman et al., 2000). Even more importantly, gneisses pervasively penetrated by melt can become homogenised by high strain such that it becomes very difficult to recognise the two different components. In order to address the fundamental issues it is imperative that samples are taken from as low-stain areas as possible and that the samples represent single phases and have been as little disturbed as possible by superimposed tectono-thermal events (e.g., McGregor, 1973, 1979; Nutman et al., 1999, 2007).

From the perspective of the gneisses of the North Atlantic Craton in the Nuuk region of southern West Greenland (Fig. 1, Table 1), this paper explores the route to understanding this Archaean gneiss complex within a plate tectonic framework constrained by a tectono-stratigraphic terrane model (sensu Coney et al., 1980). Here, we demonstrate how detailed structural and metamorphic field evidence integrated with geological mapping and copious U-Pb zircon geochronology shows that the Nuuk region gneiss complex contains cryptic tectonic boundaries which separate unrelated blocks of crust brought together laterally in collisional orogenic episodes (Friend et al., 1988; Nutman et al., 1989, 2013 McGregor et al., 1991; Dilek and Polat, 2008). Such structural and geochronological evidence, combined with the petrology, geochemistry and isotope geochemistry of these rocks, consistent with a plate tectonic cycle stretching back to the start of the Archaean, has also been found elsewhere, for example in Australia (e.g. Kinny and Nutman, 1996), India (Jayananda et al. 2015; Santosh et al., 2015) as well as different parts of the North Atlantic craton Labrador (e.g. Komiya et al., 2015; Salacińska et. al., 2018) and Scotland (e.g. Kinny et al., 2005).

Systematic mapping of West Greenland by the Geological Survey of Greenland (GGU) commenced in 1955, in the southernmost Proterozoic regions and, by the early 1960s, had progressed north onto the Archaean craton. The mapping was guided by the then widely accepted concept that the gneisses in this part of Greenland were broadly contemporaneous, until discovery and dating of the Eoarchaean *Amîtsoq gneisses* (an abandoned term, now part of the Itsaq Gneiss Complex) by McGregor (1968) and Black et al. (1971). It was also considered that there was a structural continuity across the region (e.g., Windley, 1968) tied to the proposition that complex fold interference patterns could be traced uninterrupted throughout the region, for example, as depicted across the 500 km north-south extent of the 1:500 000 geological map Sheet No 2, Frederikshåbs Isblink – Søndre Strømfjord (Allaart, 1982; Kalsbeek and Garde, 1989).

Mapping and interpretation of such gneiss complexes have proved to be one of the most challenging problems in basement geology. The Nuuk region of the Greenland Archaean craton exemplifies this, where the production of the 1:100 000 scale geological map sheets was not in a systematic south to north order (see Supplementary Data) , and when there were rapid developments taking place in field geology and geochronology that were not always transferred to the maps. This resulted in maps not matching across their common boundaries. For example, the map sheets Buksefjorden 63V.1 Nord (Chadwick and Coe, 1983) and Qôrqut 64V.1 Syd (McGregor, 1993) do not match across their common boundary because of philosophical arguments over the definition of mapping gneiss units. Similarly, the Qôrqut sheet and adjoining sheet to the north, Fiskefjord 64V.1 Nord, did not match because a more sophisticated sub-division of the same units of gneisses was used in the latter sheet (see details in Supplementary Data). Because of the false permanency of the printed sheet, these mismatches are still extant and so can colour any geological interpretations made, long after the maps have been superseded but not replaced. This is important to note because it applies to geological surveys worldwide, which grapple now with producing seamless digital maps from previous published printed sheets produced at different times. These frequently had different concepts of what constitutes a mapping or stratigraphic unit, lithological divisions and usually had different geochronological coverage.

The more than thirty years of work described here involved in developing the tectono-stratigraphic terrane model for the Nuuk region is embodied in the two digital maps which accompany this paper. These maps have been produced to cartographic standard colours that will reproduce from a plot file, but the colour reproduction on a screen or in a printed pdf will not always truly reproduce the colour separation. The 1:40 000 scale map of the Færingehavn area (Digital Map 1) shows the 1985 mapping by Friend and Nutman from which the tectono-stratigraphic terrane model (Friend et al., 1987, 1988) arose. The 1:100 000 scale Nuuk regional map (Digital Map 2) present our current interpretation of the region (~200 km south to north). The historical perspectives are included in this account to demonstrate the lengthy, non-linear process leading to the current interpretation of this classic gneiss complex.

3. The road to the tectono-stratigraphic terrane model

3.1. The problem of Archaean gneiss complexes

A key problem in interpreting gneiss complexes is they are dominated by very unremarkable rocks, the so-called 'grey gneisses,' which consist mostly of tonalitic palaeosome with various amounts of granitic neosome as distinct bands or nebulous patches (Fig. 2A). This makes the structural dissection of these gneiss complexes difficult. Hence, in order to understand the tectonic development, there was an early focus on establishing sequences of fold (F) and fabric development (sometimes to F7 and beyond) with attempts to correlate them over vast areas of gneisses (e.g. Hopgood, 1980).

Before the 1980s advent of SHRIMP 1 ion microprobe zircon U-Pb dating (e.g. Compston et al., 1986), the understanding of these gneiss complexes was also hampered by the lack of a sufficient quantity of accurate and precise geochronology. The world's first maps of basement geology were all produced using only lithotype as the basis for distinction of units, and the only chronology was a relative one, based on intrusive or unconformable relations (e.g., Peach et al., 1907). This was the *modus operandi* for the first geological mapping of the Nuuk region up to the early 1970s (Windley et al., 1968 and see Supplementary Data). Subsequently, in the 1970s and early 1980s, after the deployment of isotopic dating, the available whole rock Rb-Sr, Pb-Pb, and subsequently Sm-Nd isochrons on such gneisses had large errors and associated high MSWDs (mean weighted square deviates), and had the inbuilt assumptions that all the samples were cogenetic and that all had the same initial Sr, Pb and Nd isotopic ratios. This meant that often age differences of only about 250 million years (equivalent to half of the Phanerozoic) could be discriminated by these methods. The few U-Pb zircon age determinations were mostly based on upper concordia intercepts of discordant data sets acquired on multigrain fractions (but not all; see concordant data for sample 155820 in Baadsgaard, 1973). The SHRIMP 1 instrument allowed events in individual, complex zircon-bearing gneiss samples to be dated accurately and precisely (Figs. 3A, B; e.g., Compston et al., 1986; Black et al., 1984; Kinny, 1986). This meant that the collection of a suite of rocks of assorted gneissic lithologies on the basis they were assumed to be the same age was rendered redundant.

3.2. The first breakthroughs

The first important breakthrough in the Nuuk region came from the combined field geological observations of McGregor (1968, 1973), whole rock radiogenic isotope measurements at the Oxford Isotope Laboratory (Black et al., 1971; Moorbath et al., 1972) and zircon U-Pb dating (Baadsgaard, 1973, 1976). These isotopic partnerships with McGregor demonstrated unambiguously that two major groups of rocks were present in the Nuuk (then Godthåb or Godthaab) region. The first units formed in the Eoarchaean (>3.6 Ga) and the second in the late Mesoarchaean (~3.0 Ga). These were then known as the *Amîtsoq* and the Nûk gneisses respectively. This interpretation was opposed by a body of opinion that considered all rocks in excess of ca. 3.40 Ga had been obliterated by Earth's violent early history (e.g., Wetherill, 1971). McGregor (1968) had discriminated the *Amîtsoq* and Nûk gneisses in the field by the presence of the metamorphosed and deformed Ameralik (mafic) dykes in the former and their absence in the latter. Using the work of Ramberg (1948) from the northern boundary of the Archaean craton with the Palaeoproterozoic Nagssugtoqidian orogen as an example, McGregor argued that the *Amîtsoq gneisses* were older than the Nûk gneisses. These concepts were quickly applied to other parts of the North Atlantic craton and rocks of similar relations and antiquity were found in Labrador (e.g. Bridgwater and Schiøtte, 1991).

In the mid-1960s, when McGregor started geological mapping of the Qôrqut Granite Complex (Fig. 1), it was regarded as the region's only significant igneous body, and all the surrounding gneisses were regarded as 'granitised' metasedimentary rocks (e.g. Berthelsen, 1960; Lauerma, 1964; Windley et al., 1966). This was the way that all grey gneiss complexes were then interpreted, following Peach et al (1908) and Sutton and Watson (1951). It was much to the ire of his supervisors that McGregor neglected the Qôrqut Granite

Complex, and focused on the gneisses instead. The case was made even worse by his audacity to go against the then current orthodoxy when he suggested, on the basis of unequivocal field relations of cross-cutting plutonic phases (Fig. 2B), that the gneisses were derived from plutonic rather than sedimentary rocks (McGregor, 1968). Thus, McGregor (1973, 1979) showed that the banded grey gneisses that dominate the Archaean gneiss complexes in the Nuuk region were strongly deformed plutonic igneous rocks of calc-alkaline affinity, rather than representing anatectic, 'granitised' sedimentary rocks, and used this as a template for other similar complexes (McGregor, 1979). This has subsequently been elaborated by other workers on a global basis (e.g. Martin, 1994; Martin et al., 2005; Salacińska et al., 2018).

The enduring importance of the findings of McGregor and his partnership with geochronologists was a growing understanding of the 'normality' of the earliest geological record, and that some rocks from Earth's first billion years have survived through subsequent tectonic upheavals, crustal melting events and erosion cycles. Besides geochronological evidence that both late and early Archaean crust is present in the region, equally important was the low initial $^{87}Sr/^{86}Sr$ ratios of these rocks that demonstrates they represent repeated cycles of juvenile crust formation. Thus, the *Amîtsoq* and Nûk gneisses were extracted from a depleted upper mantle only a short time before they formed (Moorbath et al., 1972; Moorbath, 1975), and do not represent recycling of older 'primordial' (>4.0 Ga) crust.

McGregor (1968, 1973) had shown that the *Amîtsoq gneisses* were tectonically intercalated with Mesoarchaean volcanic and sedimentary rocks, the *Malene supracrustal rocks* (again an abandoned term) of McGregor (1973), that also occurred as strip-like enclaves within the Nûk gneisses. This structural evidence of horizontal shortening and crustal thickening led to the proposition that Archaean gneiss complexes contained structural evidence of compressional tectonics, as seen in modern collisional orogens (e.g., Bridgwater et al., 1974). Finally, at the end of the Archaean, the essentially post-tectonic 2560 Ma Qôrqut Granite Complex (McGregor, 1973; Baadsgaard, 1976; Friend et al., 1985) was intruded.

The mid-1970s interpretation of the Nuuk region gneiss complex is summarised in Fig. 4A (adapted from Nutman, 1980). An old nucleus of Eoarchaean crust consisting of the

Amîtsoq gneisses with enclaves of somewhat older supracrustal rocks such as the Isua supracrustal belt (Bridgwater and McGregor, 1974; Allaart, 1976) occurred as a mega-inclusion engulfed by the late Mesoarchaean Nûk gneisses. Following emplacement of the Nûk gneisses there was regional isoclinal folding and then upright folding with essentially a single metamorphic peak, reaching granulite facies (≥800°C) that occurred at 2850 ± 100 Ma, in areas away from the Eoarchaean nucleus (Black et al., 1973), and upper amphibolite facies (~650°C) in the Eoarchaean nucleus with tectonic intercalations of *Malene supracrustal rocks* (see Wells, 1976). The peak of metamorphism was proposed to outlast regional folding and the contrast in metamorphic grade was interpreted to show different crustal levels within the same metamorphic event. Thermal modelling was presented to indicate that the tectono-thermal expression of the late Meso- to early Neoarchaean super-event was a result of magmatic 'overplating' where the plutonic protoliths of the Nûk gneisses were emplaced on top of each other at approximately the same crustal level, along an anticlockwise P-T-t path (Wells, 1979).

3.3. Misfits to the 1970s model; Kangimut Sammissoq and elsewhere

By the end of the 1970s, data were starting to emerge that did not fit the model summarized in Fig. 4A. Of most focus was the locality of Kangimut Sammissoq (Kangimut sangmissoq in the old Greenlandic orthography) on the south coast of Ameralik fjord (Figs. 1, 4B). The orthogneisses at Kangimut Sammissoq are partially retrogressed granulite facies rocks and contain remnants of mafic dykes. Therefore, on the basis of the then accepted relative field chronology, McGregor and some other field geologists regarded these rocks as *Amîtsoq gneisses* with Ameralik dykes, but affected by the late Archaean regional granulite facies metamorphism. A similar relative field chronology interpretation had been made for rocks further south at Tinissaq (Fig. 1; Chadwick et al., 1974). Focusing on the Kangimut Sammissoq locality, Moorbath et al. (1986) demonstrated that in terms of their Sr and Nd isotopic systematics, these rocks were extracted from the mantle in the Mesoarchaean, and could not be Eoarchaean *Amîtsoq gneisses*. Similar evidence had been produced to the south at Tinissaq where granulite facies gneisses with remnants of mafic dykes were shown by U-Pb zircon geochronology to have formed at ~2.9 Ga (Schiøtte et al., 1989). Prior to the tectono-stratigraphic terrane model, field geologists sought to reconcile the field interpretations and isotopic data by suggesting that granulite facies metamorphism could flush-out the radiogenic Sr and Nd accumulated in rocks since the early Archaean to 'reset' the whole rock ages (Collerson et al., 1986). However, this could not explain the lack of any Eoarchaean zircon in these rocks (Kinny, 1987; Schiøtte et al., 1989). This showed that some gneisses with amphibolitised dyke remnants are more than 700 million years younger than the Eoarchaean *Amîtsoq gneisses*, contravening the simplicity of the McGregor (1973) chronology.

Another problem was that the age of formation of Nûk-like gneisses and superimposed granulite facies metamorphism in the Fiskenæsset region south of Nuuk (2900-2800 Ma Fig. 4B; Pidgeon and Kalsbeek, 1978) was significantly younger than the age of the type Nûk gneisses and superimposed granulite facies metamorphism north of Nuuk (3100-3000 Ma; e.g., Taylor et al., 1980; Baadsgaard and McGregor, 1981).

Complexities were also arising in interpreting the metamorphic history of the gneisses. Dymek (1984) documented evidence for poly-metamorphism in the Nuuk region, which was incompatible with the concept of a single prograde metamorphism during the late Mesoarchaean super-event. Evidence of initial isobaric cooling of the granulite facies rocks south of Nuuk such as late garnet between plagioclase and orthopyroxene requiring an anticlockwise P-T-t path (Wells, 1976), was at odds with the evidence for isothermal decompression (early kyanite, then sillimanite followed by cordierite requiring a clockwise P-T-t path) in rocks showing supposedly coeval amphibolite facies metamorphism (Fig. 5; Nutman et al., 1989). This latter interpretation has recently been corroborated by Dziggel et al. (2012, 2014).

Thus in the early 1980s a scientific impasse had arisen between the predominantly field-based geologists and laboratory isotope geochemists about how to interpret and reconcile all the geological information from the Nuuk region. Given this impasse, Friend, Nutman and McGregor decided to go back to the drawing board, and to look at the rocks afresh. The area chosen to start was around Færingehavn (Fig. 1; Digital Map 1), because (a) it contained the boundary between granulite facies rocks to the east (which included the contentious Kangimut Sammissoq and Tinissaaq localities) and amphibolite facies rocks to the west, and (b) it was logistically easy, with a highly indented coastline but with low relief and excellent exposure, making boat-based geological studies most effective (Fig. 6). During the August field season in 1984 (curtailed to work only around Nuuk - Færingehavn because of atrocious weather and sea ice conditions) it was concluded that the boundary between the amphibolite facies and granulite facies areas was an early (amphibolite facies, sillimanite grade) shear zone, meaning that, contrary to the 1970-80s model (Fig. 4A), metamorphic and structural continuity across it could not be assumed (McGregor et al., 1986). However, a linear extrapolation of this boundary north-eastwards along the peninsula from the mouth of Buksefjorden towards Kangimut Sammissoq was problematic because it did not properly fit the known distribution of granulite and amphibolite facies rocks to the north (blue arrow at Præstefjord, P, Fig. 4B). It was then decided to address this problem by traversing from granulite facies rocks at Kangimut Sammissoq towards an area thought never to have been to granulite facies, (blue arrow at KS, Fig. 4B). During this walk it was suggested 'What if the granulite facies boundary is folded?' This idea would imply major tectonic activity *after* the peak of Neoarchaean metamorphism, in conflict with the 1970s model where peak metamorphism *outlasted* major deformation (c.f. Fig. 4A). This idea could be tested by sailing into Buksefjorden and climbing the 1000m cliffs to the northern plateau to examine metamorphic relationships in a large fold nose (green arrow at Buksefjorden Fig. 4B). This was duly accomplished and once on the plateau it was evident that the boundary of rocks affected by granulite facies is indeed folded. By this observation the first steps had been taken to produce a new tectonothermal evolution model for the region, by dispensing with the 1970s mantra that peak Neoarchaean metamorphism outlasted all significant ductile deformation producing regional fold structures.

3.4. Færingehavn 1985 and Nuuk region 1987, 1988

The 1985 field season was in the Færingehavn area undertaking detailed field observations and mapping at 1:10,000 scale (compiled at 1:40,000 scale; Digital Map 1; Friend et al., 1987). It was discovered that there are three packages of Archaean gneisses in the area; (a) the *Amîtsoq gneisses*, (b) homogeneous, grey orthogneisses with distinct pegmatite bands that had **not** undergone granulite facies metamorphism and (c) heterogeneous nebulitic orthogneisses that had suffered granulite facies metamorphism that had been partially retrogressed under amphibolite facies conditions. Subsequently, the homogeneous grey gneisses were dated by H. Baadsgaard and turned out to be a previously unrecognised ca. 2820 Ma group of rocks (Friend et al. 1988, 2009). Respectively, these three groups of rocks became known as the Itsaq Gneiss Complex (Nutman et al., 1996) within the Færingehavn terrane (Friend et al., 1988), the 2825 Ma Ikkattoq gneisses of the Tre Brødre terrane (Friend et al., 2009) and (unnamed) 2920-2800 Ma gneisses of the Tasiusarsuaq terrane (Friend et al., 1987; 1988) (see Fig. 1, Digital Map 2).

The boundaries between the three terranes were confirmed to be folded, deformed, amphibolite facies meta-mylonites, commonly only a couple of metres wide, but with distinct strain gradients towards them (Friend et al., 1987, 1988). Despite their profound nature, they were interpreted to be so narrow because in later tectonic events they were ductilely-attenuated or excised (Nutman and Friend, 2007). Lithologically, the mylonites are mostly strongly banded, siliceous rocks with rootless folds of pegmatitic material (Fig. 7A), but elsewhere there can be homogeneous foliated rocks (meta-ultramylonites), or marked by massive, coarse-grained, fuchsite-bearing, quartz seams. Such seams can have associated ultramafic and gabbroic pods that are restricted to the mylonites. As an indication of post-mylonite metamorphism, garnets can be found growing across the mylonitic fabrics (Fig. 7B) The detailed mapping in the Færingehavn area demonstrated that the 2825 Ma Ikkattoq gneisses of the Tre Brødre terrane affected by only amphibolite facies metamorphism were structurally **below** those affected by 2795 Ma (Pidgeon et al., 1976; Crowley, 2002) granulite facies metamorphism (Digital Map 1). Thus, structurally lowest are the Færingehavn and then Tre Brødre terranes, followed on top by the granulite facies rocks of the Tasiusarsuaq terrane. Furthermore, in the edge of the Tasiusarsuaq terrane, the strain gradient structurally downwards towards the mylonite bounding the underlying Tre Brødre terrane shows progressive syn-kinematic obliteration of the granulite facies assemblages (Figs. 7 C, D). Thus the rocks with 2795 Ma granulite facies assemblages had been retrogressed when tectonically emplaced over rocks that only experienced amphibolite facies metamorphism (Nutman et al., 1989). The meta-mylonites were mapped around fold interference patterns, demonstrating that after the granulite facies metamorphism in the

Tasiusarsuaq terrane, the three terranes had been juxtaposed and thereafter shared a complex tectonic and metamorphic history (Friend et al., 1987).

The Færingehavn area geology was used in 1987 and 1988 fieldwork as a template to reinterpret the geology of the entire Nuuk region (Friend et al., 1988; Nutman et al., 1989; McGregor et al., 1991). This was an audacious undertaking, considering the limited logistical resources of the three people involved, the vast size of the region (~10,000 km^2) and at that time there were very few accurate and precise isotopic absolute age determinations. The work was guided by the lithological maps published by the Geological Survey of Greenland (GGU; now part of GEUS – the Geological Survey of Denmark and Greenland), which were of great assistance in delineating major structural trends, and generally showed where there were Eoarchaean versus (undifferentiated) younger gneisses.

Based on two helicopter reconnaissance flights and some long foot traverses inland southwards from the coast of Ameralik, the tectonic boundary of the southern Tasiusarsuaq terrane was extrapolated eastwards through Qarliit Nunaat to the inland ice (Fig. 1). This demonstrated that the contentious Kangimut Sammissoq locality was in the Tasiusarsuaq terrane, and thus there was no reason that its orthogneisses with dykes need correlate with the *Amîtsoq gneisses* (now the major components of the Itsaq Gneiss Complex). Instead, Nutman and Friend (1989) suggested they simply represent an old component within the Tasiusarsuaq terrane. This was already demonstrated by ~2920 Ma SHRIMP U-Pb ages obtained for igneous zircons in the Kangimut Sammissoq rocks (Kinny, 1987) as opposed to ~2860-2820 Ma ages for most of the orthogneisses in that terrane (Friend and Nutman, 2001; Crowley, 2002). The tectonic boundary of the Tasiusarsuaq terrane has been named the Qarliit Nunaat Thrust (QNT, 7, on Fig 1) (Friend et al., 1988).

The Eoarchaean Færingehavn terrane was followed northwards into the Godthåbsfjord region. Here, it was discovered that along its western edge was a thin tectonic slice of the Tre Brødre terrane, and then the extensive Akia terrane, which contains the Nûk gneisses *sensu stricto* (see Friend et al., 1988; Digital Map 2). The eastern edge of the Akia terrane is marked by the Ivinnguit Fault (IF, 8, on Fig 1) (McGregor et al., 1991), an almost straight, mostly steeply westerly dipping structure trending NNE. This was followed for 150 km from the coastal region southwest of Nuuk to the head of Godthåbsfjord at Ilulialik (Fig. 1;

Digital Map 2). The metamorphic grade of the fault is epidote amphibolite facies, and it was shown to be late Archaean in age, because some granite sheets associated with the 2560 Ma Qôrqut Granite Complex were deformed within it and truncated, whereas others cut it. It was discovered that the Ivinnguit Fault ran along the top of the mountain Store Malene, east of Nuuk (Digital Map 2), and cut through the middle of the type locality unit of Malene supracrustal rocks (McGregor, 1973). This means that >3.0 Ga amphibolites lie on the west side of the unit, in the Akia terrane (Nutman et al., 1989) whereas ~2840 Ma metasedimentary rocks in the Tre Brødre terrane, lie to the east (Nutman and Friend., 2007). Consequently, the term *Malene supracrustal rocks* was abandoned (Nutman et al., 1989).

The region between the Ivinnguit Fault (IF, 8) and the Qarliit Nunaat Thrust (QNT, 7, on Fig.1) was named the Akulleq terrane (Fig. 4C; McGregor et al., 1991), a composite body of the Færingehavn and Tre Brødre terranes, sandwiched between the more extensive Akia and Tasiusarsuaq terranes. The Akulleq terrane (now an abandoned term) was regarded to mark a collisional orogeny between the Akia and Tasiusarsuaq terranes. All four terranes were interpreted as arc-like, calc-alkaline juvenile crustal constructs formed at unrelated convergent plate boundaries, but subsequently sequentially brought together by collisional orogeny later in the Archaean (McGregor et al., 1991; Table 1). This paper presented a set of cartoons (see Fig. 3 of McGregor et al. (1991), reproduced here as Fig. 4C), showing the later Archaean (post-Itsaq gneiss complex) development of the terranes; for the first time explicitly within a specific plate tectonic scenario. The subsequent work has shown that the sequence of events shown by McGregor et al. (1991) was incomplete and was wrong in some details. However, the basic interpretation was correct: blocks of crust representing unrelated magmatic arcs of different age have been brought together by collisional orogeny later in the Archaean. For example, the ~3800 Ma TTG component of the Itsaq gneiss complex is shown to comprise high-Al tonalites with calc-alkaline affinities and derivation from melting leaving a residue of a garnet + amphibole + clinopyroxene (Nutman et al., 1999). Jenner et al. (2009) presented data on the Isua ~3800 Ma mafic volcanic rocks and their relationships with subduction, which was amplified by Nutman et. al. (2013). In this way, each terrane has unrelated early generation and tectono-thermal histories, but then a common history after the terranes were amalgamated (Fig. 4C; Table 1). The presently recognised terranes and a summary of the events leading to their formation are summarised in Table 1 and their geochronology in Figure 8.

4. Igneous rocks and isotopic signatures

4.1. Mafic rocks

Mafic rocks form <10% of all the terranes in the Nuuk region and generally, in any one given terrane, they are amongst the oldest rocks present. Due to high strain and metamorphism they are usually found as hornblende + plagioclase + quartz ± pyroxene ± garnet tectonites, usually devoid of any of their original protolith features. In rare low strain zones, for example the Isua supracrustal and Ivisartoq supracrustal belts, where protolith features are occasionally preserved, they are found to be derived largely from pillow lavas and layered gabbros (Fig. 9A, B; e.g., Bridgwater et al., 1976; Hall and Friend 1979; Komiya et al., 1999). Despite early claims of komatiites (e.g., McGregor and Mason, 1977), komatiites are either entirely absent or exceedingly rare in the Nuuk region (c.f. Hollings et al., 1999). We regard the early claims of komatiites as part of the 1970s global 'komatiite fever', when it seemed that, lacking the modern discriminatory geochemistry, any high-Mg meta-igneous Archaean rock became a komatiite. Instead, the chemistry of the mafic rocks is overall more arc-tholeiitic, picritic or more rarely boninitic (Polat et al., 2002; Polat and Hofmann, 2003; Garde, 2007; Dilek and Polat, 2008; Jenner et al., 2009).

Being able to distinguish with certainty between komatiite and arc-tholeiite signatures in the Archaean record is particularly important, because komatiites are dry, decompressional, high-percentage partial melts of diapirically-rising mantle (e.g., Arndt, 2003), whereas the arc-tholeiite and boninitic signatures indicate essentially isobaric fluid-fluxing melting of upper mantle by addition of fluids driven off a subducted slab (e.g., Pearce et al., 1995; Pearce, 2008). The former decompressional melting setting could operate independently of a plate tectonic regime, such as variants of the static lid scenario, where melting products of plumes repeatedly resurface the planet, and buried older crust founders vertically and is recycled (e.g., Griffin et al., 2014). The latter setting of fluid-fluxing would be a strong indicator of some form of subduction and hence a plate tectonic regime (Dilek and Polat, 2008). Trace element chemistry of the mafic rocks is particularly powerful to distinguish the two possibilities. Nearly all of the Nuuk region analysed amphibolites display primitive mantle normalised trace element patterns marked by modest enrichment of the large ion lithophile (LIL) elements and the light REE (rare earth elements), depletion of niobium, tantalum and titanium, enrichment in Pb and relatively flat heavy REE (e.g., Polat et al., 2002; Polat and Hoffman, 2003; Jenner et al., 2009; Polat et al., 2011). The modest enrichment in the LIL, light REE and Pb is due to their preferential incorporation into fluids driven off the subducted slab and their migration upwards into a mantle wedge, whereas the depletion of Nb, Ta and Ti is caused by their retention in HFSE-rich phases such as rutile and humite group minerals in the subducted slab (e.g., Izuka and Nakamura, 1995; Katyama et al., 2003). Hence the almost universal appearance of these signatures in 3.85 to 2.8 Ga pillow lavas and gabbros of the Nuuk region is very powerful evidence for episodic subduction over a billion years of Archaean history (Dilek and Polat, 2008).

4.2. Igneous rocks with 55-70 wt.% SiO_2

The most voluminous rocks of the Nuuk region gneiss complex are broadly tonalitic orthogneisses with typically 65-70 wt.% SiO_2, low K_2O and high Na_2O. These form 70-80% of the individual terranes, and hence understanding their petrogenesis is paramount in understanding Archaean crustal evolution in the Nuuk region. McGregor (1979), following his recognition that most of these rocks have plutonic igneous protoliths (dominantly tonalites), used the chemistry of ~3.0 Ga Nûk and >3.6 Ga *Amîtsoq gneisses* to demonstrate their calc-alkaline affinity, and thereby liken them to magmatic suites formed in Phanerozoic arc complexes at convergent plate boundaries. This was broadly true, but mounting geochemical data has indicated that there are some geochemical differences between modern calc-alkaline arc assemblages and the Archaean tonalitic gneisses like those found in the Nuuk region (e.g., Martin, 1986; Martin et al., 2005). Most important are features such as the strong depletion of the heavy REE versus strong enrichment of the light REE, and the overall higher SiO_2 and lower MgO of the Archaean rocks compared to most modern arc suites. Trace element modelling suggested that this Archaean signature most likely indicates melting of eclogitised mafic rocks in a subduction zone (Arth and Hanson, 1972; Martin, 1986; Martin et al., 2005; Steenfelt et al., 2005; Hoffmann et al., 2011; Nagel et al., 2012), although recently, an alternative explanation has been proposed (Moyen and Laurent, 2018). Studies of the Archaean grey gneisses of the Nuuk region have confirmed this as the most likely petrogenetic model, for example from comparison of 3800 Ma tonalites from south of the Isua supracrustal belt (Nutman et al., 1999) to similar-aged gneisses on the outer coast (Nutman et al., 2007) and into the Mesoarchaean gneisses in Akia (Garde et al., 2000; Garde, 2007). Thus the TTG which are the bulk of the rocks forming the Nuuk region gneiss complex, seem to be derived from high pressure melting of mafic rocks as either garnet-bearing granulites or eclogite, with the inference that over a billion years there were repeated convergent plate boundary settings.

A minority of the grey gneisses consist of higher MgO, lower SiO_2 rocks, with overall quartz-dioritic chemistry (see Drummond and Defant, 1990 and references therein). Compared with the tonalites, they show a lesser degree of fractionation of the REE, and they resemble much more the composition of andesites and quartz-diorites in modern arc systems produced by the fluxing of a mantle wedge over a subduction zone (Steenfelt et al., 2005; Nutman et al., 2007; 2013). Where sufficient U-Pb zircon geochronological data are available, they seem to be marginally older than the bulk of the high SiO_2 tonalites in the same terrane (Nutman et al., 2013).

4.3. Granites sensu stricto

All terranes contain granites *sensu-stricto*, with SiO_2 >70 wt.% and high K_2O. The granites fall into two categories, ones that are restricted to individual terranes (e.g., Fig. 9C) and those that stitch terranes, i.e. they transgress the tectonic boundaries. The clearest example of the latter is the 2560 Ma Qôrqut Granite Complex (Fig. 9D) that is unambiguously intruded across the folded tectonic boundaries between the Tasiusarsuaq, Tre Brødre and Færingehavn terranes (Friend et al., 1988, 1996; McGregor et al., 1991). Minor granite sheets formed at 2720-2710 Ma following crustal thickening by stacking of the Tasiusarsuaq, Tre Brødre and Færingehavn terranes are also examples of stitching bodies (Friend et al., 1996; Crowley, 2002). Much of this granite was generated at deeper crustal levels in the Færingehavn terrane, where it can form diffuse migmatite domains and locally coalesce into small bodies of granite, with variable amount of restitic palaeosome. At higher structural levels at ~2710 Ma, such as in the Tasiusarsuaq terrane, 2720-2710 Ma granites tend to occur as sharp-margined, late kinematic sheets (Friend et al., 1996).

Additionally, there are granitic bodies that are restricted to each particular terrane. These are interpreted as an expression of intra-crustal melting following, or late in, the crust formation reflected in that terrane. In the northern part of the Isukasia terrane, juvenile 3700 Ma tonalites are cut by extensive swarms of gently inclined 3650-3630 Ma granite sheets (Baadsgaard et al., 1986; Nutman and Bridgwater, 1986; Nutman et al., 1996; Crowley et al., 2002). Likewise, in the Akia and Kapisilik terranes, 3070-3000 Ma juvenile crustal components are intruded by 2970-2960 Ma crustally-derived granites (Garde et al., 2000; Friend and Nutman, 2005). The widespread occurrence of these late granites is probably related to thickening of the crust late in terrane creation, which, particularly in the Archaean, led to rapid radiogenic heating, partial fusion with granite production and ductile collapse (e.g., Rey and Coltice, 2011).

4.4. Peri- and intra-terrane detrital zircon signatures

Rocks with sedimentary protoliths form only a tiny amount (<2%) of the Nuuk region Archaean exposures. They are particularly sparse *within* the terranes, and somewhat more prevalent along the margins of the terranes, particularly associated with Tre Brødre terrane margins. Two of the first three publications of the Nuuk region rocks to be investigated by SHRIMP U-Pb zircon geochronology were on samples interpreted as having sedimentary origins. Compston et al. (1986) reported zircon ages from what was interpreted as a volcanic debris unit with large clasts in the Isua supracrustal belt, and found a unimodal age population of 3806 ± 2 Ma (2σ), indicating a simple volcanic provenance. This unit has been re-interpreted as a tectonised and altered package of dacitic-rhyolitic flows (e.g., Nutman et al., 2015b), rather than of clastic sedimentary origin. Schiøtte et al. (1988) reported zircon ages from two meta-sandstones from islands south of Nuuk and ascribed them to the then *Malene supracrustal rocks*. These revealed a spread in detrital zircon ages of mostly 2800-2900 Ma, but with some older components. This study also revealed (the then) surprisingly young ages of ~2650 Ma for low Th/U metamorphic overgrowths.

Since these pioneering studies, several workers have presented detrital zircon ages from Nuuk region metasedimentary rocks. These results have been collated in Fig. 10 (see caption for data sources). These data have been filtered so that only the analyses most likely to reflect undisturbed detrital ages remain. Culled are analyses of definite metamorphic overgrowths and recrystallisation areas, those whose $^{206}Pb/^{238}U$ versus $^{207}Pb/^{206}Pb$ ages are >10% different, and ones with >2% ^{206}Pb modelled as common Pb on the basis of measured ^{204}Pb. Additionally, it was found that some rare remaining analyses displayed U-Pb ages that are impossibly young to represent an authentic age for a detrital component. In some rocks with very low zircon yields (notably BIF of the Isua supracrustal belt), such rare grains with Neoproterozoic or even younger ages are clearly laboratory contaminants. In other cases, grains with impossibly young ages (e.g. late Palaeoproterozoic ages in a Mesoarchaean rocks) were found to display high U+Th contents, and therefore are likely to be older grains that suffered ancient loss of radiogenic Pb. This appraisal and culling of the aggregated data from many sources left 471 robust ages on detrital zircons in metasedimentary rocks (Fig. 10).

The compiled age spectra indicate an important contrast from samples that are intra-terrane, and those that lie at terrane boundaries. Ones that are entirely within a terrane show closest to unimodal age distributions (panels A and B of Fig. 10 for the Tasiusarsuaq and the Akia/Kapisilik terranes). This feature is still found within the ~3700 Ma terrane of the intensely-studied Isua supracrustal belt. Thus, sedimentary rocks in the ~3700 Ma part of the belt are dominated by detrital grains derived from ~3700 Ma igneous sources, with only sparse grains back to ~3740 Ma (Fig. 10C; e.g., Nutman et al., 2009b). In contrast, detrital sedimentary rocks in the ~3800 Ma part of the belt are dominated by ~3800 Ma grains derived from igneous sources of that age, but there is also a significant sub-population of ~3850 Ma grains, and a single ~3890 Ma grain (Fig. 10D). The older grains are all found within a rare quartz-fuchsite quartzite, along with ~3800 Ma grains (Nutman et al., 1997). On the other hand, a sample of graded quartz-dolomite sandstone closely associated with ~3800 Ma metavolcanic rocks contains only ~3800 Ma grains. This shows mixture of slightly older crustal components into this terrane at ~3800 Ma, in contrast to the ~3700 Ma part of the terrane, that is largely devoid of older components (Fig. 10C and D).

Peri-terrane sedimentary rocks present more diverse and complex detrital zircon spectra. A sedimentary rock sandwiched between a klippe of mafic rocks ascribed to the Kapisilik terrane and Eoarchaean Isukasia orthogneisses south of Isua (Nutman et al., 2004a) shows detrital zircons derived from both the Eoarchaean Itsaq Gneiss Complex and 3000-3100 Ma sources ascribed to the Kapisilik terrane (Fig. 10E). The Isua supracrustal belt Dividing Sedimentary Unit (Nutman et al., 2009b) occurring at the tectonic boundary between the ~3700 and ~3800 Ma parts of the belt is dominated by BIF and quartz- and carbonate-rich sedimentary protoliths with low zircon yields. Dominant are ~3750 Ma euhedral grains of likely volcanogenic origin (not matching the age of any igneous components in the adjacent parts of the belt), with a minor ~3800-3850 Ma component (like found associated with rare fuchsite quartzite in the ~3800 Ma part of the belt), but also with >3900 Ma grains present (Fig. 10F). These rare >3900 Ma grains are the oldest crustal component recognised in the Itsaq Gneiss Complex; whereas its oldest extant zircon-bearing rocks are meta-tonalites with an age of ~3890 Ma (e.g. Nutman et al., 2007a).

The metasedimentary rocks with the most fecund detrital zircon yields occur at the tectonic boundary between the Færingehavn and Tre Brødre terranes in the outer Godthaabsfjord and the coastal regions to the south (Fig. 10G), and at margins of the Færingehavn ± Kapisilik terrane and likely correlatives of the Tre Brødre terrane in the inner fjord eastern regions (Fig. 10H). All samples from these peri-terrane locations show complex detrital zircon age spectra, but always with a dominant population at ~2830-2840 Ma (e.g., Schiøtte et al., 1988; Nutman et al., 2004a; Nutman and Friend, 2007) with a lesser number from older sources.

Sedimentary rocks entirely within terranes versus those at terrane boundaries show contrasting detrital zircon patterns. Detrital sedimentary rocks that are entirely within a terrane and intruded by local TTG show closest to unimodal age distributions, suggesting derivation from single igneous sources during terrane development as series of arc-like constructs – as first shown graphically in figure 3 of McGregor (1991); reproduced here as Figure 4B. On the other hand, metasedimentary rocks at terrane boundaries always produce more complex detrital zircon age spectra, but with all grains (apart from two 3300-3450 Ma grains in one sample; Fig. 10E) matching known igneous ages in the Nuuk region (Fig. 8). At the Isukasia-Kapisilik boundary the signature is derived from both the Mesoarchaean

Kapisilik and the Eoarchaean Isuksia terranes (Fig. 10E). For sedimentary rocks associated with the Færingehavn + Tre Brødre terrane boundary on the outer coast and the Færingehavn ± Kapisilik terrane and likely correlatives of the Tre Brødre terrane in the inner fjord eastern regions (Fig. 10G, H), there is always with a dominant population at ~2830-2840 Ma (e.g., Schiøtte et al., 1988; Nutman et al., 2004a; Nutman and Friend, 2007). This is marginally older than the ~2825 Ma Ikkattoq gneisses (Friend et al., 2009) of the Tre Brødre terrane, but matches the age of a dominant TTG component within the Tasiusarsuaq terrane to the south (Fig. 8; e.g., Friend and Nutman, 2001). Some older grains in these sedimentary rocks also match the age of older components within the Tasiusarsuaq terrane (notably ~2860 and ~2940 Ma), whereas others match the ~3000-3250 Ma components normally ascribed to the Akia terrane (Fig. 8; e.g., Garde et al., 2001). Only one Eoarchaean grain (from >200 analysed in this category of sample) has been detected. One interpretation is that these grains were derived from the three separate Tasiusarsuaq, Akia/Kapisilik and Færingehavn terranes. Alternatively, the Tasiusarsuaq terrane could be the sole source, because it is now known to contain small >3600 Ma and 3000-3250 Ma gneiss components (e.g., Næraa et al., 2012; Yi et al., 2014). Here in this paper, we interpret these older components within the Tasiusarsuaq terrane to indicate that it contains one or more ribbons of these older terranes, engulfed in the voluminous TTG of the Tasiusarsuaq terrane (Fig. 11e, f). We interpret the complex zircon age spectra in the peri-terrane sedimentary rocks to indicate their deposition in closing ocean basins, with more complex detrital sources compared with most intra-terrane sedimentary rocks, derived from simple juvenile arc sources. This is the same scenario as found in the Phanerozoic, where in ocean basin closure older sedimentary rocks associated with intra-oceanic arcs have simple, generally unimodal, detrital zircon age signatures, whereas later sedimentary rocks deposited during ocean closure show more complex detrital zircon age patterns. A modern example of this is the Himalaya system, with the ongoing collision of India and Eurasia. In this setting, the early intra-Tethys juvenile Jurassic-Cretaceous arcs have simple zircon populations, whereas with passing of time and the extinction of these arcs, the sourcing of sediments first from proximal different continental masses and then from the mountains raised upon continental collision, leads to the detrital zircon signatures become more complex (see overview by Blum et al., 2018).

4.5. Radiogenic isotopic signatures

The tonalites that dominate all the terranes are marked by low initial $^{87}Sr/^{86}Sr$ ratios (Moorbath et al., 1972; Moorbath, 1975; Baadsgaard et al., 1986), positive initial εNd values (Baadsgaard et al., 1986; Moorbath et al., 1986; Bennett et al., 1993, 2007) and zircon initial εHf values that are essentially chondritic in the Eoarchaean and positive in the Meso and Neoarchaean (e.g., Hiess et al., 2009, 2011; Kemp et al., 2009, Næraa et al., 2012; Fig. 11). These different isotopic system signatures corroborate each other and show that each terrane represents new crust formed out of a depleted mantle reservoir only a short time before. These isotopic data are strong evidence that these terranes evolved separately, created in intra-oceanic settings, to be coalesced later in their history. If the rocks were formed by repeated magmatism within a single coherent body of crust, then from the Eo- to Neoarchaean tonalite initial $^{87}Sr/^{86}Sr$ ratios would become progressively elevated and initial εNd and εHf values would have become negative (Fig. 11).

5. The present tectono-stratigraphic terrane interpretation

5.1. Zircon U-Pb geochronological database

Since 1991, we have dated more than 250 rocks from the Nuuk and adjoining regions by the SHRIMP U-Pb technique. The majority of data were acquired in the Research School of Earth Sciences of the Australian National University (ANU), with the rest at Hiroshima University (HU), the Japanese National Institute of Polar Research, the Korean Basic Science Institute, The Chinese Academy of Geological Sciences (Beijing) and at Geoscience Australia. Additionally, other workers have published >50 U-Pb zircon dates on Nuuk region rocks using SHRIMP and Cameca ion probes, laser ablation ICPMS and modern single grain isotope dilution thermal ionisation techniques. Of particular importance is the study of Crowley (2002) who presented zircon geochronology from the different terranes of the Færingehavn region and confirmed the tectono- stratigraphic terrane model put forward by Friend et al. (1988), Nutman et al. (1989) and McGregor et al. (1991). The dates are shown on Digital Maps 1 and 2, and are summarised in Figure 8. This figure presents >300 age determinations on igneous protoliths and superimposed metamorphic events. In total, this is based on >5,000 individual zircon analyses. The caption of Figure 8 gives the sources of the data embodied in it. An additional ~60 samples with reconnaissance analyses (<6 analyses per sample) that were mainly undertaken at HU are not shown on this figure, but are given in italics without analytical errors on Digital Map 2.

5.2. How many terranes?

When the first plate tectonic synthesis of the entire Nuuk region was presented by McGregor et al. (1991), the only U-Pb age determinations for the ~3500 km^2 area between inner Ameralik fjord in the south, Godthåbsfjord in the west and definite Eoarchaean Itsaq Gneiss Complex to the north on Ujarsagssuit Nunaat (Fig. 1), were three SHRIMP U-Pb zircon age determinations of ~2820 Ma (H. Baadsgaard and L. Schiøtte, unpublished data). These rocks showed no evidence of granulite facies and had the same ages within error as the Ikkattoq gneisses of the Tre Brødre terrane. Taking into account that the ~3.0 Ga Nûk gneisses were thought to be confined to the Akia terrane west of the Ivinnguit Fault, in the late 1980s – early 1990s it was assumed that the grey gneisses throughout this area formed a large extent of Tre Brødre terrane (McGregor et al., 1991) i.e. they were designated as Ikkattoq gneisses. However, subsequent SHRIMP U-Pb zircon geochronology (Friend and Nutman, 2005a; Hollis et al., 2005) indicated that ~3.0 Ga orthogneisses are also important in this area. These Mesoarchaean orthogneisses and the rocks of the supracrustal belt on Ivisaartoq (Digital Map 2) have the same ages as those in the Akia terrane (e.g., Baadsgaard and McGregor, 1981; Garde et al., 2000; Garde, 2007), but they were discriminated as the Kapisilik terrane because they are separated by the Ivinnguit Fault (Fig. 1, Tables 1, 2). SHRIMP U-Pb dating reported in Friend and Nutman (2005) also highlighted important differences in the Meso- to Neoarchaean history of the Itsaq Gneiss Complex rocks in the Godthåbsfjord – Færingehavn area and those in the north on Ujaragssuit Nunaat and the Isukasia area (Figs. 1 and 8). Those of the Godthåbsfjord – Færingehavn area show important metamorphic events at ~2720-2700 and 2690-2680 Ma, but *none* in the Mesoarchaean, whereas the Itsaq gneiss complex rocks on Ujaragssuit Nunaat showed 2960-2905 Ma *and* 2690-2680 Ma metamorphic events but *not* the 2720-2700 Ma event (e.g. Digital Map 2; Friend and Nutman, 2005a, Nutman et al., 2015b). Because the Itsaq Gneiss Complex rocks of the Ujaragssuit Nunaat and Isukasia area were regarded as tectonically separate from the Færingehavn terrane in the Mesoarchaean, they were named the Isukasia terrane (Friend and Nutman, 2005b).

Six terranes (Færingehavn, Isukasia, Akia, Kapisilik, Tasiusarsuaq and Tre Brødre; Figs. 1 and 8) are used to portray regional geology in the 1:100 000 scale map (Digital Map 2), and their attributes are summarised in Table 1. It is important to note that crust in the Færingehavn and Isukasia terranes formed in the same Eoarchaean interval (Nutman et al. 2015a), likewise for the Akia and Kapisilik terranes in the Mesoarchaean. Relationships between these terranes are explored in the Discussion section of this paper.

5.3. Terranes within terranes

The large zircon U-Pb geochronology database (Fig. 8) also provides details of intra-terrane history. Such histories are known best from the Isukasia terrane, because of the interest as the world's best-preserved old rocks (e.g., Nutman and Friend, 2009; Nutman et al., 2013), the chemical indications for life through light C isotope signatures (Schidlowski et al., 1979; Rosing, 1999) and signs of early life in the form of stromatolites (Nutman et al., 2016). Nutman et al. (1996, 1997, 2002) presented evidence that the Isukasia area contains a cryptic suture dividing it into crust formed at ~3.7 Ga in the north, from crust in the south formed and ~3.8 Ga. U-Pb zircon geochronology by Crowley et al. (2002) and Crowley (2003) confirmed the interpretation of Nutman et al. (1997, 2002). Hence the vast amount of zircon geochronology accrued over the past two decades has demonstrated that there can be several pulses of juvenile crust formation and suturing within each terrane.

Further work has provided a detailed chronology of the evolution of the sub-terranes, particularly the ~3.7 Ga portion of the Isukasia terrane (Nutman et al., 2000, 2009, 2013, 2015a; Friend and Nutman, 2011). The ~3.7 Ga terrane shows evolution of an arc-like package from early ~3.72 Ga arc-tholeiites and boninites, to 3.72-3.71 Ga andesitic/quartz dioritic and magnesian tonalite components, followed by packages of 3710-3700 Ma felsic volcano-sedimentary rocks, uplift, erosion and weathering, followed by regression and the deposition of dolostones, marls, cherts and banded iron formations at 3690 Ma, coeval with intrusion of less magnesian more siliceous tonalites at 3690-3680 Ma (Nutman and Friend, 2009; Nutman et al., 2013). This sequence of events is remarkably similar to those seen in the life cycle of evolving intra-oceanic arcs in the Phanerozoic (e.g., Shervais, 2001; Dilek and Polat, 2008).

5.4. Anomalous ages within the Tasiusarsuaq terrane

The initial impetus leading to the tectonostratigraphic terrane interpretation for the Nuuk region Archaean geology, was interpretation of the granulite facies orthogneisses cut by mafic dykes at Kangimut Sammissoq (Fig. 1). Radiogenic dating showed these were not Eoarchaean *Amîtsoq gneisses*, but instead simply an older (~2.92 Ga) component in 2.86-2.82 Ga Mesoarchaean gneisses (Moorbath et al., 1986; Kinny, 1987), now recognised as part of the Tasiusarsuaq terrane (Friend et al., 1988). However, in the subsequent three decades of field work and zircon geochronology, rare migmatite components in the Tasiusarsuaq terrane with ages of 3.8-3.6 Ga and 3.25-3.1 Ga have been recognised (Digital Map 2).

These ages appear anomalous because they match those diagnostic of the Færingehavn-Isukasia terranes and the older component of the Akia-Kapisilik terranes. Our explanation for this is that the Tasiusarsuaq terrane contains one or more ribbons of Færingehavn – Isukasia – Akia - Kapisilik terrane that in the Mesoarchaean was rifted-off into the oceanic realm, wherein subduction subsequently produced the Mesoarchaean arc-related rocks of the Tasiusarsuaq terrane (Fig. 12E). In the Phanerozoic, numerous examples of such a process can be found. For example, in the Middle East, the life cycle of the Palaeo- and Neotethys Oceans involved rifted fragments of Gondwana being transported and isolated in the Tethyian oceans (Şengör, 1984; Ricou, 1994; Robertson et al., 1996). This produced Gondwanan continental blocks such as the Sanandaj-Sirjan Zone (Fergusson et al., 2016) now in Iran. Consumption of Tethyian oceanic crust by several subduction zones formed Mesozoic-Cenozoic arc complexes. These arc complexes now occur as tectonically-disrupted assemblages interspersed with Gondwana continental fragments, which are again in close proximity to the margins of the Arabian microcontinent, a larger fragment of Gondwana (see review by Ali et al., in press). As another analogy, with future subduction and closure of the Tasman Sea oceanic crust, Gondwanan crust as an isolated fragment in New Zealand will be reunited with coeval Australian rocks the eastern edge of Gondwana –

albeit interspersed and inundated by young arc rocks and separated by sutures (analogous to Fig. 12F).

5.5. 2.96 Ga collisional orogeny

Itsaq Gneiss Complex rocks along the southern fringe of the Isukasia terrane show widespread development of 2.96-2.95 Ga low Th/U metamorphic zircon overgrowths (Friend and Nutman, 2005a; Nutman et al. 2013; Figs. 1 and 8; Digital Map 2). This zone continues as a thin very strongly deformed panel north-westwards, where Eoarchaean rocks also contain 2.96-2.95 Ga metamorphic zircon (data in Hanmer et al., 2002). Near the edge of the inland ice, east of Ujaragssuit Nunaat, there is widespread development of 2.96-2.95 Ga metamorphic zircon in Itsaq gneiss complex rocks, the Ameralik dykes widely carry metamorphic garnet and there are rare relicts of high pressure granulite (Nutman et al., 2015b). On Ujaragssuit Nunaat, Itsaq Gneiss Complex rocks are overlain by a folded klippe of amphibolite facies, massive, altered ultramafic rocks and metasedimentary rocks with detrital zircons derived from ~3.1-3.0 Ga and Eoarchaean sources with crystallisation of 2960-2950 Ma metamorphic zircon (Friend and Nutman, 2005b). On southern Ujaragssuit Nunaat and Ivisaartoq 3.07 Ga volcanic rocks and tonalites with juvenile $\varepsilon Hf_{(t\text{-zircon})}$ values of +4.6 to +1.7 are intruded by the 2960 Ma granites of the Ivisaartoq dome with $\varepsilon Hf_{(t\text{-zircon})}$ values of -13.9 to -2.2 indicate the latter incorporated melt from Eoarchaean crust, even though it was intruded into juvenile Mesoarchaean crust (Fig. 11; Nutman et al., 2015b). This is in accord with the observation by Hall and Friend (1983) that the Ivisaartoq granitoid rocks contain enclaves of partially melted Eoarchaean gneisses.

These diverse data can be interpreted to indicate collision between a juvenile (island?) arc in the Kapisilik terrane represented by 3.07 Ga Ivisaartoq and southern Ujaragssuit rocks and Eoarchaean crust of the Isukasia terrane (Fig. 12A; Nutman et al., 2015b). The klippe of metasedimentary rocks with both 3.1, 3.0 Ga and Eoarchaean detrital zircons might represent a sequence formed immediately prior to the collision. We propose that the arc overrode the southern edge of the Isukasia terrane, causing transitory high pressure metamorphism up to high pressure granulite facies conditions and melting at ~2.95 Ga to produce the crustally-derived granites of the Ivisaartoq dome with their magmatic zircons showing strongly negative $\varepsilon Hf_{(t\text{-zircon})}$ values.

5.6. 2.71-2.70 Ga collisional orogeny

Integrated field, metamorphic and zircon U-Pb zircon dating studies by Friend et al. (1996) concluded that assembly of the Færingehavn, Tre Brødre and Tasiusarsuaq terranes as a series of thrust sheets occurred between 2720-2710 Ma (Figs. 1, 12B). This finding was confirmed by the independent geochronological studies of Crowley (2002) and metamorphic studies by Dziggel et al. (2014). In the overlying Tasiusarsuaq terrane, metamorphism at ~2.71 Ga seems to be marked by retrogression of the terrane's 2.79 Ga (Crowley, 2002) low – medium pressure granulite facies assemblages under low pressure amphibolite facies conditions (Fig. 5; Nutman et al., 1989), corroborated by Dziggel et al. (2012). The structurally underlying Færingehavn and Tre Brødre terranes showed evidence of transitory high pressure metamorphism during this event. Metapelitic rocks of the Tre Brødre terrane show early kyanite development followed by regional garnet + sillimanite assemblages which were subsequently widely replaced by cordierite and, where mafic rocks locally preserve relicts of high pressure granulite facies assemblages (Fig. 5; Nutman et al., 1989). More detailed zircon U-Pb geochronology and REE chemistry integrated with metamorphic petrology including the characterisation of zircon inclusions, confirmed a clockwise P-T-t loop at 2.71-2.70 Ga, and identified possible relict eclogite assemblages preserved as inclusions within garnet (Nutman and Friend, 2007; Dziggel, et al., 2014). The P-T-t loop involved decompression at ≥650°C with the consequence that in higher water fugacity domains such as shear zones, the Itsaq gneiss complex underwent *in situ* anatexis (Figs. 5, 12B; Nutman et al., 1989; Friend et al., 1996). The transitory 2.71-2.70 Ga high pressure event is not recorded in the Isukasia terrane in the north. However, both the Færingehavn and Isukasia terrane record some growth of low Th/U metamorphic zircon at 2.69-2.68 Ga, coeval with the emplacement of granitic sheets (Fig. 8; Nutman and Friend, 2007).

5.7. The 2.66-2.63 Ga event

Evidence has been found for an additional metamorphic event at 2.66-2.63 Ga (Hollis et al., 2006; Nutman and Friend, 2007; Nutman et al., 2007). This event seems to be restricted to a panel of ~2.84-2.80 Ga rocks (Digital Map 2) which in our present interpretation might lie along a décollement (initially a thrust) between a footwall of predominantly orthogneisses **devoid** of the 2720-2710 Ma metamorphic event, and a hanging wall that experienced it. Figure 12C shows a schematic cross section demonstrating this configuration. Within this panel there are relicts of ~2.66 Ga high pressure granulite facies assemblages within mafic rocks. This is shown by 2.66 Ga metamorphic zircons that equilibrated with garnet *and* plagioclase with quartz and clinopyroxene (Nutman and Friend, 2007). Metapelites carry relict kyanite and later sillimanite, whilst metamorphic monazite and zircon from the rocks yield ages of 2.66-2.63 Ga (Nutman and Friend, 2007). The setting to this metamorphic event is as yet enigmatic, but it certainly appears to indicate crustal thickening (Nutman and Friend, 2007). However, it might be distal to the collisional event that caused it, such that a suture of this age is not present in the Nuuk region (Fig. 12F). The 2.66-2.63 Ga assemblages are developed proximal to a folded amphibolite facies shear zone (labelled X on Fig. 1 and Digital Map 2), that cuts across the ~2.7 Ga shear zones/terrane boundaries but is truncated by the Qôrqut Granite Complex. In the southeast of the region, a satellite shear to the main structure contains pegmatite lithons with a magmatic U-Pb zircon age of 2661±3 Ma (Nutman and Friend, 2007). This is interpreted as linking this regional shear zone to the 2-66-2.63 Ga metamorphic event.

5.8. Late Neoarchaean crustal reworking and granites sensu stricto

The deepest post-2.63 Ga structural level in the Nuuk region is exposed around the head of Kapisillit Kangerluat fjord (Fig. 1). This occurs below the panel of rocks which display the 2.66-2.63 Ga metamorphism, and is marked by anatectic granites formed between 2.63-2.59 Ga (Friend and Nutman, 2005a). These are regarded to reflect heating in tectonically-thickened crust, leading to partial melting and rising in a diapiric fashion. Lenses of granite of similar age occur sporadically throughout the Nuuk region, such as on Ivisaartoq (Nutman and Friend, 2007). These bodies are invariably late kinematic, but generally are partially sheared or truncated in late ductile shear zones.

The largest and most prominent body of granite sensu stricto is the ~2.56 Ga Qôrqut Granite Complex (Digital Map 2). It consists of myriads of gently inclined, cross-cutting granite sheets emplaced at approximately the same crustal level in a gentle arch, but fed from a steeper feeder zone to the west (Friend et al., 1985). Whole rock isotopic studies demonstrated that the granite formed by partial melting of a mixture of ‘Amîtsoq’ and ‘Nûk’ gneiss country rocks (Moorbath et al., 1981). As partially melting ‘Amîtsoq’ gneisses could be found in the lower zone, this mixture of country rocks was utilized for the geochemical modelling presented in (Brown et al., 1981; Friend et al., 1985). A more accurate and precise age on the granite is 2.56 Ga from U-Pb zircon dating by SHRIMP (Nutman et al., 2010), and the mixed origin of the granite is supported by the presence of both Eoarchaean and Mesoarchaean inherited zircons within it. In early studies the Qôrqut Granite Complex was regarded as essentially post-tectonic (e.g., McGregor et al., 1973). Although the main body of the Qôrqut Granite Complex is essentially non-deformed, continuations of it to the north and south are not. This is best indicated by field observations and zircon dating from the Færingehavn region. A large 2.57-2.55 Ga sheeted granite complex on hills northwest of Færingehavn (Skinderhvalen, Fig. 1) becomes progressively deformed eastwards into the ‘Færingehavn straight belt’ (Chadwick and Coe, 1983; Digital Maps 1, 2), in which a strongly foliated concordant granite body has a U-Pb zircon age of 2565 ±12 Ma, whereas a less deformed discordant granite sheet has an age of 2555 ±8 Ma (Nutman et al., 2010). Likewise, in the northeast west of Itinnera, a granite lithon within an amphibolite facies mylonite (Fig. 7A) has a U-Pb zircon age of 2559 ±3 Ma (Nutman et al., 2010). This shows that emplacement of the granite was coeval with movement on steeply dipping shear zones that were partitioning the previously assembled terranes of the Nuuk region. The Ivinnguit Fault marking the eastern margin of the Akia terrane might be a related shear zone formed at approximately the same time. It has the same strike as the syn-Qôrqut Granite Complex Færingehavn straight belt (Digital Maps 1 and 2) and a weakly deformed granite sheet that cuts the mylonite fabric of the Ivinnguit Fault has yielded U-Pb zircon and monazite ages of 2536 and 2531 Ma, respectively (Nutman et al., 2010). There are no mafic intrusions within the Qôrqut Granite Complex that might be interpreted to represent the thermal trigger for melt production. Therefore, the trigger for forming the Qôrqut Granite Complex is enigmatic, beyond that any thick ‘continental’ crust in the Archaean had a propensity to melt partially and collapse due to greater internal radiogenic heat production in it than today (Rey and Coltice, 2011). An alternative mechanism of granite production explored by Nutman et al. (2010) was that granites of this age are focused in 'jogs' in craton-wide wrench fault systems, where an extensional regime creates space and permits meteoric water to enter the middle-deep crust (e.g., De Lemos et al., 1992). Heating of these water-enriched areas could then trigger melting. Aspects of this model are disputed by Næraa et al. (2014) who, despite there being copious field evidence that the country gneisses were undergoing partial melting (the Lower zone of Brown et al., 1981) and that the granite is rich in inherited zircons derived from the Itsaq Gneiss Complex, model the granite as having a lower crustal mafic origin.

Granites of the same age occur throughout the North Atlantic Craton. Examples dated by U-Pb zircon occur further north in Greenland at Itilleq (66°32'N) and 600 km to the south in the Taartoq area (61°37'N; Nutman, unpublished data) and in the western edge of the Craton on the Labrador coast (Baadsgaard et al., 1979).

6. Discussion

6.1. Terranes

The field geology, metamorphic history and associated geochemical and isotopic data from the gneisses of the Nuuk region currently suggest that there are six established terranes. Given the current data it might now be argued that the Isukasia terrane (Digital Map 2, Table 1) can be divided into two parts along the major 3.69-3.66 Ga tectonic contact within the Isua supracrustal belt (Nutman and Friend, 2009). This tectonic contact is contained entirely within the Isua supracrustal belt but clearly separates two groups of rocks with quite different protolith ages and metamorphic histories. From a broader perspective, given the complexity of the geology of the whole West Greenland Archaean Craton, it is too early to suggest that all of the terranes have been identified or properly correlated through the craton (e.g., compare Friend and Nutman, 2001 and this paper, with Windley and Garde, 2009). New fieldwork and geochronology from the Maniitsoq area to the north of the Akia terrane is now extending the identification of crustal blocks with quite different metamorphic histories (e.g. Kirkland et al. 2018).

6.2. Deep exposure level and comparison with Phanerozoic collisional orogens

The field geology and associated geochemical and isotopic data from the gneiss complex of the Nuuk region may be interpreted to preserve a series of amphibolite-granulite facies terranes of unrelated orthogneisses and associated supracrustal and gabbroic rocks. These terranes are bounded or separated by mylonite belts, which were later folded and metamorphosed. As pointed out by Nutman and Friend (2007), these terrane boundaries should not be regarded as pristine, unmodified sutures (see Fig. 7B). In some cases, such as the Kapisilik and Isukasia terrane boundary, it seems that a ~2.69 Ga shear zone has excised the original suture (see also Nutman et al., 2015b). Between the Færingehavn and Kapisilik terrane around the eastern end of Ameralik fjord, the terrane boundary mylonite contains isolated lenses of altered ultramafic rocks, metagabbros with development of fuchsite (chrome-muscovite) in the adjacent mylonites. These might represent extremely disrupted mafic assemblages restricted to the terrane boundary. In other instances, such as the boundary between the Færingehavn and Tre Brødre terranes, there is a discrete panel of mylonitised largely supracrustal rocks consisting of altered felsic volcanogenic rocks (now cordierite, sillimanite and garnet bearing gneisses), amphibolites of island-arc tholeiite affinity and lenses of peridotite.

When examining Archaean gneiss complexes for evidence for ancient plate tectonics, an important caveat that must always be remembered is the relative exposure levels. Thus we propose that mylonitised supracrustal rocks restricted to terrane boundaries are deeper crustal equivalents of parautochthonous cover sequences and allochthonous "ophiolitic"/accretionary assemblage nappes in younger orogens, such as the European Alps. Because of the deep crustal exposure level in the Nuuk region, these supracrustal assemblages are expressed as thin, often discontinuous packages, in which intense strain has obliterated the relationships between different lithologies (ultramafic, mafic and metasedimentary rocks). The orthogneiss-dominant tectono-stratigraphic terranes in the Nuuk region can be likened to higher crustal level crystalline basement nappes and massifs in younger orogens (Nutman and Friend, 2007). The Nuuk region terranes show earlier cycles of crustal evolution specific to each terrane (Friend et al., 1988; Nutman et al., 1989), in the same way other European crystalline basement massifs preserve earlier histories, for example pre-Caledonian, Proterozoic events in the Moine of Northwest Scotland, or of Hercynian evolution in Alpine complexes.

In the Nuuk region, other supracrustal rocks occur *within* terranes which are intruded by the tonalites that dominate each terrane (Friend et al., 1988; Nutman et al., 1989; Friend and Nutman, 2005). These intra-terrane supracrustal rocks are commonly truncated at terrane boundaries, where they may be in tectonic contact with other supracrustal units that are restricted to the terrane boundary area. For example, major units of >2.97 Ga mafic rocks in the Akia terrane are truncated at the Archaean Ivinnguit Fault, along parts of which they are in tectonic contact with ~2.84 Ga supracrustal rocks (Nutman et al., 1989; Digital Map 2).

6.3. Roots of arc complexes

The mafic volcanic, gabbro, diorite and tonalite rocks that volumetrically dominate the Nuuk region terranes have geochemical signatures that strongly suggest they are linked to plate tectonic processes at convergent plate boundary processes (overviewed by Dilek and Polat, 2008) with the partial melting of mafic eclogites ± high pressure granulites being the dominant melting components (e.g., Nutman et al., 1999; Nagel et al., 2012), but fluid-fluxing of peridotite is also recognised (e.g., Polat and Hofmann, 2003). This concept has been supported with data from supracrustal rocks and a large layered gabbro-anorthosite body within the Tasiusarsuaq terrane (Hoffmann et al., 2012). However, the realisation that Nuuk region gneisses are dominated by arc-like magmatism products extends back to McGregor (1973, 1979), with his accounts of the igneous protoliths of the gneisses and likening their origin to that of Phanerozoic arcs. Shortly after the recognition of the tectonostratigraphic terranes, this arc connection was extended to a specific tectonic scenario of sequential arc development (see Fig. 4C; after McGregor et al., 1991).

Evidence for (anhydrous) decompression melting of peridotite is restricted to volumetrically small units of rocks, such as ~3.5 Ga Ameralik (basaltic) dykes that cut the Itsaq Gneiss Complex. These dykes probably are the local manifestation of a Palaeoarchaean mantle plume/overturn event that fragmented a proposed Eoarchaean continent 'Itsaqia' that had formed by ~3.6 Ga (Nutman et al., 2014).

6.4. High pressure metamorphism

One argument against some form of plate tectonics operating in the Archaean was the lack of evidence for eclogites and high pressure granulite metamorphic rocks that form in a high dP/dT apparent thermal gradient (e.g., Brown, 2006). This is important because in plate tectonic regimes this type of metamorphism is restricted to subduction zones and collisional crustal thickening; both a reflection of lateral crustal movements in plate tectonics. However, even in the Phanerozoic such rocks are extremely rare, which is indicative of a low preservation potential in the geological record. The reason for their low preservation is that once formed, they have to be brought up to the surface via the high temperature decompression segment of a clockwise P-T-t loop. As this path is commonly accompanied by ductile deformation, the high pressure assemblages are commonly replaced by lower pressure ones. Thus rapid exhumation and the entrapment of these rocks with the dense high-pressure assemblages in buoyant lower density rocks are important factors in their (partial) survival (e.g., England and Holland, 1979; Rubatto and Hermann, 2001).

It transpires that as research on Archaean complexes continues, high dP/dT metamorphic assemblages are being found. Of particular importance is that Mints at al. (2010) report Mesoarchean (2.87 Ga) eclogites from the Kola Peninsula (Russia). Also, within the Nuuk region, small remnants of high pressure metamorphic rocks are being found. On southern Qilangaarssuit (Digital Map 2) ~2.84 Ga supracrustal rocks in tectonic contact with the Færingehavn terrane preserve relict high pressure granulite facies assemblages in mafic rocks, metasedimentary rocks show early kyanite and high-X_{Ca} garnet centres rarely contain inclusions of rutile + kyanite + quartz + plag, suggesting pressures of ~1.2 GPa (Nutman and Friend, 2007). At ~650°C, this indicates marginal eclogite facies conditions. This 'high pressure' locality was independently studied by Dziggel et al. (2014), who corroborated the structural sequence, the transient high-pressure and the clockwise P-T-t loop, and presented a refinement of our earlier model.

East of Ujaragssuit Nunaat, near the edge of the Inland Ice where the Itsaq Gneiss Complex shows a strong 2.96-2.95 Ga metamorphic overprint (Nutman and Friend, 2005; Nutman et al., 2015b), mafic rocks locally preserve strongly retrogressed high pressure granulite facies assemblages. Finally, Nutman et al. (2013) reported very tiny remnants of

3.66 Ga high pressure granulite facies rocks from shear zones in the Isukasia area (Digital Map 2). Thus evidence for transitory high pressure metamorphic events over almost 1 billion years is emerging from the Nuuk region gneiss complex. This strengthens the case that crustal development involved episodic collisional orogeny with crustal thickening and associated clockwise P-T-t loops in the deeper parts of the crust.

6.5. Thermal evolution of the Earth and interpreting the tectonic record

The Nuuk region Archaean geology shows the following tectonothermal hallmarks; (a) repeated high-pressure metamorphism with clockwise P-T-t loops, (b) tectonically stacked supracrustal packages and crystalline basement orthogneiss terranes and (c) orthogneiss terranes have different ages but all are products of juvenile crust formation, with geochemical and radiogenic isotopic signature of arc-like processes at convergent plate boundaries. This suggests similarities between the plate tectonic driving forces behind both Archaean and Phanerozoic collisional orogeny.

It is important to stress though that Phanerozoic and Archaean geodynamics and crust formation were not identical. The main reason for this appears to be the hotter state of the early Earth. This has three important consequences that will bring about apparent differences between Phanerozoic and Archaean crust formation and orogeny:

(1) The first is that on average, subducted Archaean oceanic crust was hotter than now. This hotter crust was consequently more buoyant and, arguably thicker. Generally, it would not undergo steep-angled subduction as is commonplace at modern convergent plate boundaries. Instead, it may have mostly formed imbricate packages in the lower crust or upper mantle which, as they heated-up under high pressure, melted to form the higher SiO_2 lower MgO tonalites that dominate Archaean crust (e.g., de Wit, 1998; Nutman et al., 2007, 2013; Nagel et al., 2012). This will lead to a different geometry and chemistry of Archaean juvenile crust, compared to that forming today. In our opinion, when all other evidence is taken into account, this does not necessitate a completely non-uniformitarian crust formation mechanism for the Archaean, but instead can be accommodated within an evolving plate tectonic regime that reflects the changing thermal state of the Earth through time.

(2) In Archaean times, once ‘continental’ crust of appreciable thickness had formed by collisional orogeny by amalgamation of terranes, the greater radiogenic heat production from K, U and Th meant that at depth it would have had a great propensity to melt partially and collapse laterally (Rey and Coltice, 2011). Even in the Himalayas, which is the largest modern collisional orogeny, this factor permits only a maximum topography of ~8 km, and shortening is now being accommodated by lateral escape of ductile lower crust under the Tibetan plateau, rather than the Himalayas increasing in altitude (Duclaux et al., 2007). Earlier in Earth history, the greater heating of the crust restricted topography, to perhaps only 1 km in the Eoarchaean (Rey and Coltice, 2011). Thus recycling of orogenic crust would be strongly biased to lateral crust flow with migmatisation and granite production, with less occurring via erosion and formation of massive turbidite sedimentary systems such as the modern Bengal fan sourced from the Himalayas.

(3) The increased temperature of orogenic crust would further mitigate the preservation of high pressure metamorphic assemblages that even on the modern Earth have a very low preservation potential.

Therefore, as far back as the Eoarchaean, using evidence from the Nuuk region, we contend that there is no necessity for entirely non-uniformitarian processes to form crust and cause orogeny. Clearly, at some stage earlier in the Hadean prior to Earth having a retained hydrosphere, then recollecting the adage ‘No water, no granite – no oceans, no continents’ of Campbell and Taylor (1983), non-uniformitarian processes must have operated. However, as this part of Earth’s history is older than that preserved in the Nuuk region rock record, we do not speculate on it here.

We contend that back to at least ~3.9 Ga, as observed in the Nuuk region, that crust formation processes were quasi-uniformitarian. Quasi-uniformitarian is apt, because given the hotter state of the early Earth compared with now, mantle dynamics and consequently magmas and tectonic structure of convergent plate boundaries were somewhat different than on the modern Earth. Figure 12D-F is a set of schematic palaeogeographic cartoons explaining our present crustal evolution model for the Nuuk region gneiss complex from ~3.0 Ga onwards.

7. Conclusion

There is now widespread evidence that, whilst there may be exceptions, e.g. the Minnesota area (see Mueller and Nutman, 2017), many Archaean gneiss complexes, as exemplified by the Nuuk region, comprise disparate tectono-stratigraphic terranes that initially evolved individually and were subsequently assembled to form broader regions of Archaean continental crust. The Nuuk region gneiss complex shows repeated cycles of a billion years of periodic juvenile crust production with geochemical signatures indicating magma formation at convergent plate boundaries and repeated amalgamation of unrelated crustal blocks causing collisional orogeny with transient high pressure metamorphism.

Acknowledgements

This work was last supported through the Australian Research Council grant DP120100273. Over the past 40 years, many other organisations have contributed to the work leading to the regional map represented here and the geological interpretations embodied in it. These are the Geological Survey of Denmark and Greenland (GEUS), block funding to the Australian National University, the University of Wollongong, The Royal Society and NERC (U.K.) Grants Grants GR3/8879 and GR3/13039 for funding our field programmes, and Hiroshima University, the Korean Basic Science Institute, the National Institute of Polar Research (Japan), the Chinese Academy of Geological Sciences together with NSERC (Canada) grants to Toby Rivers and Halfdan Baadsgaard. Many people in Greenland and elsewhere assisted philosophically and logistically in development of this work. Philospohically, we would like to thank Vickie Bennett and the late Vic McGregor, who have given stimulating discussion on crustal evolution and provided checks and balances on our developing ideas. In particular we would like to thank Ole Christiansen, then with the exploration company Nunaminerals A/S, as he was responsible for the early digital maps developing from a tool that was being used only by us to keep track of the geological changes being made, into a set of documents that could be used by others. The base maps have been used with permission from GEUS. We also thank J. Hollis and A. Steenfelt for their helpful comments on early editions of the geological maps. P. Cawood and P. Mueller are thanked for their reviews and suggestions for improvements to the manuscript.

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Figure Captions

Figure 1. (A) Inset showing the location of the Nuuk region in West Greenland Archaean craton.

(B) Summary sketch map showing the distribution of Archaean tectono-stratigraphic terranes in the Nuuk region. Abbreviations: B, Buksefjorden; Ik, Ikkattoq; It, Itinnera; Iu, Ilulialik; KS, Kangimut Sammissoq; M, Store Malene; Q, Qooqqut (Qôrqut); QN, Qarliit Nunaat; T, Tinissaq. For the numbering of the terrane boundaries, 1-9, see Table 2. Note, this is *not* a lithological map and, therefore, most individual geological units (other than the Isua supracrustal belt, some important marker horizons and the Qôrqut Granite Complex) are not shown.

Figure 2. (A) A complex outcrop of Eoarchaean banded orthogneiss (bgn) from the Nuuk region (64°28.75'N 50°39.83'W, GPS datum WGS-84). Up to the early 1970s such rocks were interpreted as strongly metamorphosed sedimentary rocks. Tight to isoclinal folding is superimposed on several generations of palaeosome and neosome. Fold generations such as these were used in the 1970s to try and correlate tectonothermal events across the entire Archaean craton of West Greenland (>500 km north-south). The dark strip-like amphibolite (Ad) is an attenuated, dismembered (~3.5 Ga) Ameralik dyke.
(B) Polyphase injection relationships between different phases of the metaplutonic Nûk gneisses (~3.0 Ga components of the Akia terrane; 64°21.41'N 51°19.35'W). With increasing strain such rocks are transformed laterally into the typical regional banded grey gneisses. Outcrops such as these were used by McGregor (1968, 1973) to demonstrate that the Nuuk region gneisses have mostly plutonic protoliths.

Figure 3. (A) Example of cathodo-luminescence imaging guiding modern *in situ* U-Pb zircon analysis using micro analytical techniques such as large high resolution ion microprobes or by Laser Ablation ICP-MS. Itsaq Gneiss Complex sample from 63°47.12'N 51°45.08'W. By this integrated technique, accurate and precise ages can be acquired on individual zircon grains.
(B) The complete data set acquired from zircons of the sample represented by the grains in (A), portrayed on a $^{238}U/^{206}Pb$ – $^{207}Pb/^{206}Pb$ concordia diagram. The protolith age is ~3800 Ma, and the rock underwent renewed zircon growth and recrystallisation at ~3650 and 2700 Ma (figure adapted from Nutman et al., 2002).

Figure 4. Evolving interpretations of the Nuuk region Archaean gneiss complex represented by schematic maps. (A) Crustal evolution model at the beginning of the 1980s, adapted from Figure 4.11 of Nutman (1980). A fragment of an Eoarchaean crust-forming super-event occurs as a mega-enclave within largely plutonic rocks formed in a craton-wide

late Meso- early-Neoarchaean crust-forming super-event. Note how granulite facies metamorphism was regarded largely to outlast ductile deformation, the latter being portrayed by two major generations of folds giving rise to regional interference patterns. The locations of the 'problem' Kangimut Sammissoq localities are shown, as are the ages of orthogneiss protoliths and granulite facies metamorphism to the northwest and southeast of Nuuk.

(B) The model produced by McGregor et al. (1986), with the proposed boundaries of the granulite facies metamorphism. The blue and green arrows indicate the directions of traverses that began to show the tectonic and metamorphic problems. Abbreviations: KS, Kangimut Sammissoq; M, Store Malene; Q, Qôrqut; Qi, Qillangaarsuit; T, Tinissaq. Proterozoic fault; KF, Kobbefjord Fault.

(C) First detailed crustal evolution scenario for the Nuuk region, presented as Fig. 3 in McGregor et al. (1991), involving the development of several arc complexes followed by their tectonic juxtaposition. The *Akulleq terrane* (now an abandoned term) running through Godthåbsfjord was regarded as a composite entity containing the Færingehavn and Tre Brødre terranes. The *Akulleq terrane* was regarded to contain exotic crust trapped in a continent-continent collision zone between the more extensive Tasiusarsuaq and Akia terranes. Collision first occurred between the Akulleq and Tasiusarsuaq terranes (hence its boundary is folded), followed by juxtaposition of these terranes and the Akia terrane (hence its boundary is straighter).

Figure 5. Pressure-temperature diagrams demonstrating the conflicting temporal histories of peak metamorphism from adjacent granulites facies rocks of the Tasiusarsuaq terrane and amphibolite facies rocks of the Færingehavn and Tre Brødre terranes. Adapted from Figure 3 of Nutman et al. (1989). Dates are from Crowley (2002) and Nutman and Friend (2007).

Figure 6. 100% exposure of the outer-coast archipelago in the Færingehavn area, chosen to resolve controversies over interpretation of the Nuuk region gneiss complex. The photograph was taken during the reconnaissance work in 1984. The large amounts of sea ice hampered boat access to the excellent exposures. In the ice-free conditions of 1985 this was an ideal

area to gather the information leading to the tectonostratigraphic terrane model. Tent for scale in the foreground indicated by arrow.

Figure 7. (A) Example of an Archaean terrane boundary mylonite (deformed and metamorphosed in superimposed tectonothermal events). Note the strips of pegmatite and quartz-rich material forming discontinuous layers and rootless folds in the matrix. Tectonic boundary between the Færingehavn and Kapisilik terranes, south side of Kapisillit Kangerllua, west of Itinnera (Boundary 5 (Fig. 1) at 64° 24.50'N 50° 25.86'W.
(B) Garnet overgrowing mylonitic fabric between the Færingehavn and Tre Brødre terranes, north of the mouth of Ikkattoq, 63° 40.20'N 51° 32.26'W).
(C) Partially retrogressed but little-deformed (2.79 Ga) granulite facies assemblages ~1 km from the Qarliit Nunaat thrust in Ikkattoq fjord; Fig. 1; 63°36.36'N 51°23.08'W). The rock has a nebulitic structure, and a blebby texture due to the growth of pyroxene porphyroblasts in neosomes during granulite facies metamorphism. These have been largely replaced by ortho-amphibole + quartz symplectites with hornblende haloes, with only small remnant cores of orthopyroxene. (D) Totally retrogressed Tasiusarsuaq terrane granulite facies gneisses within the ductile strain gradient <100 m from the Qarliit Nunaat thrust in Ikkattoq (63°37.10'N 51°23.33'W). All pyroxene has been broken down and is replaced by hornblende aggregates. These and the earlier syn-granulite structures are aligned into a new amphibolite facies foliation parallel to the terrane boundary.

Figure 8. Summary of zircon U-Pb geochronology for igneous and metamorphic events for the Nuuk region tectonostratigraphic terranes, integrated with key tectonic and metamorphic signatures demonstrating a billion years of Archaean geodynamics resembling plate tectonics. This data set of ~250 age determinations is based on >5,000 individual zircon analyses. The data sources are as follows: Bennett et al. (1993, 2002, 2007), Compston et al. (1986), Crowley (2002, 2003), Crowley et al. (2002), Friend and Nutman (2005a,b, 2010), Friend et al. (1986, 2002), Garde (2007), Garde et al. (2001), Hanmer et al. (2002), Hiess (2008), Hiess et al., (2009), Hollis et al. (2005), Honda et al. (2003, 2004), Horie et al. (2010), Kinny (1986, 1987), Lee (2007), Nilsson (2009), Nutman (2001), Nutman and Collerson (1991), Nutman and Friend (2007, 2009), Nutman et al. (1993, 1996, 1997a,b,

1999, 2000, 2002a,b, 2004a, 2007a,b,c,d, 2009, 2010, 2013, 2015a,b, unpublished data), Næraa et al. (2012), Rodgers et al. (1996), Schiøtte et al. (1988, 1989). The colours used for each terrane follow those on the main map.

Figure 9. (A) Rare example of reserved pillow structures in 3.8 Ga amphibolites of the southern side of the Isua supracrustal belt (65°08.01'N 50°11.64'W).
(B) Neoarchaean layered gabbro-anorthosite from the Tre Brødre terrane (63°40.41'N 51°30.44'W).
(C) Preserved Eoarchaean plutonic relationships in a low strain zone north of the Isua supracrustal belt (65°10.36'N 49°59.40'W). ~3.70 Ga tonalites (t) are cut first by a 3.66 Ga dioritic dyke (di) and then by ~3.65 Ga granite sheets (g). There has been no deformation at this locality since 3.65 Ga.
(D) Qôrqut Granite Complex – a large mass of ~2.56 Ga granite that cuts major Neoarchaean tectonic boundaries such as the Qarliit Nunaat Thrust, thereby giving the minimum age of terrane amalgamation. The granite consists of myriads of sheets emplaced at the same crustal level over a short period (Friend et al., 1985). Image is of a >200 m cliff section at the western edge of the body, where the country rocks predominate over the granite sheets.

Figure 10. Detrital zircon ages from Archaean metasedimentary rocks of the Nuuk region. Data from Nutman et al. (1997, 2004, 2009b), Garde et al. (2001), Kamber et al., (2005), Garde (2007), Nutman and Friend (2007, unpublished data).

Figure 11. Zircon initial εHf versus age diagram for orthogneisses and granitoids from the Nuuk region gneiss complex. Data are from Hiess et al. (2009, 2010), Kemp et al. (2010), Næraa et al. (2012), Yi et al., (2014), Nutman et al., 2015.

Figure 12. Schematic cross sections A-C and palaeogeographic cartoon maps D-F (with no specific orientation) portraying our current interpretation for the evolution of the Nuuk region from ~2.97 to 2.6 Ga. These diagrams indicate relative relationships only. (A and D) By ~2.97 Ga, consumption of oceanic crust to produce arc-like rocks in the Akia and Kapisilik

terranes led to their collision with the Itsaq Gneiss Complex (Færingehavn and Isukasia terranes). The Isukasia terrane was proximal to the suture and its edge was overridden by a Mesoarchaean arc (as represented in the Ivisaartoq area). This caused transient high pressure metamorphism in the edge of the Isuakasia terrane and melting at greater depths to give granitic bodies such as forming the Ivisaartoq dome (Nutman et al., 2915b). Subsequent rifting left a composite assemblage of the Itsaq Gneiss Complex (Færingehavn and Isukasia terranes) together with the Akia and Kapisilik terranes as a 'continental' block. Ribbons rifted off this 'continental' block contained both the Eoarchaean and Mesoarchaean components (B and E). These volumetrically minor ribbons were engulfed by the production of largely juvenile late Mesoarchaean to early Neoarchaean arc complexes. The arc rocks of the Tre Brødre terrane might have formed proximal to the Itsaq Gneiss Complex – Akia – Kapisilik 'continent' and assimilated large amounts of older crust (E), as evidenced by their whole rock Nd isotopic signatures (Friend et al., 2009). (B and F) There was collision between the composite Færingehavn-Isukasia-Akia-Kapisilik block shown in (A and D) and ~2.92 to ~2.73 Ga complex arc assemblages, embodied by the Tasiusarsuaq and Tre Brødre terranes. The youngest (~2.73 Ga) juvenile arc rocks are not found in the Nuuk region, but are extensively developed in a continuation of the Tasiusarsuaq terrane ~300 km north of Nuuk (Nutman, Friend and Bennett, unpublished data) within an entity named the Tuno terrane (E) by Friend and Nutman (1992). Collision was completed by ~2.71 Ga, with the granulite facies Tasiusarsuaq terrane emplaced on top of lower grade Tre Brødre and Færingehavn terranes (B and F). This caused transient high pressure metamorphism along a clockwise P-T-t path in the deep crust, with high temperature isothermal decompression between 2.71-2.70 Ga (Nutman et al., 1989; Nutman and Friend, 2007; Dziggel et al., 2014). The high temperatures caused development of 2.71-2.70 Ga extensive granite neosome deep in the Færingehavn terrane, some which was intruded in the overlying terranes as sharp-edged, syn- to post-kinematic intrusive sheets (Friend et al., 1996; Crowley, 2002). Subsequently 2.69-2.68 Ga intracrustal shearing was associated with further emplacement of granite sheets and also dismemberment of the previous tectonic boundaries. Thus the original suture between the Kapisilik and Isukasia terranes have been replaced by a (folded) ~2.69 Ga shear zone (Nutman et al., 2015b). This scenario explains the entire known distribution of metamorphic events in the Nuuk region.

Tables

Table 1. Summary of the sequence of the main terrane assembly events identified in the Nuuk region.

Table 2. List of terrane boundaries presently identified in the Nuuk region, with a brief description. These are numbered on Figure 1 and on Digital Maps 1 and 2.

Supplementary Data

Digital maps as Supplementary Material

Digital Map 1. 1:40 000 scale map of the Færingehavn – Tre Brødre area.

Digital Map 2. 1:100 000 scale map of the Nuuk region between Sermilik – Akia and Nuuk – Isukasia.

Summary of the published GGU/GEUS 1:100,000 scale maps of the Nuuk region

The systematic geological mapping of Greenland was commenced in the early 1950s by the Geological Survey of Greenland (GGU), later to become part of GEUS (Geological Survey of Denmark and Greenland). Mapping took place at a number of different scales but mostly at 1:20 000, for compilation into the 1:100 000 scale published maps. The mapping initially started in the south of the country at Kap Farvel, in the Palaeoproterozoic Ketilidian complex and worked progressively northwards until the Nuuk region was reached. The first 100 000 maps were created using only lithological divisions and cross-cutting relations, as there was only rudimentary or no geochronology available. In the 1950s – early 1960s, simply being able to differentiate between Archaean and Proterozoic rocks and events was considered significant. The philosophy behind the 1:100 000 scale maps was that they could be combined to produce a series of 1:500 000 maps that would eventually cover all of Greenland and could show regional relationships. Sheet No 2, Frederikshåbs Isblink – Søndre Strømfjord (Allaart, 1982; Kalsbeek and Garde 1989) was the second of this scale to be produced, and the geology of the Nuuk region was integral to its production. The mapping commenced in the mid- to late 1960s and it was produced to the then accepted concept that the gneisses in this part of Greenland were broadly contemporaneous and that there was a structural continuity across the region on a scale of hundreds of kilometres, as witnessed by the way in which the complex fold interference patterns appeared to be traced throughout the region covered. This changed once it was demonstrated that the *Amîtsoq gneisses* were older (McGregor 1968, 1973).

A major problem with the compiled maps, also a common problem world-wide, was that they tended to be mapped and produced over several years and then finally printed a few years later. Combined with the vast size of Greenland, including the vast areas yet to be mapped, this gave the published maps a permanency that some may not have deserved, simply because of the desire to map more of the essentially unknown geology. Consequently, at that time, repetitive and/or revision mapping of an area was not a priority. The production of the geological map sheets covering the Nuuk region was for logistic and administrative reasons not carried out in a systematic north to south order. Additionally, there were rapid research developments taking place in both the field and laboratory, which were not always transferred to and between the published maps and was also difficult to represent retrospectively without great expense. The first map sheets to show a non-matching boundary were Buksefjorden 63V.1 Nord (Chadwick and Coe, 1983) and Qôrqut 64V.1 Syd (McGregor, 1993), referred to in the main text. The sheets did not match across their common boundary because of philosophical arguments over the use of metamorphosed dykes to distinguish different gneisses. This related to the problems of distinguishing tabular rafts of amphibolite from originally cross-cutting dykes that had been rotated into parallelism leading to problems in the definition of mapping units. Later, the Qôrqut sheet and adjoining sheet to the north, Fiskefjord 64V.1 Nord, did not match because with more extensive fieldwork it was recognised that there were ways of distinguishing different components of the granulite facies rocks which had not been employed on the already published Qôrqut sheet. Because of the permanency of the printed sheet, these mismatches are still extant.

Further, the ability to reassess localities continually as data is accumulated has proved an important tool in the work presented here. From the 1990s, the advent of PC-based digital cartography has now allowed publication-quality maps to be produced by individual researchers rather than only by big organisations, and these maps can be easily updated as new information is obtained, as is the case in the map presented here..

The following section is a short summary of the published, printed geological map sheets that cover the same area as the digital mapping presented here (Digital Map 2). The Nuuk region is taken to extend from Akia in the north to the mouth of Sermilik in the south and between Nuuk and Isukasia. The descriptions are presented in the order in which they were published.

1.1 Buksefjorden 63V.1 Nord (1983)

The first of the 1:100 000 scale maps in the Nuuk region was mapped by staff and PhD students from Exeter University between 1972 and 1977. When produced, it broke new ground as it was the first detailed map to include the ancient *Amîtsoq gneisses* (Chadwick and Coe, 1983). Thus, whilst most of the mapping followed the criteria established in 1960s in the south of the Archaean craton, this production first allowed different aged gneiss complexes to be distinguished. This was the first step towards producing maps with resolution of Archaean absolute chronology for the regional gneisses.

Whilst some scientific controversy existed over the geological configuration of the geological boundaries with the map sheet to the north, Qôrqut 64V.1 Syd, and the interpretations by V.R. McGregor of some of the lithological units within the Buksefjorden map area (e.g., Chadwick et al., 1974), the main divisions of the rocks was broadly accepted to fall within the tripartite sequence of *Amîtsoq gneisses*, Malene supracrustal rocks and Nûk gneisses established by McGregor (1973). In the absence of any regionally distributed geochronological data that proved the age of a unit, all of the TTG gneissic units between Ameralik and Sermilik not belonging to the *Amîtsoq gneisses* (McGregor, 1973), were termed Nûk gneisses. However, some of the observations made during the mapping programme have turned out to hold true. For example, the Nûk gneisses were divided into 5 zones (Coe 1980) and parts of the boundaries of some of these zones have been found to coincide with major dislocations now identified as the terrane boundaries.

1.2 Isua 64V.2 Nord (1987)

The Isua area map was published in 1987 and is to the immediate north of the Ivisaartoq map area. It was mapped synchronously with it and the geological boundaries matched across it. The map was divided into two parts by the Proterozoic Ataneq Fault. The more complex eastern section comprises the old *Amîtsoq gneisses* that contained the internationally important Isua supracrustal belt. A major effort was directed towards producing the first detailed study and geological map of the belt (Nutman, 1986) which served as a prelude to modern research. The *Amîtsoq gneisses* then passed southwards into Nûk gneisses with *Malene supracrustal rocks* that had suffered various partial melting events producing several granitoids and related migmatites. The western section comprises two parts, a complex of Nûk gneisses and Malene supracrustal rocks into which a large, relatively simple intrusive body, the Taserssuaq tonalite was emplaced.

The re-evaluation of the Isua supracrustal belt formed the basis for the first digital map, a 1:20 000 scale revision of the component parts of the belt demonstrating its tectonic division into two separately evolved parts (Nutman and Friend, 2009).

1.3 Ivisaartoq 64V.2 Syd (1988)

The Ivisaartoq area is located across the head of Godthåbsfjord and its junction with Kangersuneq and contains the eponymous semi-nunatak immediately south of Isua. It was also mapped by an Exeter University team between 1982 and 1984 (Chadwick and Coe 1988). This area was essentially mapped in just two field seasons, following reconnaissance mapping for the 1:500 000 scale map in 1976. The area was found to contain some the most difficult geology to be examined in the Nuuk region. There are several large areas of complex migmatitic rocks, the origins and ages of which were uncertain, particularly as the true nature of the protoliths had yet to be established. Subsequently these migmatites have been shown to be of several different ages (e.g., Nutman and Friend, 2005a).

However, following the earlier reconnaissance mapping in 1976-77, the main gneisses were again divided into the older *Amîtsoq gneisses* and the younger Nûk gneisses and all the supracrustal rocks, other than those trains of rafts and enclaves associated with the Isukasia area, were attributed to the *Malene supracrustal sequence*.

1.4 Fiskefjord 64V.1 Nord (1989)

The Fiskefjord sheet (Garde, 1989) was compiled from both new mapping and detailed earlier studies of particular smaller areas, e.g. Lauerma (1964). Parts of the mapping overlapped with the mapping of the Ivisaartoq area. Its big contribution was to advance knowledge of the constituent units of the ortho-gneisses and their response to polyphase granulite and amphibolite facies metamorphism. A large part of the area was the focus of a detailed study of the gneisses by Garde (1990, 1997) and the work led to a concept that this section of the crust had grown and matured rapidly (Garde et al. 2000).

The map was important as it was the first to utilize cartography to represent those areas which had been subjected to granulite facies metamorphism, those areas retrogressed from granulite facies, and those areas which had only ever been to amphibolites facies. The publication of this map before the Qôrqut sheet, the mapping of which had finished much earlier, produced a common boundary mismatch as there was no funding available to go back into the field to follow the newly identified lithological and metamorphic boundaries southwards.

1.5 Qôrqut 64V.1 Syd (1993)

The area immediately around the mouths of the fjords at Nuuk and Ameralik comprises an archipelago with major peninsulas allowing access to many clean outcrops along the extensive coastline. This permitted a high degree of certainty with the mapping and correlation of most of the units. The mapping of this sheet (McGregor 1993) commenced in 1965 and was finished in 1979, but the map and memoir took much longer to produce. The map sheet was in production at the start of the introduction of the terrane model and was too far down the process route to be revised. However, based on McGregor et al. (1991) the accompanying text was revised to include a summary of the terranes present in the area and how they were thought to fit regionally (see McGregor 1993, Fig. 3). The map thus reflects the position immediately prior to the development of the terrane model and originally correlated all of the TTG gneisses that were not part of the Itsaq Gneiss Complex as Nûk gneisses. This was backed up by a fortuitous set of isotopic samples which came essentially from along strike which produced a whole-rock isochron age of 2980 ±50 Ma (Taylor et al. 1980). This was corroborated by several bulk zircon ages on individual Nûk gneiss samples (Baadsgaard and McGregor 1981).

1.6 Kapisillit 63V.2 Syd (2011)

This sheet covers the ground around the fjords Itilleq and Ameralla at the head of Ameralik, and Kapisillit Kangerllua and Kangersuneq at the head of Godthåbsfjord (Nuup Kangerllua). It was the last sheet to be produced, with mapping commencing in 2005, following coastal reconnaissance work in 2004. Mapping was finished in 2007 and the map was published in 2011 (Rhenstrom, 2011). Whilst using many of the basic criteria established at the outset of the regional basement mapping, the sheet does not geologically match *any* of the surrounding sheets, e.g. the Qôrqut map to the west, because of cartographic/compilation decisions.

At the start of the project GEUS had commenced a zircon U-Pb LA-ICP-MS dating project to aid the regional mapping and so this was the first map sheet to have the possibility of including geochronological data that was obtained simultaneously with the mapping. However, the old philosophy of lithological units having the same base colour irrespective of age was followed, which resulted in all the Meso- and Neoarchaean gneisses having the same colour. This was despite that at the time of mapping they were already known to be of different ages and to form unrelated, tectonically-partitioned units. Equally, all of the three generations of anorthosite on the map, irrespective of their age, have the same colour and consequently appear to be coeval.

The sheet includes two inset maps which indicate a distribution of different ages and some tectonic boundaries but these are difficult to reconcile with the main body of the map.

2. The new digital 1:100 000 scale geological map of the Nuuk region

The GGU/GEUS 1:100 000 scale maps of the Nuuk region were the carefully constructed product of fieldwork by many geologists between 1965 and 2007. This massive work was an essential component used to produce the seamless Digital Map 2. The degree of detail in this seamless map across the entire region is only possible with this prior geological survey work, because of the sheer size of the region (approximately half of Switzerland) with the expensive logistics required to map systematically remote mountain areas. The Digital Maps 1 and 2 incorporate all zircon U-Pb data and our remapping from numerous field seasons from 1984 onwards. As our new data has been acquired, continued revision was required – it is an iterative process of mapping, interpretation, age dating and re-interpretation.

The production of our own regional geological map started in 1990 and grew out of a need to represent our accumulating SHRIMP U-Pb zircon geochronological data. The first iteration was hand drawn and produced at 1:250 000 scale and was simplified to show only the main TTG gneisses, units of supracrustal rocks and mafic intrusions, mainly the anorthosite complexes. This was the first manifestation for the Nuuk region of a geochronologically-constrained tectonic map and was an important tool in assisting us to interpret the regional geology. The rate and scale of geochronological data acquisition and mapping revisions rendered it impossible to revise continually a hand drawn map. Therefore, in order to have flexibility, information was transferred to the PC-based digital cartographic package Freehand™. Even though the map could now be easily revised, its scale limited how much data and detail could be represented. The next development was to produce detailed inserts for this map at a larger scale, portraying key sub-areas with the largest amounts of data. In 2000, Ole Christiansen, then CEO of the exploration company NunaMinerals A/S, gave us seed funding to produce new digital versions of the published GGU/GEUS 1:100 000 scale maps covering the Nuuk region. This was done to assist the company's exploration work, by showing the terrane geology more effectively and to incorporate all the new accurate and precise zircon U-Pb geochronology. Digital Map 2 was made by fusing all these separate sheets together, to produce a seamless map. This seamless map in the PDF rendition presented with this paper can be explored in the modern way, onscreen (even on a smartphone in the field) and at different magnifications.

Note however, that the present product – whose topographic base is the same as the printed GGU/GEUS maps, is **not** georeferenced. In this respect extra complexities are that the adjoining 1:100 000 scale Buksefjorden and Qôrqut map sheets were each based on a different geographic datum, with the bizarre consequence that, although the topography of the maps meet on their western side, there is eastwards a swathe of terrain broadening to >100 m that does not exist on either of the maps. This has been reconciled (fudged) for Digital Map 2 by extrapolating the geology across the *terra nullis*.

More recently, the concept of a more useable map has been developed by GEUS and there is now the start of a series of interactive digital maps available, see http://maps.greenmin.gl/geusmap/?mapname=greenland_portal&lang=en#baslay=baseMapGl &optlay=&extent=-4251735.740740741,4947572.199074074,5079745.740740741,11100517

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.800925925&layers=northpole_graticule

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01/03/2018 Fig. 1a,b - Terranes

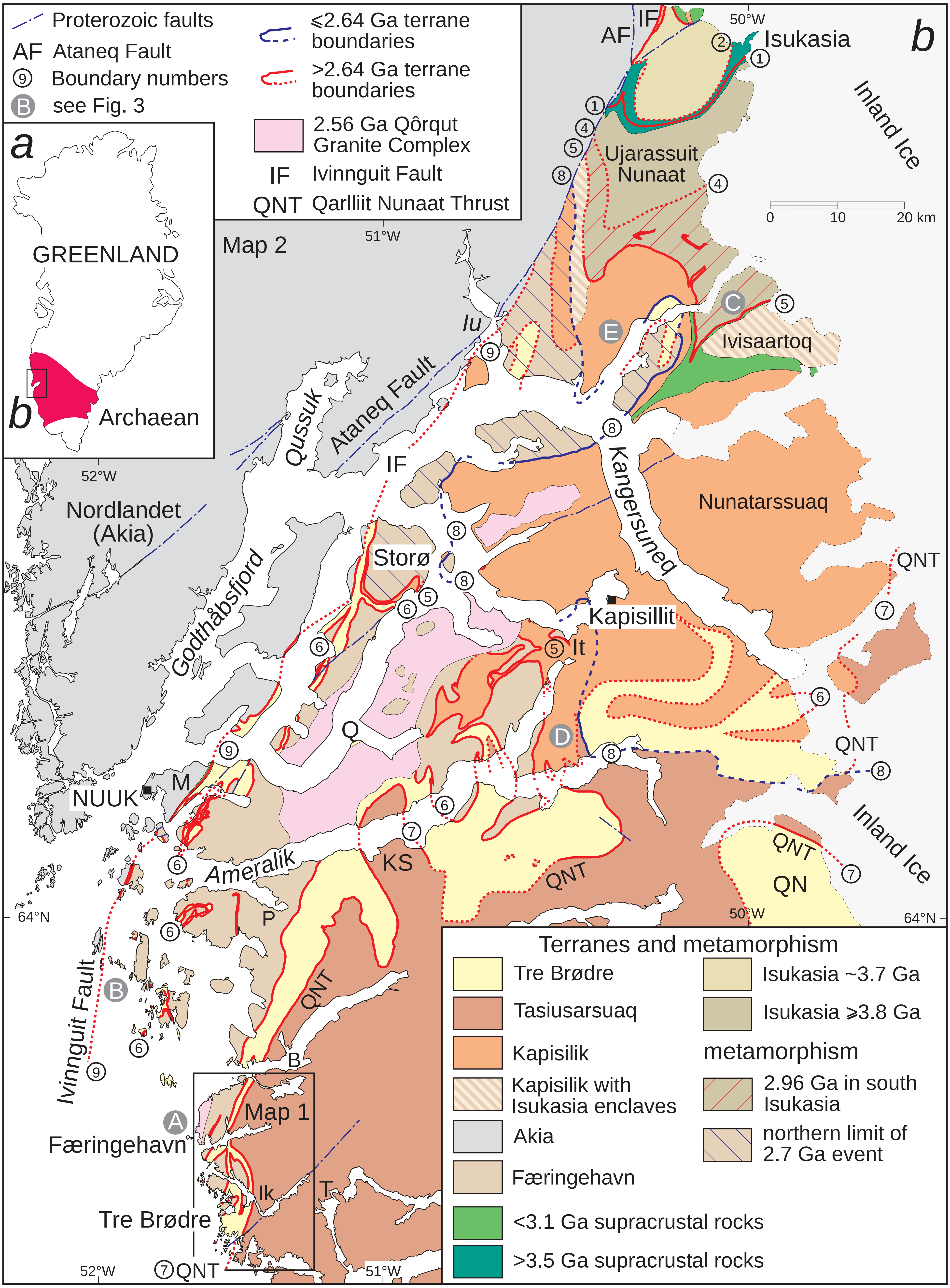


Figure 2

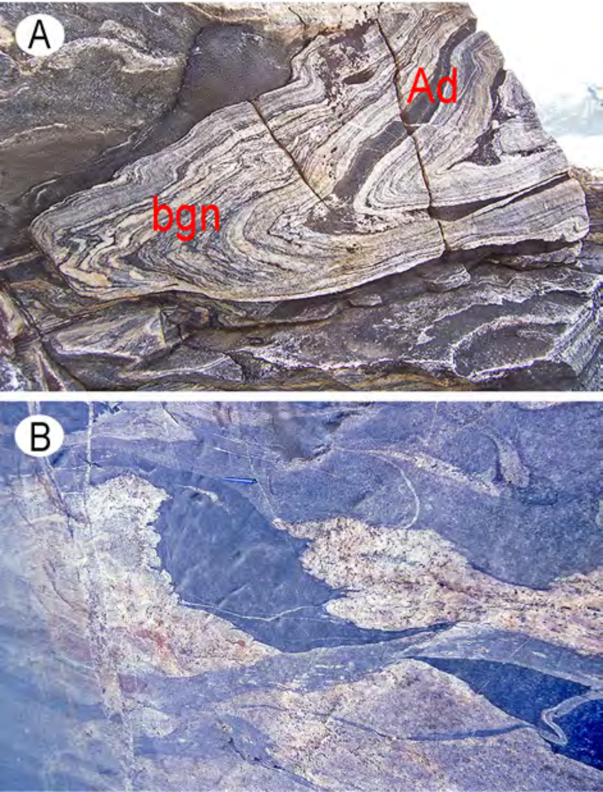
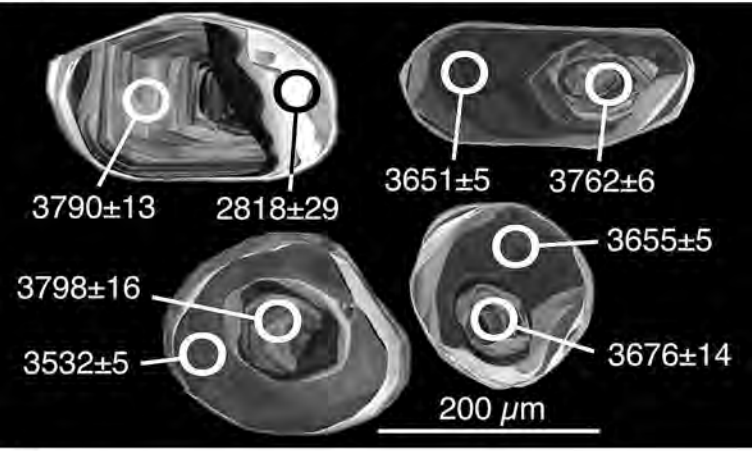


Figure 3

A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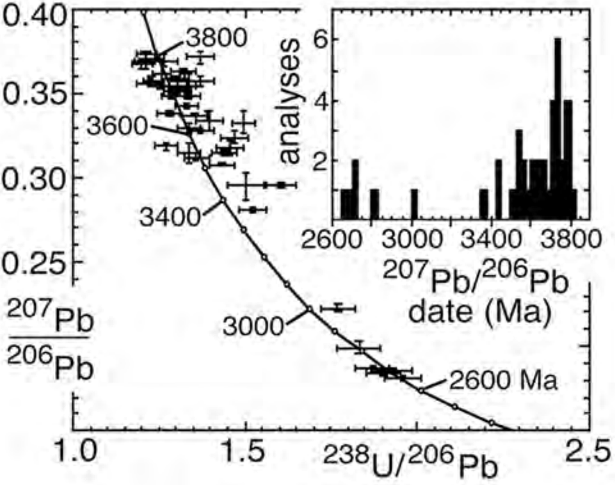
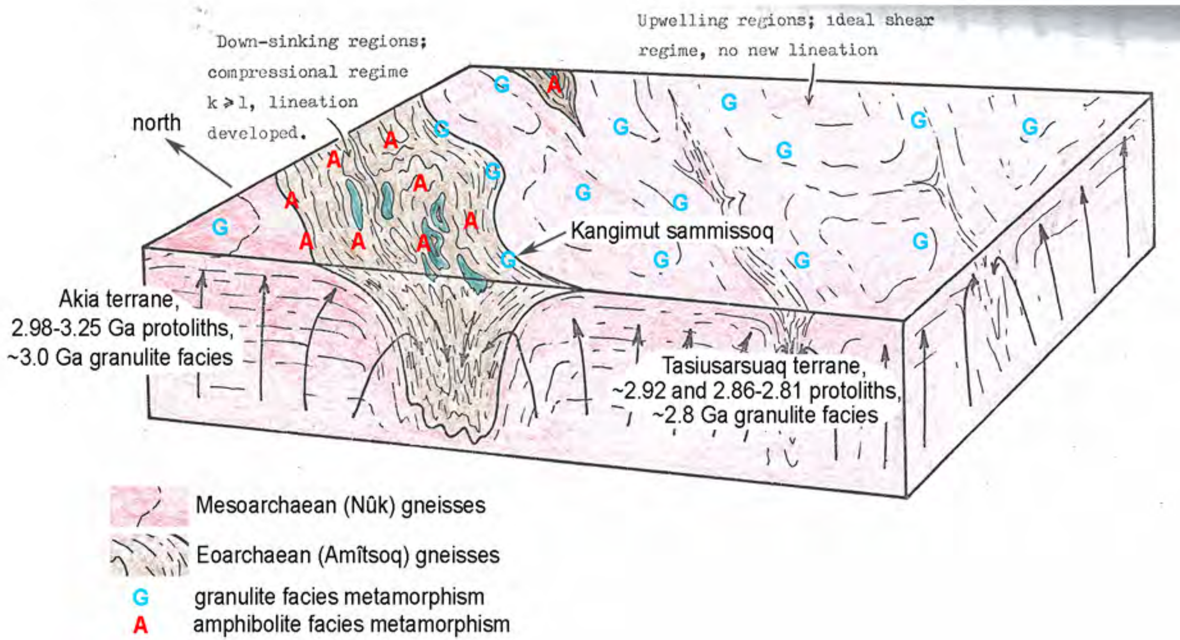
3651±5
3762±6
3655±5
3798±16
3532±5
3676±14
200 μm

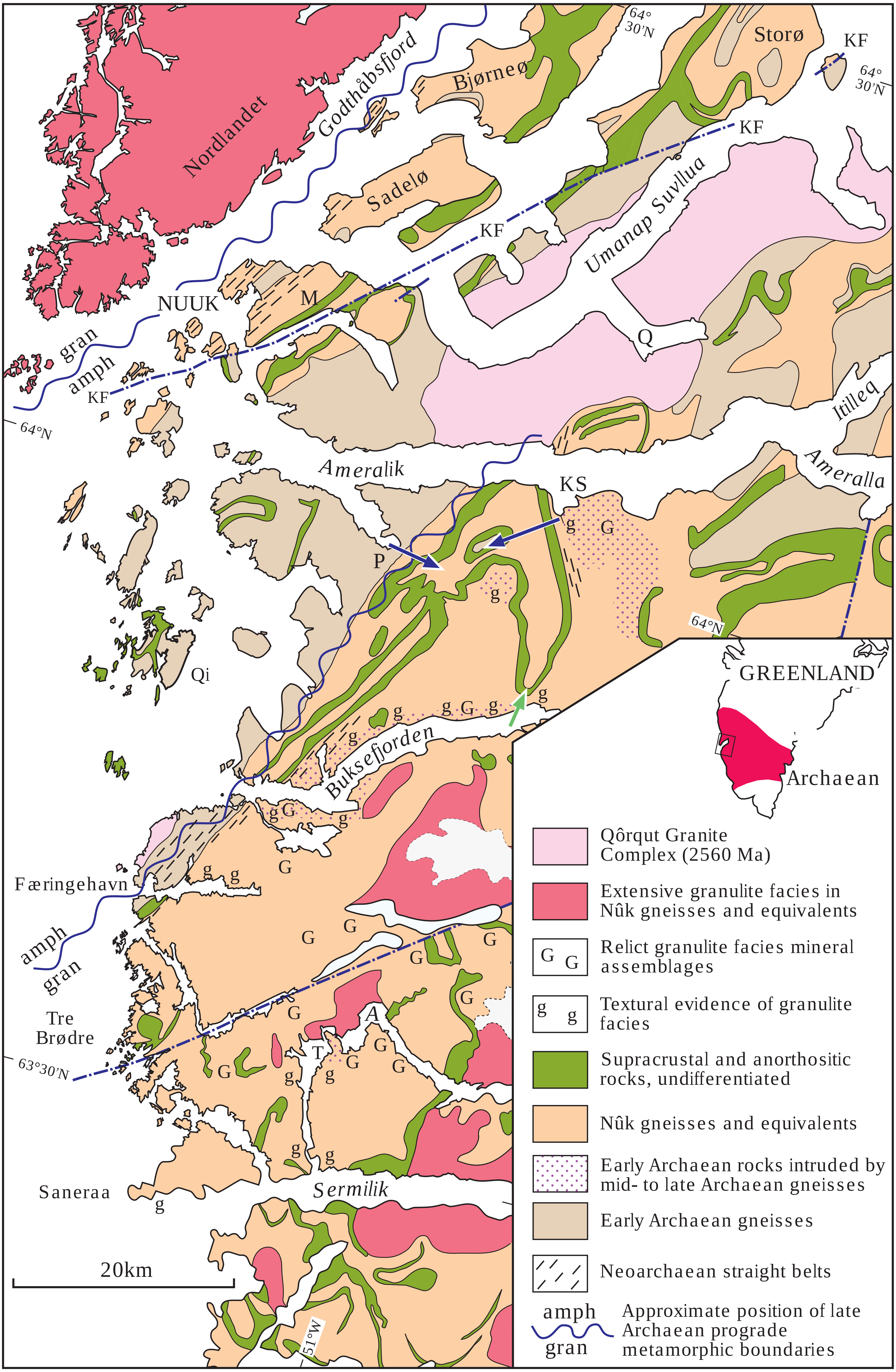
B


0.40
0.35
0.30
0.25
3800
3600
3400
3000
2600 Ma
207Pb/206Pb
1.0
1.5
2.5
238U/206Pb
analyses
6
4
2
2600
3000
3400
3800
207Pb/206Pb date (Ma)

Friend and Nutman Figure 3

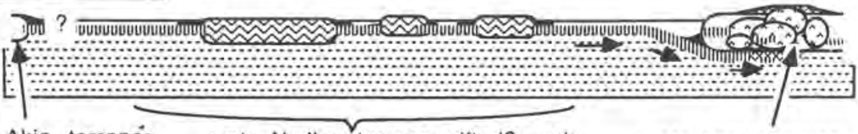


01/03/2018 Fig. 4B - 1986 model



Late Archaean evolution of the Godthåbsfjord region

2840-2860 Ma

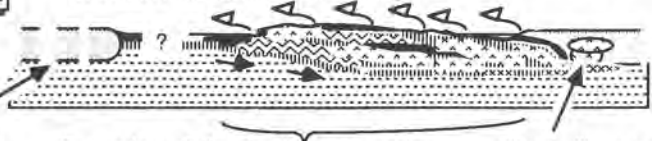


proto-Akia terrane; dominated by 3000 and 3200 Ma gneisses

proto-Akulleq terrane; rifted? early Archaean continental crust (cut by mafic dyke swarms), quartzites, pelites and oceanic crust. Quartz cordierite gneisses may be (altered) volcanics associated with rifting.

proto-Tasiusarsuaq terrane; active volcanic arc, containing inclusions of oceanic crust and also 2920 Ma gneisses

2810-2825 Ma



proto-Akia terrane

Formation of the Akulleq terrane by intercalation of lithologies(above), and the emplacement of the syntectonic Ikkattoq gneisses. Quartz cordierite gneisses may be volcanic equivalents (altered) of the Ikkattoq gneisses

Ilivertalik granite complex in the Tasiusarsuaq terrane

2700-2720 Ma

Akia terrane arrives via predominantly strike slip motion? Reactivation of the boundary between the Akulleq and Tasiusarsuaq terranes forming the Qarlliit nunaat thrust. Intrusion of granite sheets

Ivinnguit fault

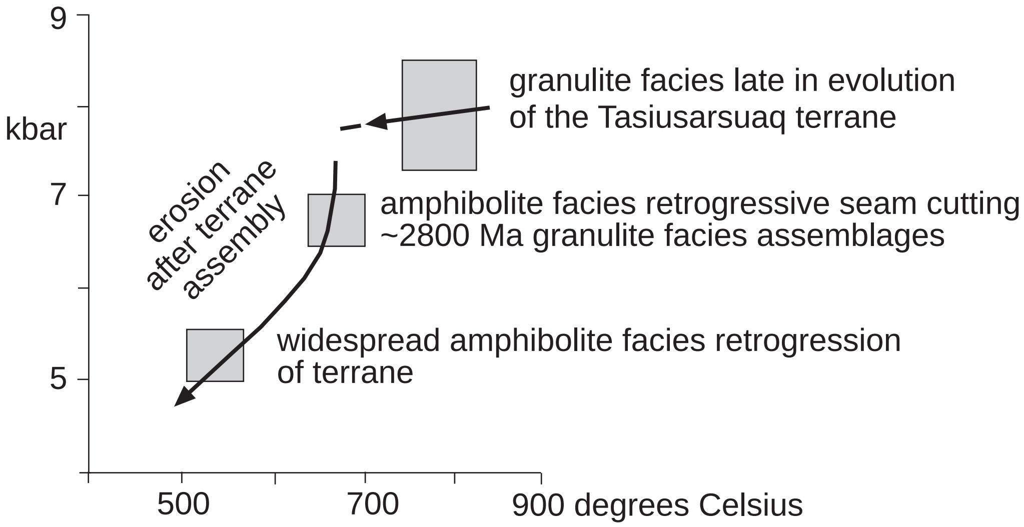
Qarlliit nunaat thrust

2700-2490 Ma

Sporadic deformation and emplacement of granitic bodies (e.g. 2550 Ma Qôrqut granite complex), with cooling and erosion of tectonically thickened crust.

Friend and Nutman Figure 4

Tasiusarsuaq terrane: granulite facies with isobaric cooling at 2805±5 Ma



Tre Brødre terrane: clockwise P,T,t with isothermal decompression at 2713±4 Ma

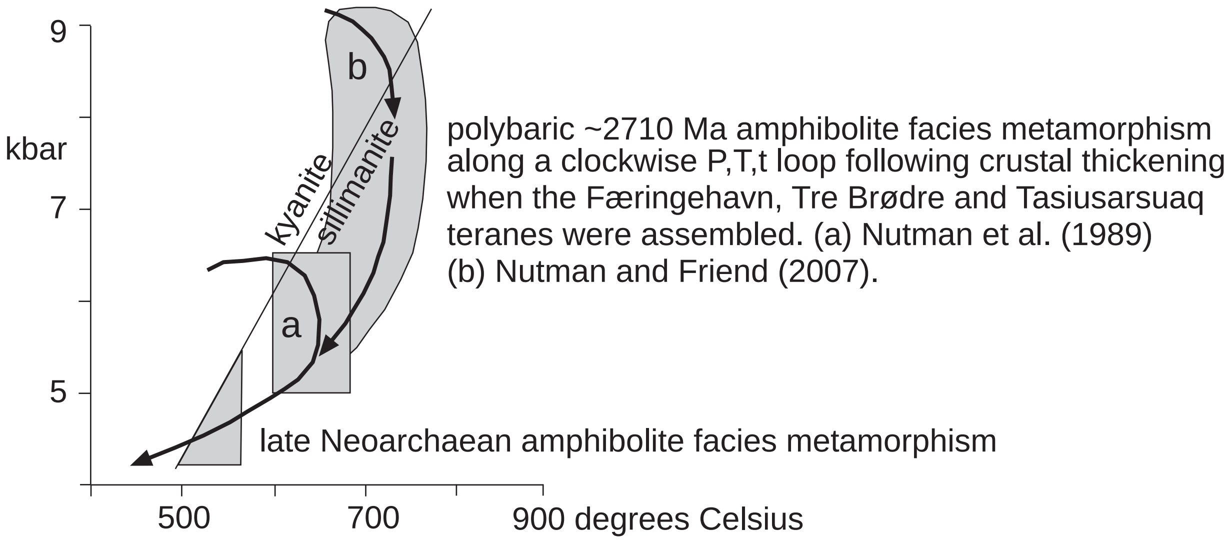
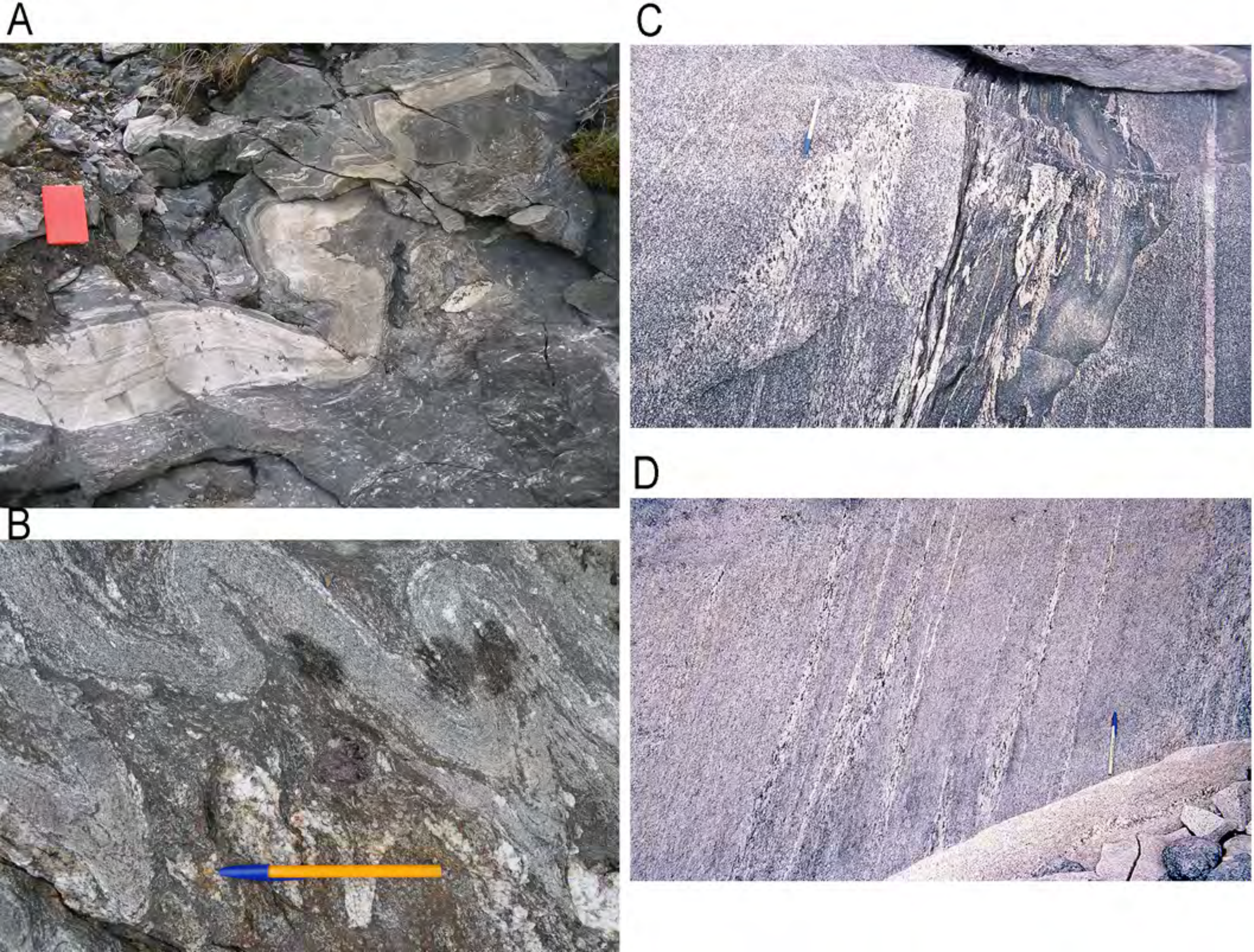
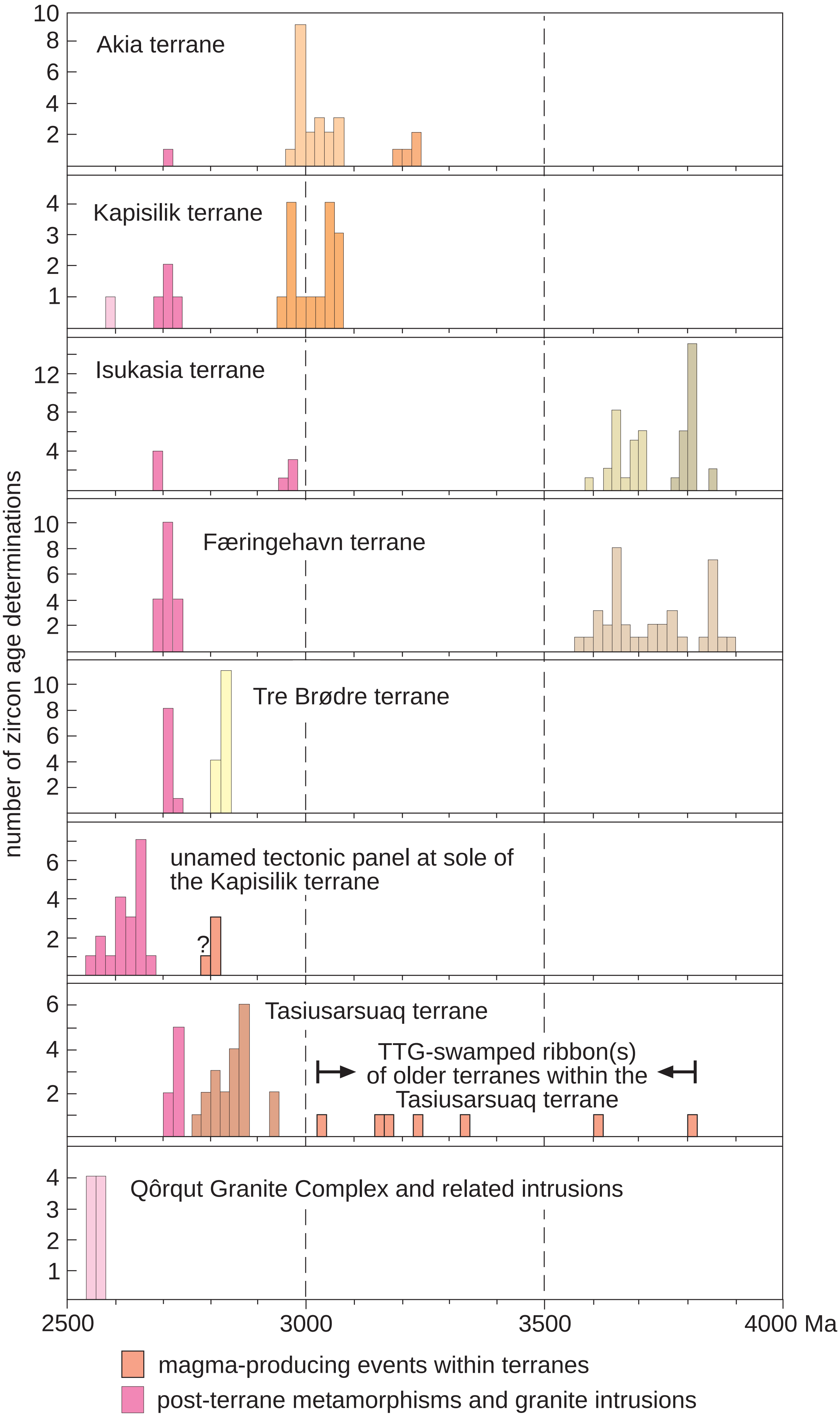


Figure 6.

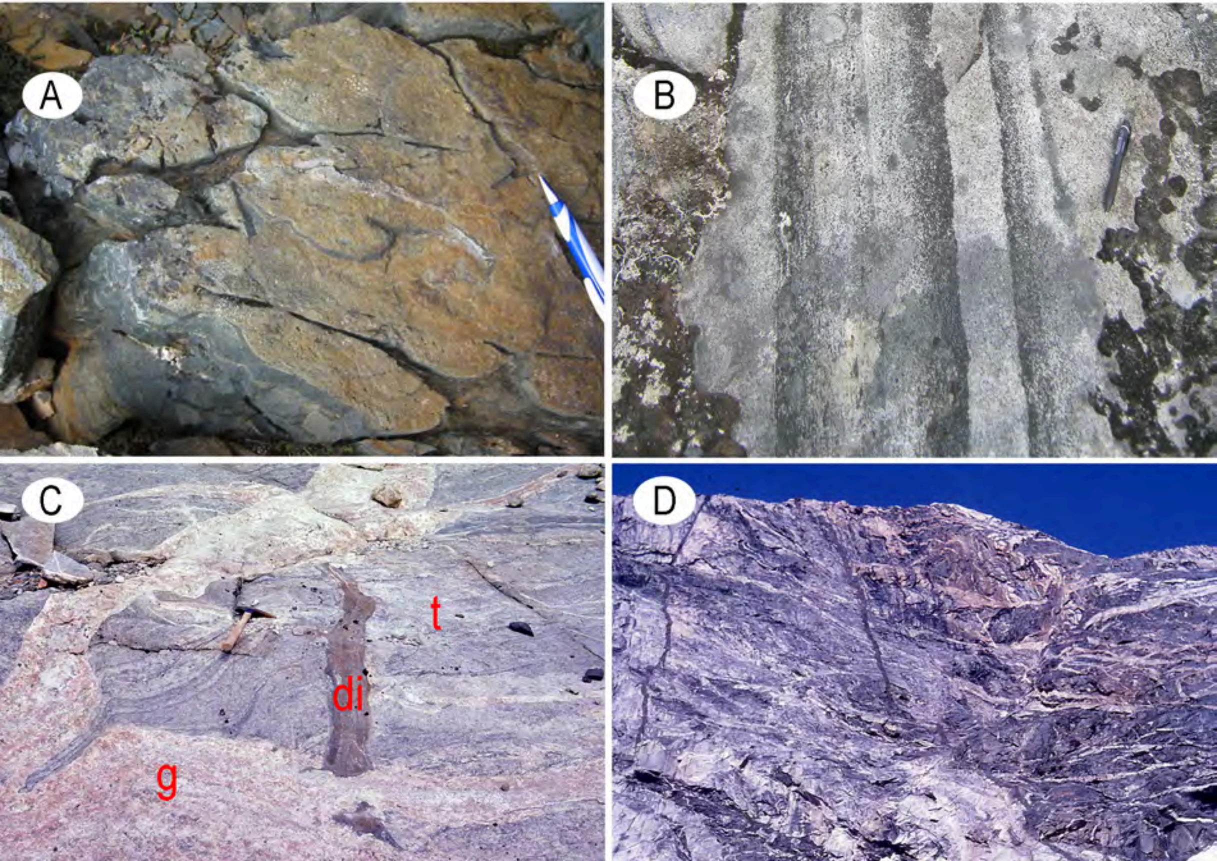
Figure 7



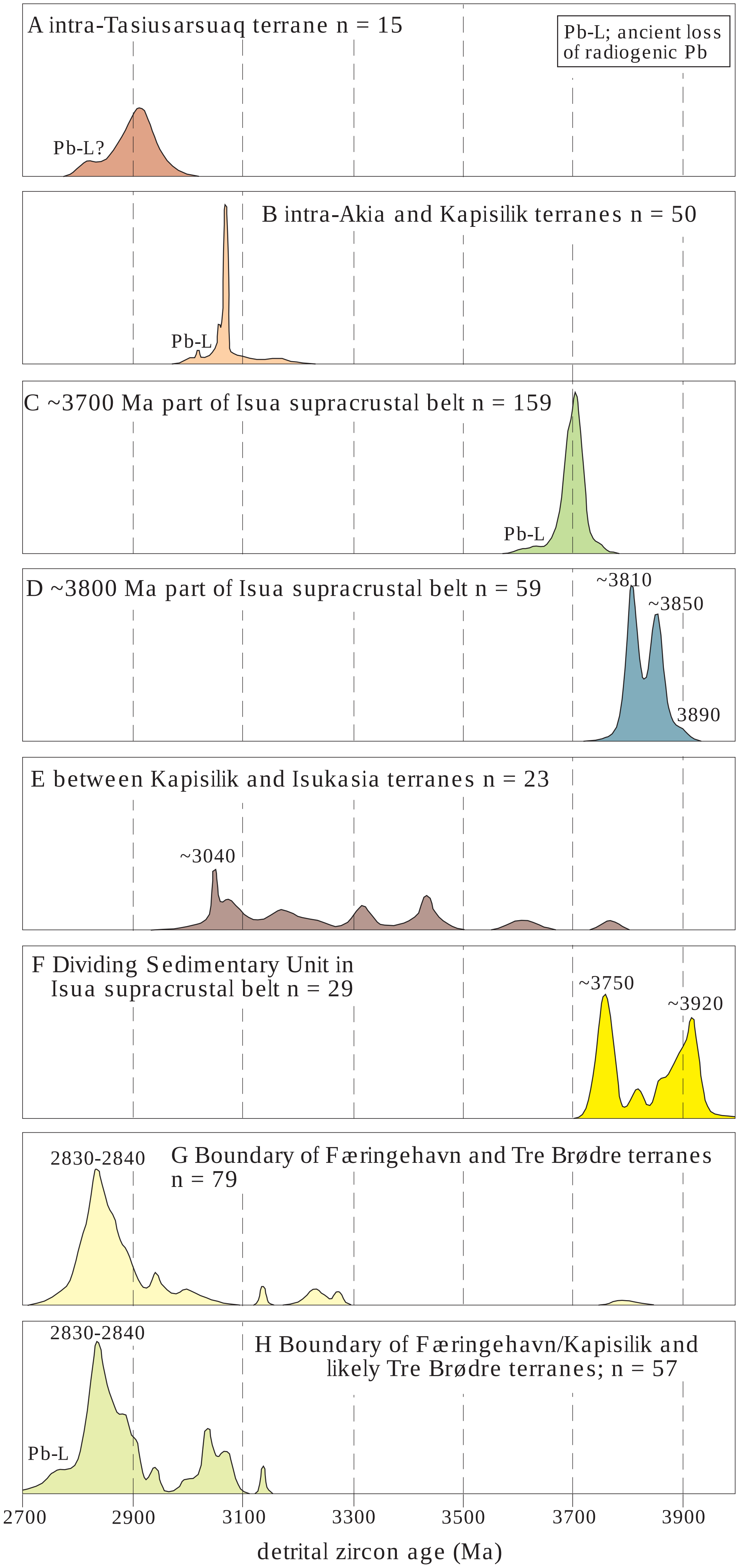
01/08/2018 Fig. 8 - Geochron summary



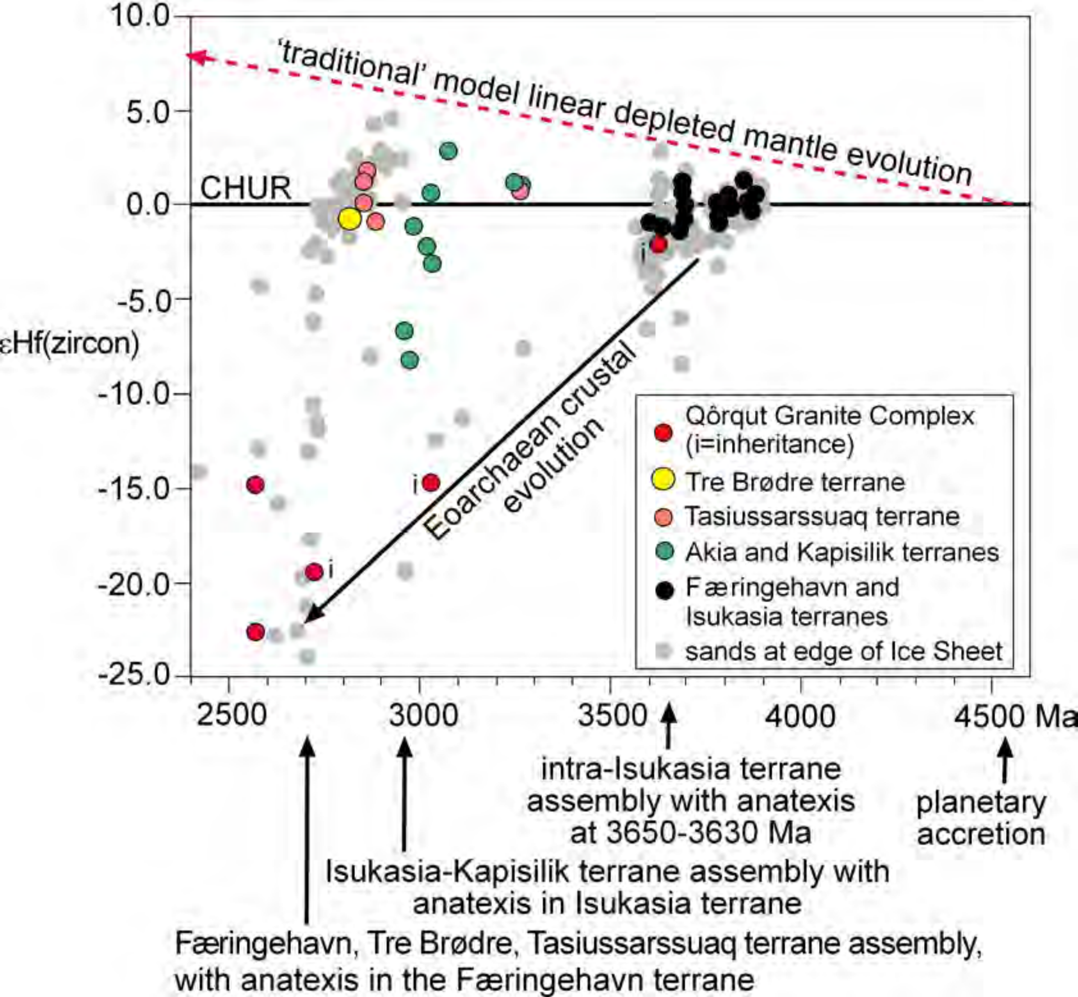
Friend and Nutman Figure 9



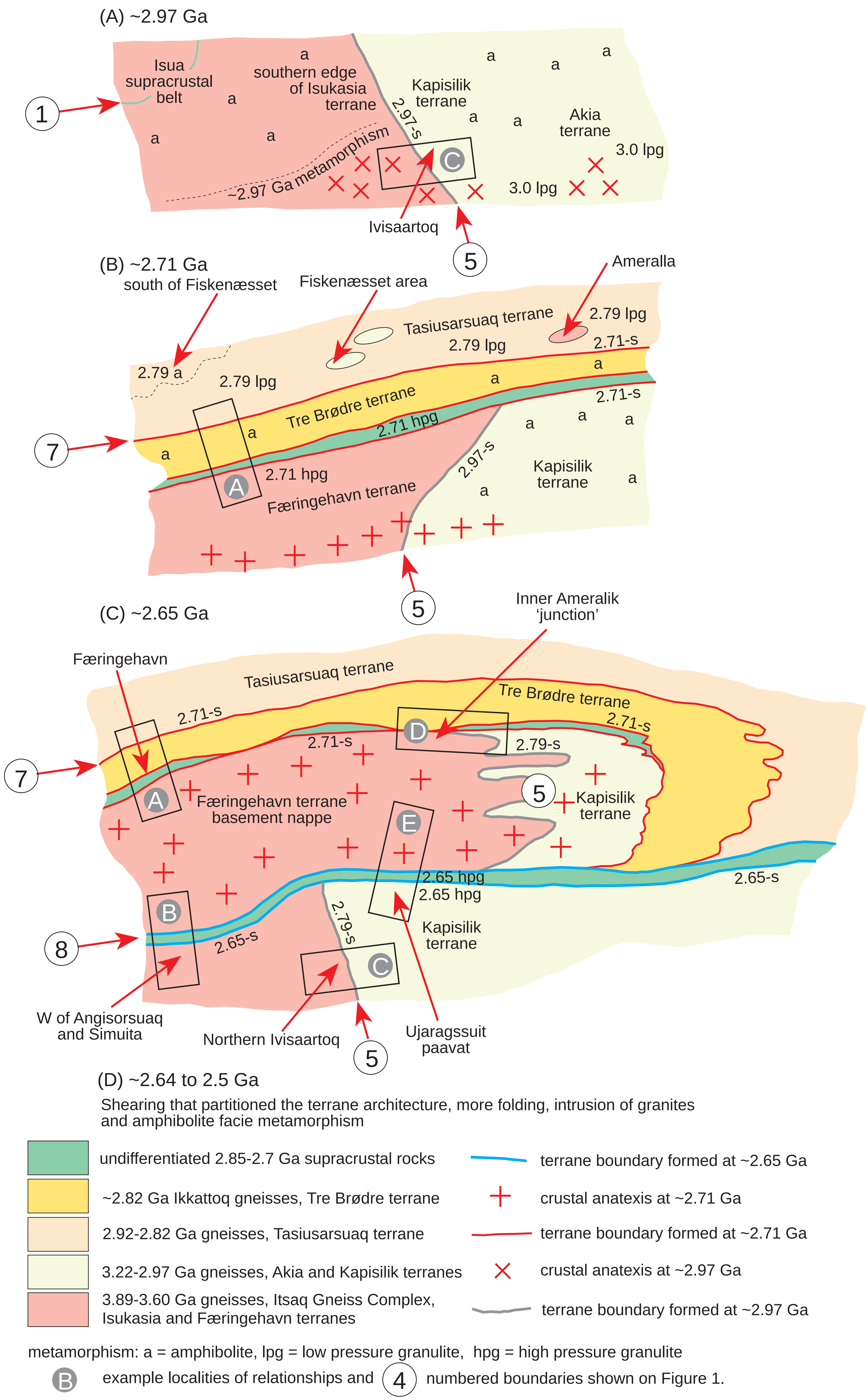
01/08/2019 Fig. 10 - Detritals geochron summary



Friend and Nutman Figure 11

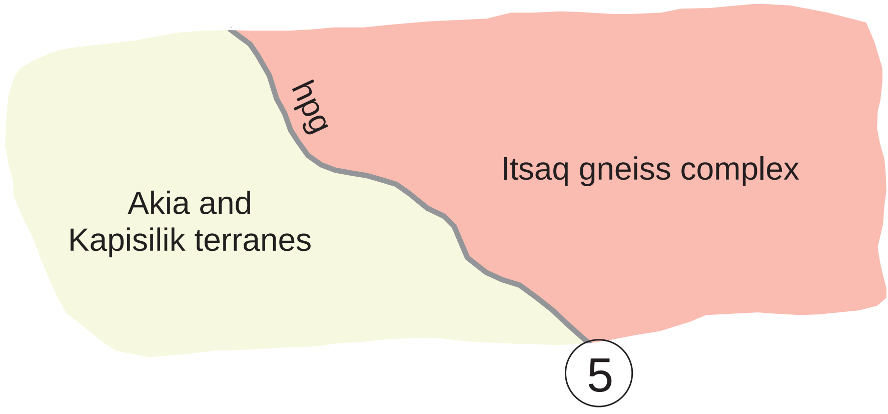


Friend and Nutman Fig12 LHS

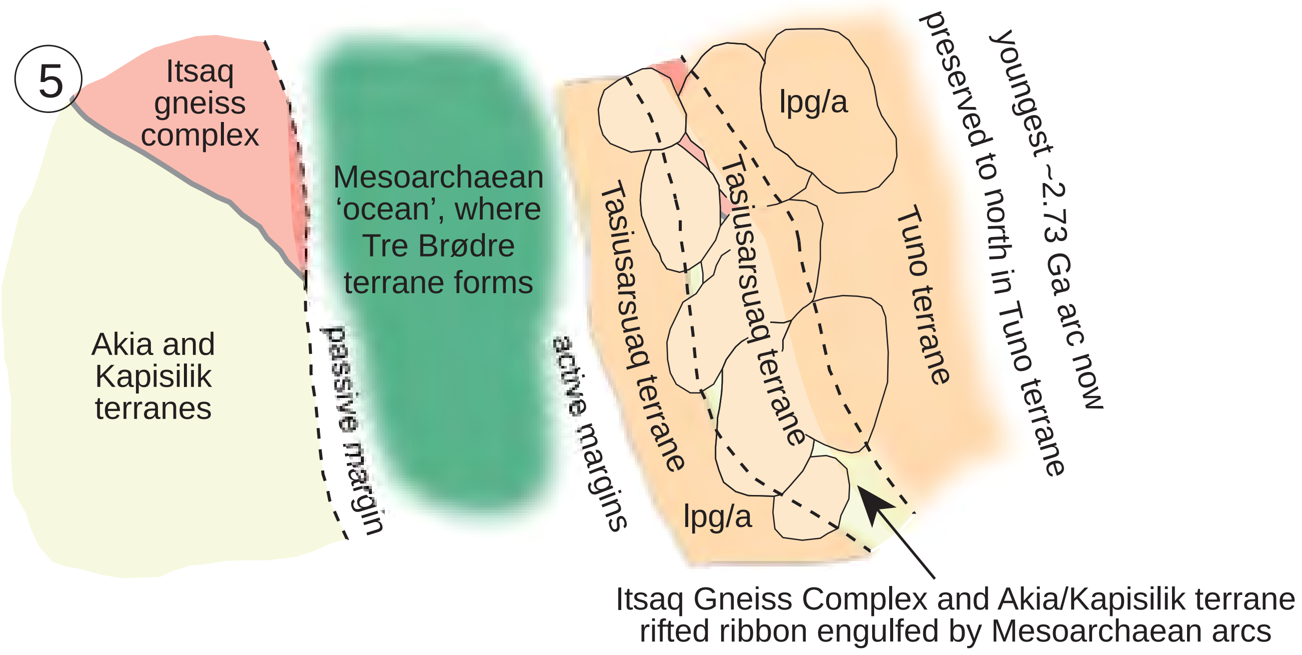


Friend and Nutman Figure 12RHS

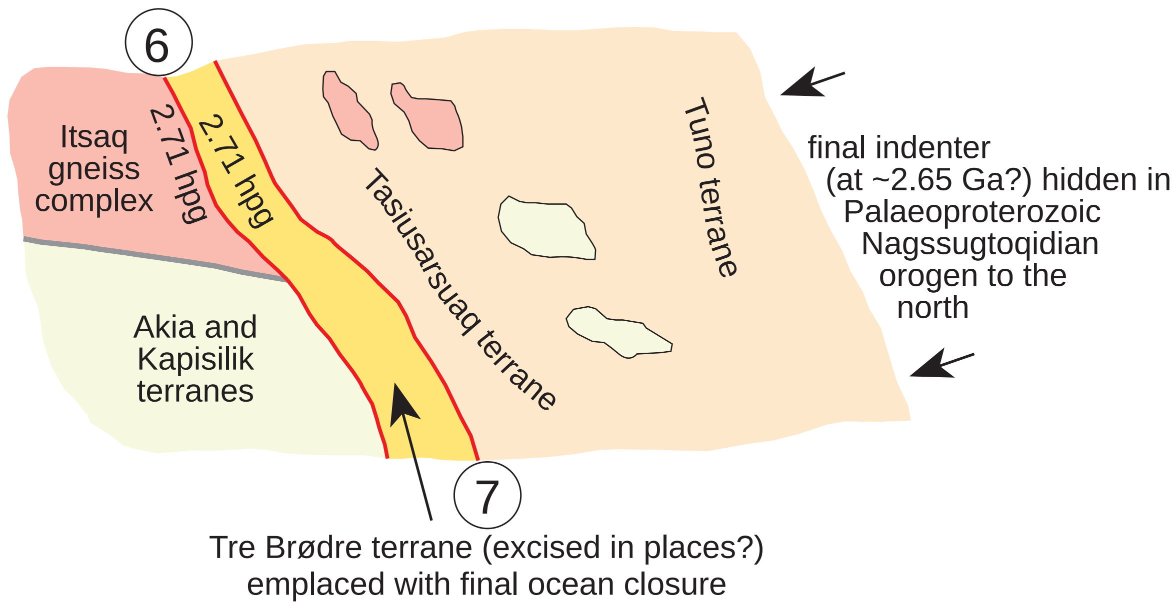
(D) Amalgamation of Akia+Kapisilik terranes and Itsaq gneiss complex
extensive ‘continent’ by ~2.96 Ga



(E) <2.97 Ga rifting, then development of multiple arcs - 2.92-2.73 Ga



(F) 2.71 Ga cessation of active arcs. Collision gives transient high pressure metamorphism



(G) ~2.64 to 2.5 Ga

Shearing that partitioned the terrane architecture, more folding, intrusion of granites
and amphibolite facie metamorphism

- Mesoarchaean ocean
- ~2.82 Ga Ikkattoq gneisses, Tre Brødre terrane
- 2.92-2.82 Ga gneisses, Tasiusarsuaq terrane
  2.76-2.73 Ga gneiss, Tuno terrane
- 3.22-2.97 Ga gneisses, Akia and Kapisilik terranes
- 3.89-3.60 Ga gneisses, Itsaq Gneiss Complex, Isukasia and Færingehavn terranes
- terrane boundary formed at ~2.71 Ga
- terrane boundary formed at ~2.97 Ga

metamorphism: a = amphibolite, lpg = low pressure granulite, hpg = high pressure granulite

Table 1

Age (Ma)	Akia		Kapisilik	Isukasia (old)	Isukasia (young)		Færingehavn	Tre Brødre	Tasiusarsuaq
	Straight-belt deformation across region								
2555			granite emplacement				emplacement of Qôrqut granite complex		
2600			metamorphism						
	Juxtaposition with Akia terrane - Ivinnguit Fault 9								
	Common deformation across region								
2650	Final terrane assembly with HPG on lower side 8								
2690							metamorphism and anatexis		
2710-2730	Qarussuk dykes			metamorphism			metamorphism and anatexis with stitching granite sheets		
							Emplacement of Tasiusarsuaq terrane on top of the Færingehavn and Tre Brødre terranes - Qarliit Nunaat Thrust 7		
2790-2805									granulite facies
2810									Ilivertalik granite
<2825							Juxtaposition of the Færingehavn and Tre Brødre terranes 6		
2825								TTG protoliths	
>2825								anorthosite	
								supracrustal rocks	
2840									TTG protoliths
									Fiskenæsset
>2840									anorthosite
2860									TTG protoliths
>2860									supracrustal rocks
2915				metamorphism					
2922									TTG protoliths
2940			Juxtaposition with Kapisilik terrane 5						
2950			TTG protoliths						
	TTG protoliths								
2990	Tasersuaq tonalite								
2980-3000	granulite facies								
3026-3050			TTG protoliths						
>3050	supracrustal rocks		anorthosite						
			supracrustal rocks						
3200	TTG protoliths								
3260	anorthosite			Ameralik Dykes			Ameralik Dykes		
	supracrustal rocks								
3453							Ugpik metadolerite		
3550				Ameralik Dykes			Ameralik Dykes		
3600-3610				metamorphism - amphibolite facies - anatexis			metamorphism		
3640							Augen geneisses		
3650				metamorphism - White gneisses			granulite facies		
3660				Inaluk Dykes					
				Intercalation between 3690-3660					
					BIF				
3690					TTG protoliths		TTG protoliths		
					intercalation of mantle				
					and supracrustal rocks				
<3750				Dividing Sediment					
3750				TTG protoliths			TTG protoliths		
3790				TTG protoliths			TTG protoliths		
3800				TTG protoliths					
				intercalation of mantle					
>3800				and supracrustal rocks					
>3800				supracrustal rocks					
3880							TTG protoliths		
							gabbro-anorthosite		
							Components of the Akilia		
							supracrustal rocks		

Table 2
List of terrane boundaries and major faults.

No.	Name	Age	Description
9	Ivinnguit Fault	~2550 Ma	Brings in the Akia terrane - syn Qôrqut Granite Complex
8		≥2650 Ma	Separates areas with 2710 Ma metamorphism from those without
7	Qarliit Nunaat Thrust	<2790 Ma	Brings Tasiusarssuaq terrane over Tre Brødre, Færingehavn and Kapisilik terranes
6		<2825 Ma	Joins the Tre Brødre with Færingehavn and Kapisilik terranes
5		Post-2960 Ma	Joins the Færingehavn and Kapisilik terranes
4		Post-2960 Ma	Separates the 2960 Ma metamorphic event within Færingehavn and Kapisilik terranes
3		3650–3600 Ma	Partitions Isua supracrustal belt and 3690 Ma gneisses
2		Post-3690 Ma	Dissects units within ~3700 Ma component of ISB and soclinally folded
1		3690–3660 Ma	Separates the 3800 and 3700 Ma components within Isukasia supracrustal belt