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~3,850 Ma tonalites in the Nuuk region, Greenland: geochemistry and their reworking within an Eoarchaeon gneiss complex

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Abstract

The Eoarchaeoan (>3,600 Ma) Itsaq Gneiss Complex of southern West Greenland is dominated by polyphase orthogneisses with a complex Archaean tectonothermal history. Some of the orthogneisses have c. 3,850 Ma zircons, and they vary from rare single phase metatonalites to more common complexly banded migmatites. This is due to heterogeneous strain, in situ anatexis and granitic veining superimposed during younger tectonothermal events. In the single-phase tonalites with c. 3,850 Ma zircon, oscillatory-zoned prismatic zircon is all 3,850 Ma old, but shows patchy ancient loss of radiogenic Pb. SHRIMP spot analyses and laser ablation ICP-MS depth profiling show that thin (usually < 10 µm) younger (3,660-3,590 Ma and Neoarchaeoan) shells of lower Th/U metamorphic zircon are present on these 3,850 Ma zircons. Several samples with this simple zircon population occur on islands near Akilia. In contrast, migmatites usually contain more complex zircon populations, with often more than one generation of igneous zircon present. Additional zircon dating of banded gneisses across the Complex shows that samples with c. 3,850 Ma igneous zircon are not just a phenomenon restricted to Akilia and adjacent islands. For example, migmatites from Itilleq (c. 65 km from Akilia) contain variable amounts of oscillatory-zoned 3,850 Ma and 3,650 Ma zircon, interpreted, respectively, as the rock age and the time of crustal melting under Eoarchaeoan metamorphism. With only 110-140 ppm Zr in the tonalites and likely magmatic temperatures of >850°C, zircon solubility - melt composition relationships show that they were only one-third saturated in zircon. Any zircon entrained in the precursor magmas would thus have been highly soluble. Combined with the cathodoluminescence imaging, this demonstrates that the c. 3,850 Ma oscillatory zoned zircon crystallised out of the melt and hence gives a magmatic age. Thus the rare well-preserved tonalites and palaeosome in migmatites testify that c. 3,850 Ma quartzo - feldspathic rocks are a widespread (but probably minor) component in the Itsaq Gneiss Complex. C. 3,850 Ma zircon with negative Eu anomalies (showing growth in felsic systems) also occurs as detrital grains in rare c. 3,800 Ma metaquartzites and as inherited grains in some 3,660 Ma granites (*sensu stricto*). These demonstrate that still more c. 3,850 Ma rocks were present, but were recycled into Eoarchaeoan sediments and crustally derived granites. The major and trace element characteristics (e.g. LREE enrichment, HREE depletion, low MgO) of the best-preserved c. 3,850 Ma rocks are typical of Archaean TTG suites, and thus argue for crust formation processes involving important contributions from melting of hydrated mafic crust to the earliest Archaean. Five c. 3,850 tonalites were selected as the best preserved on the basis of field criteria and zircon petrology. Four of these samples have overlapping initial ϵ_{Nd} (3,850 Ma) values from +2.9 to +3.6 ± 0.5, with the fourth having a slightly lower value of +0.6. These data provide additional evidence for a markedly LREE-depleted early terrestrial mantle reservoir. The role of c. 3,850 Ma crust should be considered in interpreting isotope signatures of the younger (3,800-3,600 Ma) rocks of the Itsaq Gneiss Complex. © Springer-Verlag 2007.

Keywords

geochemistry, gneiss, greenland, region, nuuk, tonalites, ma, 850, 3, eoarchaeoan, within, reworking, their, complex, GeoQUEST

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**~3850 Ma tonalites in the Nuuk region, Greenland:
Geochemistry and their reworking within an Eoarchaeon
gneiss complex**

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Abstract The Eoarchaeon (>3600 Ma) Itsaq Gneiss Complex of southern West Greenland is dominated by polyphase orthogneisses with a complex Archaean tectonothermal history. Some of the orthogneisses have c. 3850 Ma zircons, and they vary from rare single phase metatonalites to more common complexly-banded migmatites. This is due to heterogeneous strain, *in situ* anatexis and granitic veining superimposed during younger tectonothermal events.

In the single-phase tonalites with c. 3850 Ma zircon, oscillatory-zoned prismatic zircon is all 3850 Ma old, but shows patchy ancient loss of radiogenic Pb. SHRIMP spot analyses and laser ablation ICP-MS depth profiling show that thin (usually <10 μm) younger (3660-3590 Ma and Neoarchaeon) shells of lower Th/U metamorphic zircon are present on these 3850 Ma zircons. Several samples with this simple zircon population occur on islands near Akilia. In contrast, migmatites usually contain more complex zircon populations, with often more than one generation of igneous zircon present. Additional zircon dating of banded gneisses across the Complex shows that samples with c. 3850 Ma igneous zircon are not just a phenomenon restricted to Akilia and adjacent islands. For example, migmatites from Itilleq (c. 65 km from Akilia) contain variable amounts of oscillatory-zoned 3850 Ma and 3650 Ma zircon, interpreted respectively as the rock age and the time of crustal melting under Eoarchaeon metamorphism.

With only 110-140 ppm Zr in the tonalites and likely magmatic temperatures of >850°C, zircon solubility – melt composition relationships show that they were only a third saturated in zircon. Any zircon entrained in the precursor magmas would thus have been highly soluble. Combined with the cathodoluminescence imaging, this demonstrates that the c. 3850 Ma oscillatory-zoned zircon crystallised out of the melt and hence gives a magmatic age. Thus the rare well-preserved tonalites and palaeosome in migmatites testify that c. 3850 Ma quartzofeldspathic rocks are a widespread (but probably minor) component in the Itsaq Gneiss Complex. C. 3850 Ma zircon with negative Eu anomalies (showing growth in felsic systems) also occurs as detrital grains in rare c. 3800 Ma metaquartzites and as inherited grains in some 3660 Ma granites (*sensu stricto*). These demonstrate that yet more c. 3850 Ma rocks were present, but were recycled into Eoarchaeon sediments and crustally-derived granites. The major and trace element characteristics (e.g. LREE enrichment, HREE depletion, low MgO) of the best preserved c. 3850 Ma rocks are typical of Archaean TTG suites, and thus argue for crust formation processes involving melting of hydrated mafic crust to the earliest Archaean.

Five c. 3850 Ma tonalites were selected as the best preserved on the basis of field criteria and zircon petrology. Four of these samples have overlapping initial ϵ_{Nd} (3850 Ma) values from +2.9 to +3.6 $\pm$ 0.5, with the fourth having a slightly lower

of value of +0.6. These data provide additional evidence for a markedly LREE-depleted early terrestrial mantle reservoir. The role of c. 3850 Ma crust should be considered in interpreting isotope signatures of the younger (3800-3600 Ma) rocks of the Itsaq Gneiss Complex.

Keywords: Eoarchaeon, Tonalites, Crustal Evolution, Zircons, Greenland, Nd isotopes, Itsaq Gneiss Complex

Introduction

Eoarchaeon rocks (>3600 Ma) provide a geochemical window onto the early Earth. These rocks are predominantly tonalitic-granitic “banded grey gneisses” derived from plutonic protoliths, that enclose remnants of ultramafic, gabbroic and supracrustal rocks (e.g., McGregor 1973, 1979; Bridgwater et al. 1976; Collerson and Bridgwater 1979; Black et al. 1986; Myers 1988; Schiøtte et al. 1989; Bowring et al. 1989; Song et al. 1996; Kinny and Nutman 1996, Nutman et al. 1996, 2000; Bowring and Williams 1999, Mojzsis and Harrison, 2002). All these rocks are in high-grade terrains, where they have mostly been affected by strong ductile deformation and variable degrees of *in situ* migmatization, so that as now preserved, they are complex and chemically modified products of superimposed tectono-thermal events. The variable state of preservation and hence of chemical integrity of these key old materials can make them difficult targets for geochemical and isotopic investigations. Thus it is always necessary to single-out the rare, best-preserved materials for geochemical tasks, by integrating field geology with geochemical approaches (e.g., Nutman et al. 1999; Bennett et al. 2002; Polat et al. 2002; Frei and Polat, 2007).

When using the geochemistry of these ancient rocks to extract information on the early Earth, U/Pb zircon dating is the most reliable approach to constrain their ages. Zircon dating in the Eoarchaeon rocks of the Nuuk region (Fig. 1) in southern West Greenland is summarised in Fig. 2. From field geology and SHRIMP (Sensitive High mass Resolution Ion MicroProbe) U/Pb zircon dating, Nutman et al. (1993, 1996, 1997a, 2000, 2002a) concluded that granitoids of several ages back to c. 3850 Ma are present in the Complex. This SHRIMP-based conclusion grew out of earlier bulk zircon ID-TIMS (isotope dilution thermal ionisation mass spectrometry) dating of cross-cutting orthogneiss components in the north of the complex near the Isua supracrustal belt, which showed that plutonic rocks with different ages are present (Baadsgaard et al. 1986). There is now a consensus that different-aged plutonic components up to c. 3800 Ma *are* present in the orthogneisses of the Complex. For example, dating of abundant 3810 and 3790 Ma tonalites with quartz diorites immediately south of the Isua supracrustal belt (Nutman et al. 1993, 1996, 1999, 2000) has been replicated by Crowley (2003) and Kamber et al. (2003) and the dating of 3650 Ma granites cutting 3700 Ma tonalites north of the Isua supracrustal belt (Baadsgaard et al. 1986; Nutman et al. 1993, 1996, 2000) has been replicated by Crowley et al. (2002).

One age for orthogneisses that remains contentious is 3850 Ma (Whitehouse and Kamber, 2005 and Nutman et al., 2004 and references therein). The contention

concerns how to interpret the oldest zircons within these rocks. The view taken by Nutman and co-workers is that for most migmatites with tonalitic palaeosome, the petrographic and geochronological data from their oldest zircon population(s) are interpreted to give the time when the igneous protolith(s) in the palaeosome formed (Nutman et al., 2000). Whitehouse and co-workers have interpreted near identical zircon data in a different fashion, and although they now also consider the possibility that these oldest zircons show the presence of pre-3800 Ma crustal components in the Itsaq Gneiss Complex, they strongly suggest that these zircons might represent xenocrystic grains in younger (c. 3660 Ma) magmatic rocks (Whitehouse et al., 1999; Whitehouse and Kamber, 2005). In addition to interpretation of the zircon data, there is continuing divergence of opinion on the field relationships. In discussing previous work (Nutman et al., 1997a; 2000 and Mojzsis and Harrison; 2002), Whitehouse and Kamber (2005) summarise some of their concerns as: “ In the case of the much discussed Akilia locality, the question is clearly that of how old the relative field relationships are (which some interpret as igneous cross-cutting), and it is, therefore, critically important to test whether these rocks underwent significant, pervasive partial melting that would have obliterated older structural relationships pertaining to the original, magmatic emplacement.”.

The contentious gneisses are within the more strongly reworked southern part of the Complex, where the presence of neosome produced by *in situ* melting followed by strong deformation clouds their interpretation (e.g., Nutman et al. 1996, 2000). To date, contention has focussed on Akilia and neighbouring islands (Fig. 1). Nutman et al. (1993, 1996, 1997a, 2000, 2002) presented increasingly more detailed data that they interpreted as showing that c. 3850 Ma (“pre-Isua”) rocks are present – variably and mostly strongly modified in superimposed tectonothermal events. These c. 3850 Ma zircon ages and the conclusion that they are crystallisation ages have been replicated by workers who used Cameca ion-microprobe zircon U/Pb dating, which included depth profiling (Mojzsis and Harrison, 2002 – working on a sample they recollected from the G93/05 sample locality from Nutman et al., 1997a) and by ID-TIMS zircon U/Pb dating (Krogh et al. 2002). These workers concluded that c. 3850 Ma rocks are present. Whitehouse and Kamber (2005) also found c. 3850 Ma zircons in an Akilia rock, and although not necessarily agreeing that they give the actual intrusion age of the rock, they did conclude these zircons must demonstrate the presence of c. 3850 Ma grey gneisses within the Itsaq Gneiss Complex.

The present paper first presents results from a small area of fortuitously well-preserved homogeneous metatonalite (Figs. 3 and 4), which we interpret to be 3849 ± 9 Ma old. Then, via a progression from almost homogeneous metatonalites to

banded migmatitic gneisses, we demonstrate how c. 3850 Ma rocks (Fig. 5) and their igneous zircons have been variably modified. This is a result of ductile deformation combined with *in situ* neosome production and veining during several post-3850 Ma tectonothermal events, which makes it hard to recognise these oldest components (e.g. Nutman et al. 1996, 2000, 2002; Friend and Nutman 2005a). Via reconnaissance zircon dating of many migmatites, we show that c. 3850 Ma zircons interpreted to date tonalitic palaeosome occur at several localities across the Complex (Fig. 1). Lastly, there are 3850 Ma zircons derived from quartzo-feldspathic rocks found as xenocrysts within some 3600-3660 Ma granites *sensu stricto* (Friend and Nutman, 2005a) and as detrital grains in c. 3800 Ma detrital sediments (Nutman et al., 1997b). When combined, we interpret these data to demonstrate that a c. 3850 Ma “pre-Isua” (i.e. pre-3700-3800 Ma) tonalitic crust is a widespread, albeit probably volumetrically minor component, within the Itsaq Gneiss Complex.

Eoarchaeon Itsaq Gneiss Complex

Geological overview

The Eoarchaeon rocks of the Nuuk region, Greenland (Black et al. 1971; Moorbath et al. 1972; Baadsgaard 1973) are mainly quartzo-feldspathic gneisses (formerly the *Amîtsoq gneisses*, McGregor 1973) that were derived from several generations of petrogenetically diverse diorites, tonalites, trondhjemites (TTG suite rocks) and granites (e.g. O’Nions and Pankhurst 1974; McGregor 1979; Nutman et al. 1984; Baadsgaard et al. 1986; Nutman and Bridgwater 1986; Nutman et al. 1996, 1999, 2000; Crowley et al. 2002; Crowley 2003). The term *Itsaq Gneiss Complex* embraces all the Eoarchaeon rocks of the Nuuk region (Nutman et al. 1996). The largest body of basic, ultramafic and metasedimentary rocks in the Complex is the c. 35 km long *Isua supracrustal belt* (e.g. Moorbath et al. 1973, Bridgwater and McGregor 1974 and Allaart 1976 for the first studies and Nutman et al. 1997b, Maruyama et al. 1992; Komiya et al. 1999, Rosing 1999 and Polat et al. 2002 for examples of new work). Smaller higher-grade bodies dominated by amphibolite occur throughout the rest of the Complex. These are similar to, though not necessarily contemporaneous with, mafic rocks of the Isua supracrustal belt (Nutman et al. 1996).

The Itsaq Gneiss Complex is cut by the Mesoarchaeon Ameralik dykes (McGregor 1973; Gill and Bridgwater 1979; Chadwick 1981; Nielsen et al. 2002; Nutman et al. 2004a). It is tectonically intercalated with terranes of Neoarchaeon gneisses devoid of Eoarchaeon material and is also intruded by younger bodies of

crustally-derived granite (Friend et al. 1987, 1988, 1996; McGregor et al. 1991; Crowley 2002; Friend and Nutman 2005b). The Complex is now considered to consist of separate tectonic slices – the *Færingehavn terrane* in the south (indicated by F's on Fig. 1), and the *Isukasia terrane* in the north (indicated by I's on Fig. 1), that are interpreted to have been brought into their present disposition during several later Archaean tectonic events (Friend and Nutman 2005b).

Heterogeneous strain and migmatisation

At most localities in the Itsaq Gneiss Complex, detailed field evidence for the Eoarchaeon evolution of the rocks has been obliterated by strong polyphase ductile deformation during Neoarchaeon terrane assembly events (McGregor, 1973; Friend et al. 1987, 1988; McGregor et al. 1991; Nutman et al. 1996, 2000; Crowley, 2002). During these events the originally cross-cutting Ameralik dykes were mostly transformed into sub-concordant, disrupted tabular amphibolites (McGregor 1973; Chadwick and Nutman 1979; McGregor et al. 1991). However, there are small low-strain domains in the Complex where the Ameralik dykes still cross-cut relatively undeformed Eoarchaeon country rocks. The largest of these domains are in the northern end of the Complex near to the Isua supracrustal belt and show cross-cutting relationships preserved between the plutonic protoliths of the orthogneisses (e.g., Bridgwater and McGregor, 1974; Nutman and Bridgwater, 1986; Nutman et al. 1996, 1999; White et al. 2000; Crowley et al., 2002).

In contrast, in smaller domains of lower Neoarchaeon strain in the southern part of the Complex, Ameralik dykes (dated at >3450 Ma – Nutman et al. 2004) cut Eoarchaeon migmatitic layering and *in situ* felsic segregations that were probably derived from arrested partial melting (e.g., Nutman et al. 1996, 2002; McGregor et al. 2000; Friend and Nutman, 2005a). This Eoarchaeon *in situ* incipient partial melting and migmatisation is correlated with textural and rare mineralogical observations such as pre-Ameralik dyke relict metamorphic orthopyroxene (metamorphic orthopyroxene in the Itsaq Gneiss Complex rocks variably replaced by amphibole + quartz $\pm$ biotite; criteria in McGregor and Friend, 1997) interpreted to reflect Eoarchaeon granulite facies metamorphism (McGregor and Mason, 1977; Griffin et al. 1980; McGregor, 2000; Friend and Nutman, 2005a). This migmatisation and higher-grade metamorphism compounds the difficulties in the interpretation of geochemical and isotopic data for the Eoarchaeon rocks.

A major goal of our studies of the southern part of the Itsaq Gneiss Complex has been to establish the age and identity of the protoliths that suffered variable amounts of *in situ* melting during granulite facies metamorphism. By building

upon our complete mapping of Akilia and the adjacent islands and mainland coast on mapping at scales of 1:10,000 to 1:100 (Nutman 1980, Friend et al. 1987; Nutman et al. 2002), weakly-deformed small domains in the southern migmatites that locally are even free of evidence of *in situ* partial melting have been identified (Nutman et al. 2000, 2002). In these domains, rare cross-cutting Eoarchaeon plutonic relationships are still preserved, albeit distorted by superimposed ductile deformation (Nutman et al. 2000; 2002). Such domains are the source of very rare, best-preserved 3850 Ma tonalites (sample G01/113; Figs. 3, 4). In this paper, the progression of samples from slightly heterogeneous/nebulous tonalite (G93/07) to veined tonalite (G01/109) to banded gneiss migmatites (VM95/02 and G05/39) illustrates how c. 3850 Ma rocks have been modified and largely obscured as one of several age components within the banded gneisses of the Itsaq Gneiss Complex. Field photographs of three variably preserved rocks (G93/07, G01/109, VM95/02) are given in Fig. 5 to illustrate this transformation. The [data repository xxxxx](#) contains petrographic descriptions, [the SHRIMP U/Pb zircon data \(Table R1\)](#) and [the SHRIMP U/Pb zircon analytical method](#).

Well-preserved c. 3850 Ma rocks

G01/113 – best preserved, single age component, c. 3850 Ma rock

G01/113 comes the southeastern side of the same island c. 1 km west of Akilia as samples G91/49 (Nutman et al. 1996, 2000) and G01/114 (Nutman et al. 2002). Sample G01/113 is from a c. 30 cm thick horizon of massive tonalite, present just above high tide level (63°55.68'N, 51°43.60'W– WGS-84 datum) (Fig. 3a). The sample G01/113 is only weakly foliated and has very few small felsic veins (Fig. 3b). The most homogeneous character of this rock is maintained over only a few m² of outcrop. The protolith characteristics of this sample are better preserved than those previously discussed G91/49, G93/05, G99/22 and G01/114 (Nutman et al. 1997a, 2000, 2002).

G01/113 yielded *only* prismatic, lilac-coloured zircons, with *no* ovoid/multifaceted grains, like those identified in the other relatively homogeneous metatonalites to which we ascribe a c. 3850 Ma age (G91/49, G93/05, G99/22, G01/114, Nutman et al. 1997a, 2000, 2002). CL imaging indicates the G01/113 zircons have oscillatory zoning parallel to the grain exteriors (Fig. 4a). Many grains have an incomplete thin ($\leq 5\ \mu\text{m}$) skin of structureless to weakly zoned zircon. However, of the 140 zircons mounted and CL-imaged, only one (grain 16, Fig. 4a) had a broad enough rim ($>20\ \mu\text{m}$) for SHRIMP U/Pb spot

dating. G01/113 with its single generation of oscillatory zoned (igneous) zircon (but partly modified by some recrystallisation) plus very restricted development of (metamorphic) rims, possesses an unusually simple zircon population for a sample from the southern end of the Itsaq Gneiss Complex. The morphology of G01/113 zircons (Fig. 4a) closely resembles those of zircons from c. 3810 Ma tonalites and quartz-diorites south of Isua (sample G97/18 ; Fig. 4b), which are widely interpreted to give the age for the rocks rather than for an inherited component (Nutman, et al., 1999; Crowley 2003; Kamber et al. 2003).

SHRIMP U/Pb zircon analyses for G01/113 zircons ([data repository xxxx Table R1](#)) are summarised in a $^{238}\text{U}/^{206}\text{Pb} - ^{207}\text{Pb}/^{206}\text{Pb}$ plot (Fig. 6a). Analyses of oscillatory-zoned zircon has Th/U ratios between 0.19 and 0.74, with most >0.4. Their ages are mostly concordant within error, with the majority of analyses giving $^{207}\text{Pb}/^{206}\text{Pb}$ dates of >3800 Ma. Where $^{207}\text{Pb}/^{206}\text{Pb}$ dates of <3800 Ma were obtained from the first analysis of a grain, multiple analysis on the same grain (e.g. grains 3, 6 and 11) found sites with ages >3800 Ma. This demonstrates that the spread of $^{207}\text{Pb}/^{206}\text{Pb}$ dates in the oscillatory-zoned zircon is due to ancient loss of radiogenic Pb from >3800 Ma grains. Applying an ancient radiogenic Pb loss interpretation to explain the dispersion in the $^{207}\text{Pb}/^{206}\text{Pb}$ dates, those with the “oldest” dates and statistically indistinguishable from each other, yielded a weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ date of 3849 ± 6 Ma (95% confidence; obtained by culling of “young” domains until MSWD<1 for the remaining group – using the program “Isoplot” of Ludwig, 1998). The only possible exception to this 3849 Ma age is grain 15, where sites with $^{207}\text{Pb}/^{206}\text{Pb}$ dates up to c. 3750 Ma were found. This could be a >3800 Ma grain with greater ancient loss of radiogenic Pb, or it could be a rare c. 3750 Ma grain, perhaps from the few thin felsic veins in the otherwise homogeneous sample (Fig. 3b). Two analyses of the only rim broad enough to take a c. 20 μm SHRIMP spot (Fig. 4a) is devoid of oscillatory zoning in CL imaging and gave young $^{207}\text{Pb}/^{206}\text{Pb}$ dates of 3619 ± 16 and 3545 ± 7 Ma (1σ), with lower Th/U of c. 0.2.

The chemistry of G01/113 zircons was also examined by Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS - analytical method and data processing are summarised in [data repository xxxx, where the data are also lodged as Table R2](#)). Where LA-ICP-MS analyses were initiated over (c. 1 μm deep), SHRIMP dating sites, there was good correspondence between the SHRIMP $^{207}\text{Pb}/^{206}\text{Pb}$ ratio and the LA-ICP-MS $^{207}\text{Pb}/^{206}\text{Pb}$ ratio at the start of the profile. The prior extensive SHRIMP U/Pb dating of these zircons indicates that they have negligible amounts of ^{204}Pb . Therefore the LA-ICP-MS $^{207}\text{Pb}/^{206}\text{Pb}$ ratios can be taken as a proxy for the $^{207}\text{Pb}/^{206}\text{Pb}$ age of the domain. In G01/113 zircons, several depth

profiles were undertaken to examine the very thin partial skins mantling oscillatory-zoned zircon that are observed in the CL images. In post-analysis CL images, the LA-ICP-MS sites show as black pits (Fig. 4a). In these depth profiles the analysis started in the interior of the zircon sectioned in half in the polished grain mount, and with time burrows down towards the grain exterior embedded in the epoxy. Analyses 3A and 10C were processed by breaking them into 2.5s slices (Fig. 7; [data repository xxxx Table R2](#)). In analysis 3A, a thin outer shell (30 to 40 s portion of the analysis) with a Neoarchaean $^{207}\text{Pb}/^{206}\text{Pb}$ age has a Th/U ratio almost two orders of magnitude less than that found in its Eoarchaeon oscillatory-zoned substrate. The $^{207}\text{Pb}/^{206}\text{Pb}$ date at the start of this profile is between 3800-3700 Ma but multiple SHRIMP dates on this grain found >3800 Ma domains and indicate that variable ancient Pb loss from a >3800 Ma crystal has occurred (Fig. 4a, Tables 1 and 2). In analysis 10A, change at the margin of the grain is neither so dramatic nor as clear, but there is a more than halving of Th/U, coupled with a reduction in apparent age. In grain 9 ([data repository xxxx Table R2](#)) a thin (<5 μm) very low Th/U rim was detected at the end of the analysis, with a $^{207}\text{Pb}/^{206}\text{Pb}$ date of 2577 Ma. The LA-ICP-MS profiling plus dating of the only rim in sample G01/113 broad enough to be accessible by SHRIMP spot analysis (c. 25 μm wide on grain 16) demonstrates that partial mantles of several previously recognised regional ages (c. 3650 and Neoarchaeon) are present on these 3850 Ma oscillatory-zoned zircons. However these are largely <5 μm wide, are volumetrically very minor and have features such as low Th/U.

Bulk rock zircon-undersaturation and interpretation of 3850 Ma zircons

Using the experimental data of Watson and Harrison (1983), Mojzsis and Harrison (2002) demonstrated that the magmatic precursor of their tonalite sample GR9716 from Akilia (their recollection of sample G93/05; Nutman et al. 1997a, 2000, 2002) would have been strongly undersaturated in zircon and thus unlikely to preserve any inheritance. The same argument also applies for 3850 Ma homogeneous single-component metatonalites ([data repository xxxx whole rock geochemistry lodged as Table R3](#)), and also for those from Isua with ages of c. 3800 Ma ((Nutman et al., 1999) and c. 3700 Ma (Nutman and Bridgwater, 1986; [data repository xxxx Fig. R1](#)). The simplest, most consistent explanation is an igneous origin for the well-preserved prismatic oscillatory-zoned zircons in these homogeneous metatonalites of different age. In contrast, in complex migmatites such as G91/33, interpreted as old banded gneisses containing copious c. 3650 Ma

partial melt (Nutman et al. 1996, 2000), corroded, pre-3650 Ma zircon of several ages back to c. 3850 Ma is encountered. This is interpreted to indicate that when c. 3650 Ma partial melts were produced *in situ* in these rocks, there was partial dissolution of the older zircons. This is in accord with the study of Watson (1996), who demonstrated that partial melt segregations should commonly carry some protolith zircon as inherited, partly resorbed cores mantled by new igneous zircon.

Whole rock major and trace element data for well-preserved 3850 Ma rocks

In Fig. 8, the geochemistry of the 5 “best” 3850 Ma rocks (plotted as solid diamonds) are compared to the average composition for >3500 Ma TTG and the trends depicted by the complete data set given by Martin et al. (2005). Also shown (as open triangles) are the 3810 and 3795 Ma rocks from Nutman et al. (1999). The c. 3850 Ma rocks correspond to typical Archaean high-Al TTG (Barker and Arth, 1976) with $\text{SiO}_2 > 68$ wt.%, alumina > 15 wt.% and with high Na_2O relative to K_2O , giving them a metaluminous character (Fig. 8a - [data repository xxxx for analytical methods and data lodged as Table R3](#)). They have low ferromagnesian components with low Cr and Ni. However, they also have low Sr (< 350 ppm) and Ba (< 125 ppm) and match the broad TTG definitions of Martin (1994) and Martin et al. (2005).

The c. 3850 Ma rocks are characterised by relatively low overall REE abundances but which display steep, enriched LREE relative to HREE chondrite-normalised patterns with $(\text{La}/\text{Yb})_N$ of > 10 (Fig. 8b, [data repository Table R3](#)), features which are consistent with garnet $\pm$ amphibole in the residues (e.g. Martin et al. 2005). Such patterns have been modelled for the c. 3810 and c. 3795 Ma TTG (Nutman et al. 1999) by up to 40% partial melting of a garnetiferous mafic source. Eu anomalies are small ($\text{Eu}/\text{Eu}^* = 0.8\text{--}1.6$).

In terms of tectonic discrimination diagrams, the c. 3850 Ma tonalites fall within the field of volcanic arc granites (VAG – Fig. 8c). As these rocks have been affected by c. 3650 Ma granulite facies, potential Rb loss must be considered. However, the Rb concentrations of these rocks overlap those of the 3810 and 3795 Ma TTG that were only ever metamorphosed to amphibolite facies conditions (Nutman et al. 1999). This suggests that any modification has not grossly altered their Rb abundances. In terms of the secular trends vs. SiO_2 (e.g. MgO , $\text{Na}_2\text{O} + \text{CaO}$, Cr, Ni and Sr), identified by Martin and Moyen (2002), Smithies et al. (2003) and Martin et al. (2005), the c. 3850 Ma rocks plot in the >3500 Ma fields predicted for their age (for example, SiO_2 vs. MgO ; Fig. 8d).

Sm and Nd isotopic analyses (see data repository xxxx for the analytical method) were undertaken only on the five 3850 Ma samples judged least modified based on field context, and characteristics of the zircon populations (abundant oscillatory zoned zircon and derived from single phase igneous protoliths). The Sm and Nd concentrations, measured isotopic compositions and calculated initial ϵ_{Nd} values are presented in data repository xxxx Table R4 and on Figure 9. The initial ratios were calculated with reference to the presently accepted Sm-Nd reference parameters for CHUR (Jacobsen and Wasserburg, 1980; Patchett et al., 2004). The error on the c. 3.85 Ga initial isotopic compositions is ≤ 0.5 epsilon units (2σ), and largely reflects the propagation of uncertainties associated with spike calibration and long term reproducibility of standards, rather than in-run measurement precision, which is typically better than 10 ppm. The Nd concentrations are 8.70 to 40 ppm. The measured isotopic compositions ($\epsilon_{\text{Nd}(0)} = -37$ to -47) reflect the great age and LREE-enriched character of the gneisses. Four of the samples have initial compositions (calculated using the zircon age) overlapping within errors ($\epsilon_{\text{Nd}(3.85)} = +2.9$ to $+3.6$) with one sample (G93/05) having a lower initial value of $\epsilon_{\text{Nd}(3.85)} = +0.6$ (Fig. 9).

The Eoarchaeon destruction of c. 3850 Ma quartzofeldspathic rocks – migmatites, zircon xenocrysts and detrital grains

C. 3850 Ma rocks that are almost homogeneous are extremely rare in the Itsaq Gneiss Complex. These are regarded as small domains that fortuitously survived the high strain, neosome production and pegmatite veining during polyphase Archaean tectonothermal events, which converted most of the Itsaq Gneiss Complex into banded multi-age component migmatites (McGregor, 1973; Nutman et al. 1996, 2000, 2002). This section describes the migmatisation, which produced rocks of mixed age and origin, ultimately leading locally to c. 3650 Ma granites *sensu stricto* that can carry older xenocrystic zircon. Also reviewed are the occurrences of c. 3850 Ma detrital zircons in c. 3806 Ma Isua sediments, interpreted to have been derived from erosion of 3850 Ma rocks.

G93/07 – representing rocks that are almost homogeneous but contain some in situ melt patches

The protolith characteristics of samples in this category are not as well preserved as G01/113 in terms of their degree of lithological homogeneity, and their zircons show a greater degree of recrystallisation. Zircon data for tonalite sample G93/07 with some nebulitic segregations are presented here. G93/07 is from a small island south of Akilia that is dominated by banded tonalitic gneisses. The sample locality (63°55.03'N, 51°40.89'W) is at the far top right of Fig. 5a and the texture of the sampled rock is shown as an insert into the field photograph. Within the zone from which the sample was taken, the Ameralik dykes are strongly discordant and crosscut plutonic relationships in the Itsaq Gneiss Complex country rocks. The dominant lithology is meta-tonalite traversed by irregular felsic veins and nebulous patches, some of which contain blocky aggregates of hornblende (bottom of Fig. 5a) that from textural arguments (criteria in McGregor and Friend, 1997) we interpret to be secondary after metamorphic orthopyroxene. Therefore these tonalites display the affects of high-grade migmatisation probably under granulite facies conditions, but because of the locally very low strain, the amount of migmatisation veins and patches could be minimised (but not entirely excluded) when sampling. Because of unusually low strain, it is clear that tonalites represented by G93/07 intrude and break-up older mafic and ultramafic rocks (Fig. 5a).

G93/07 yielded prismatic to bipyramidal lilac zircons. In CL images the grains consist of interiors with strong oscillatory-zoning, and with mantles of generally brighter (lower U) zircon that are weakly zoned to homogeneous ([data repository xxxx for CL images in Fig. R2a](#)). Some grains are dominated by 3850 Ma zircon with strong oscillatory-zoning, with only an incomplete mantle of younger zircon present. In other grains outer mantles are more volumetrically dominant (e.g. grain 3), and in some cases are clearly formed by replacement of the zoned interior (e.g. grain 9, [data repository xxxx Fig. R2a](#)). The strongly zoned zircons yielded close to concordant dates ([data repository xxxx Table R1](#), Fig. 6b), with a weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ date of 3852 ± 12 Ma (MSWD=0.93). Mantles of less strongly zoned to homogeneous zircon yielded younger ages and lower Th/U. These were not examined in as much detail with SHRIMP as the strongly zoned zircon, but from the available data, it would appear that 3740-3700 and 3650-3600 Ma zircon is present. Our preferred interpretation of these results is that tonalite G93/07 is c. 3850 Ma old, but that during later Eoarchaeon metamorphic events and development of nebulitic patches in the rock, zircon was subjected to recrystallisation and regrowth.

Migmatites and inheritance-bearing neosome

Sample G88/66 is a banded migmatitic gneiss from southwestern Akilia (see Fig. 9a of Nutman et al. 2000), and was the first proposed (albeit poorly-preserved) c. 3850 Ma rock in Greenland. In our interpretation, this gneiss contains a c. 3850 Ma component, but has been overprinted at c. 3660 Ma by development of neosome and/or veining and then strongly deformed and metamorphosed several times until late in the Archaean (Nutman, 1990; Nutman et al. 1996, 2000 and Friend and Nutman, 2005a). Here data on three additional banded gneiss samples are presented: G01/109 is a quartz diorite ([data repository xxxx Table R1](#)) with sparse veins deformed into a banding. VM95/02 and G05/39 are strongly deformed, polyphase, banded migmatites rich in neosome and palaeosome respectively. G01/109 comes from the same island c. 1km west of Akilia that yielded sample G01/113. It was collected at (63°55.83'N, 51°43.85'W) from a c. 5 m wide tract of gneiss that contains inclusions of amphibolite and (clinopyroxene-rich) skarn (Fig. 5b), suggesting that its igneous protolith was intruded into a mafic supracrustal(?) host. G01/109 is well foliated and is heterogeneous due to felsic segregations and mafic schlieren.

G01/109 gave a small yield of lilac-coloured zircons. About 90% of the grains are prismatic in habit, with the remainder being equant. CL imaging shows that the prismatic grains have oscillatory zoning parallel to the grain exteriors, but that the zoning has been widely disrupted by discordant recrystallisation domains ([data repository xxxx Fig. R2b](#)). Most grains have skins of less zoned zircon, ranging from a few microns on prismatic faces to more on pyramidal ones. Equant grains have internal structure dominated by sector zoning. Twenty-eight SHRIMP U-Pb analyses were undertaken on eighteen grains and all yielded close to concordant ages. Of these, nineteen were analyses of oscillatory-zoned zircon that yielded $^{207}\text{Pb}/^{206}\text{Pb}$ dates between c. 3850 and 3600 Ma (Table 1; Fig. 6c). Three analyses in grain 5 of oscillatory-zoned zircon displayed the same age spread. Therefore we interpret the zoned zircon as having a single age, but to have been variably disturbed through some loss of radiogenic Pb in the Eoarchaeon. Using this interpretation, seven analyses with the highest $^{207}\text{Pb}/^{206}\text{Pb}$ dates yield a weighted mean age of 3829 ± 10 Ma (95% confidence, MSWD=0.52). This is taken as the best estimate of the minimum protolith age of G01/109. Two rim analyses on prismatic grain 8 gave indistinguishable $^{207}\text{Pb}/^{206}\text{Pb}$ dates at c. 3650 Ma, whereas all seven analyses of equant sector zoned zircons gave a weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ date of 3619 ± 16 Ma (95% confidence, MSWD=1.5). The disturbance of U/Pb data from oscillatory-zoned zircon grains, coupled with CL images, indicates recrystallisation and new zircon growth in Eoarchaeon tectonothermal events.

In the fjord Itilleq and on the semi-nunatak Ivisaartoq (Fig. 1), reconnaissance geological mapping has long recognised the presence of Eoarchaeon gneisses (Allaart et al. 1977; Hall and Friend, 1979). These have been scientifically neglected compared with the gneisses of Akilia and surrounding islands in the southwest, and the Isua area in the north. The banded gneiss sample (VM95/02), as the first reconnaissance zircon dating samples from Itilleq, was deliberately collected (by the late V. R. McGregor) in contact with an Ameralik dyke, in order to give the clearest possible field setting (Fig. 5c). The banded gneiss sample contains a large amount of strongly deformed neosome, and indicates that an older component was either subjected to *in situ* incipient partial melting or was veined by granitic material, prior to strong deformation that transformed it into banded gneiss.

In keeping with the migmatitic nature of the rocks, VM95/02 zircons are structurally complex (e.g. [data repository xxxx CL images in Fig. R2c](#)). CL imaging shows that oscillatory zoned cores and rims are present in some grains, whereas in other grains only one generation of oscillatory-zoned zircon is present. Discordant recrystallisation domains that appear homogeneous in CL images disrupt oscillatory zoning. In addition some outermost (partial) rims that appear homogeneous in CL images are present.

Twenty-four SHRIMP U/Pb analyses were undertaken on seventeen zircons ([data repository xxxx Table R1](#)). Seventeen analyses yielded slightly discordant ages, whereas only seven are concordant (Fig. 6d). In addition some have strongly discordant ages and are not considered here. Two cores identified in the CL imaging, have $^{207}\text{Pb}/^{206}\text{Pb}$ dates of >3800 Ma (grain 4, [data repository xxxx Fig. R2c](#)). Most analyses from grains with only a single generation of oscillatory-zoned zircon (grain 6, [data repository xxxx Fig. R2c](#)), or from oscillatory-zoned rims in composite grains, yield a bimodal distribution of $^{207}\text{Pb}/^{206}\text{Pb}$ ages with “peaks” at c. 3665 Ma and 3625 Ma. Thus the sample contains two, or perhaps three, generations of oscillatory-zoned zircon, in keeping with the interpretation in the field of this as a composite gneiss with some palaeosome (>3800 Ma) in more abundant neosome (3660-3600 Ma).

Banded gneiss sample G05/39 from Ivisaartoq (Fig. 1) also yielded complex zircons like VM95/02, with oscillatory-zoned zircon forming the interior of grains. Grain exteriors consist of homogeneous to sector-zoned domains that appear brighter in CL images (lower U+Th). Most analyses gave close to concordant ages ([data repository xxxx Table R1](#); Fig. 6e). Analyses on the oscillatory-zoned zircon yielded ages mostly >3800 Ma. Repeat analyses on single grains indicated that spread in $^{207}\text{Pb}/^{206}\text{Pb}$ dates is due to variable Pb loss. Using an interpretation of variable amounts of ancient loss of radiogenic Pb from a single >3800 Ma population

applied to other samples, those analyses with the oldest apparent $^{207}\text{Pb}/^{206}\text{Pb}$ dates yielded ages of c. 3850 Ma. This is interpreted as the age of the palaeosome in this sample. Analyses of the homogeneous to sector-zoned grain exteriors yielded younger ages of mostly 3660-3600 Ma. In addition, a minority of oscillatory-zoned zircons (site 4.1, [data repository xxxx Table R1, Fig. R2d](#)) also yielded these young ages. These are interpreted to date high grade metamorphism, associated with neosome development and partial melting between 3660 and 3600 Ma.

To assess further the age profile of migmatite components within the Itsaq Gneiss Complex, reconnaissance zircon dating of samples is being undertaken from localities scattered across the parts of the complex where formerly there was little or no geochronological data (Fig. 1; [data repository xxxx Table R1](#)). In this reconnaissance programme that still continues (ultimately 80 more samples will be dated), analyses are undertaken mostly on the Hiroshima SHRIMP II instrument, with a lesser number having been performed on the ANU SHRIMP RG instrument. Analysis focuses on oscillatory zoned zircon forming the interior of grains, with a lesser number of analyses being undertaken on the more homogeneous exterior domains of the grains. The amount of oscillatory-zoned zircon varies considerably between samples. In some it is the dominant component, with only thin mantles of younger zircon, whereas in other it was restricted to volumetrically much smaller cores. Only the 5 reconnaissance samples so far where c. 3850 Ma (shorthand for 3840-3880 Ma) zircons were encountered are presented in this paper ([data repository xxxx Table R1, Figs. 1 and 6f](#)). The discovery of c. 3850 Ma components in migmatites at several new localities shows that this component is a widespread, but probably a volumetrically minor, component in the Itsaq Gneiss Complex.

Trace element geochemistry of c. 3850 Ma inherited zircon in granites and 3850 Ma detrital grains in metasediments

LA- ICP-MS trace element analyses of four c. 3850 Ma and one 3900 Ma detrital zircon in meta-quartzite G93/25 (Nutman et al. 1997b) and two analyses of a c. 3850 Ma inherited zircon core in 3660 Ma granite G97/92 (Friend and Nutman, 2005a) have been undertaken. The data are presented in [data repository xxxx Table R2 and](#) are summarised in Fig. 10. CL images (unpublished) of G93/25 detrital zircons show they are homogeneous or display oscillatory zoning. They have heavy REE at 1000 – 3000x chondritic abundances, with minor negative Eu anomalies, positive Ce anomalies and strong depletion of the other light REE. The 3900 Ma grain (grain 17, Nutman et al. 1997b) found in this metasediment is the oldest zircon yet published from the Itsaq Gneiss Complex. It has similar but slightly more LREE enriched

patterns compared to the c. 3850 Ma zircons from the metasediment. Likewise the c. 3850 Ma inherited core in 3660 Ma granite G97/92 igneous zircons shows similar REE patterns and abundances. This suggests crystallisation of these c. 3850 Ma zircons in the presence of plagioclase (negative Eu anomalies) and the absence of garnet (elevated heavy REE abundances). These are typical REE patterns and abundances for zircons crystallised in granitic (*sensu lato*) magmas and indicate that in the Eoarchaeon, erosion and intra-crustal partial melting were already destroying some 3900 to 3850 Ma sialic crust.

Discussion

Nature and extent of the c. 3850 Ma geological record in the Itsaq Gneiss Complex

All Eoarchaeon rocks (>3600 Ma) are contained in gneiss terrains, where they are intruded by younger granitoids, and all have undergone variable but generally strong polyphase ductile deformation under amphibolite or granulite facies metamorphic conditions, leading to variable degrees of *in situ* migmatisation. Thus >95% of the quartzo-feldspathic rocks in the ($\approx 3000 \text{ km}^2$) Itsaq Gneiss Complex are banded gneisses of little use for detailed modern isotopic and geochemical investigations concerning the accretion and differentiation of the oldest juvenile crust. The other <5% of the Complex, containing the less deformed and migmatised rocks that are suitable for such investigations, is largely in the Complex's northern end and consists of 3810, 3790, 3700 Ma tonalites and c. 3650 Ma granites (Nutman et al. 1996, 1999, 2000; Crowley et al. 2002; Crowley, 2003). In contrast, the presently *known* amount of well preserved c. 3850 Ma quartzo-feldspathic rock is much smaller and occurs in a few small domains of coinciding lower strain and less severe 3660-3600 Ma migmatisation (Nutman et al. 2000; 2002a; this paper). These provide a unique window back to the early Earth at 3850 Ma, pre- the formation of the Isua supracrustal rocks. Thus the "best" 3850 Ma metatonalite G01/113 retains its integrity (free of veining and *in situ* neosome) for only a few m^2 of the outcrop (Fig. 3).

Integrated field and zircon studies reported here have tracked the fate of such c. 3850 Ma tonalites during superimposed tectonothermal events, and here we propose that they are transformed into palaeosome components distributed within migmatites strongly affected by pegmatite veining and *in situ* melting between 3660-3600 Ma. As a continuation to the *in situ* melting and migmatisation, low temperature crustally-derived granites in the Itsaq Gneiss Complex can carry

inherited older zircon (e.g., grain 3 in 3661 Ma granite G97/92 dated by Friend and Nutman, 2005a). Furthermore, c. 3850 Ma detrital zircons are present in rare clastic metasediments in the Itsaq Gneiss Complex (Nutman et al., 1997b). Thus field and zircon data indicate that c. 3850 Ma quartzo-feldspathic rocks are a widespread, but probably now a volumetrically minor, component of the Itsaq Gneiss Complex.

Interpreting Nd isotopic data from 3850-3600 Ma Itsaq Gneiss Complex rocks

The Nd compositions presented here provide some of the oldest direct constraints on Nd mantle compositions, with only samples of the Acasta gneisses from the Slave Province of Northwest Canada, being older at 3900-4000 Ma (Bowring et al. 1989; Bowring and Housh, 1995). The new data fall within the same range, but with a narrower spread of compositions than previously presented for >3700 Ma rocks from the Itsaq Gneiss Complex (Bennett et al, 1993, Jacobsen and Dymek, 1988) (Fig. 10). The greater homogeneity apparent in the more recent data set may at least partly reflect more stringent selection criteria than previously employed. It is likely that some earlier data, for example the widely-studied banded gneiss sample 110999 (collected in the early 1970s) with $\epsilon_{\text{Nd}(3.82\text{Ga})}=+0.1$ and for 90-532, the single sample of Bennett et al. (1993) with an apparent negative initial ϵ_{Nd} , may reflect the effects of mixing of two or more gneiss components (Nutman et al., 2004b), although further work is necessary for verification. The data set for the 16 samples of >3700 Ma gneisses (with the one exception of sample 90-532), including the data for the 3850 Ma gneisses presented here, have a limited range of initial compositions, from 0 to +4.5. There is no evidence for the degree of mantle heterogeneity suggested by Nd isotope data from the slightly older Acasta gneisses (Bowring and Housh, 1995) with apparent initial ϵ_{Nd} (4.0 Ga) from +3.5 to -4.8. The lack of negative ϵ_{Nd} values in the tonalites of the Itsaq Gneiss Complex is complementary with the absence of much older zircons in the Complex and with the lack of negative initial ϵ_{Hf} (e.g. Vervoort et al, 1996) in them. On the other hand, the Acasta gneisses contain rare, significantly older Hadean zircon xenocrysts (Iizuka et al., 2006). All of these observations indicate that there was not a widespread significantly older (>3850Ma) felsic component in the sources of the Itsaq Gneiss Complex samples.

The uniformity of the isotopic data obtained from the c. 3850 Ma suite (apart from G93/05), in terms of both initial ϵ_{Nd} values and narrow range of measured

$^{147}\text{Sm}/^{144}\text{Nd}$, shows the likely consanguineous nature of these rocks. There are several possible explanations for the lower ϵ_{Nd} value of G93/05. First and foremost, the slightly lower ϵ_{Nd} of this sample as compared to the other four tonalites, may accurately reflect the source composition of the rock and indicate some mantle heterogeneity i.e. that the mantle source of this sample was less LREE depleted than that of the other samples. Other possibilities suggested may arise from misinterpretation of the age data. Assuming that the rock is only c. 3650 Ma old, with nearly all its zircon inherited, as suggested by Whitehouse and Kamber (2005), will result in the calculation of a spurious ϵ_{Nd} value at 3850 Ma. Another possibility, using our interpretation that this rock is c. 3850 Ma old, is that G93/05 was derived entirely, or at least in part, by melting of a LREE-enriched protolith appreciably older than 3850 Ma. This would be a hint that some extremely ancient (>4000 Ma) crust might have been present when some of the oldest parts of the Itsaq Gneiss Complex were formed. Finally, despite the most careful sample screening, if there was minor alteration of the Sm/Nd ratio during superimposed tectonothermal events, the calculated initial ϵ_{Nd} of this rock could be inaccurate. Nonetheless, there is much greater uniformity in our Nd isotopic data set than that obtained on polyphase migmatites such as the Acasta gneisses (Bowring and Housh, 1995; Moorbath et al., 1997). Dispersion in the initial ϵ_{Nd} values for Acasta gneisses may be due either to secondary Sm/Nd disturbance during younger superimposed tectonothermal events, or because several protolith components of different age and isotopic signatures (including some >4.0 Ga crust – Iizuka et al., 2006) are present in the samples. Clearly, working on well-preserved sets of rocks such as our “best” tonalites preserved here, generate isotopic data that are more concise and readily interpretable than data obtained from polyphase migmatites.

Depletion history of the pre-3850 Ma mantle from ^{147}Sm - ^{143}Nd isotope systematics

Initial Nd isotopic compositions reflect the time-integrated Sm/Nd ratio of the gneiss source(s) that in turn reflects the average degree of lithophile element depletion or enrichment. The degree of the depletion of the mantle in the first billion years of Earth history as recorded in the initial $^{143}\text{Nd}/^{144}\text{Nd}$ compositions of the oldest rocks has long been recognised as a key constraint for models of the early differentiation of the Earth (e.g. Jacobsen and Wasserburg, 1979; Galer and Goldstein, 1991). Owing to the significance of the results for interpreting early Earth history, there has been much controversy and debate over the meaning of

the data from the oldest rocks. Earlier aspects of this debate centred on uncertainties in the crystallisation ages used to calculate initial compositions, have now been largely eliminated through the use of modern dating methods, primarily ion microprobe U-Pb dating of single zircons combined with the use of CL imagery. The controversy has focussed more recently on the veracity of calculated initial compositions because of the potential of secondary resetting of isotopic systems including Sm-Nd (e.g. Gruau et al. 1996). An additional aspect when using felsic rocks to determine mantle compositions is that, in general, granitoids in any tectonic setting have a range of initial isotopic compositions reflecting the complexity of granite forming processes. For example Phanerozoic batholiths (e.g. Sierra Nevada Batholith) that have not experienced deformation or metamorphism, and have well defined ages, show a range in ϵ_{Nd} , from near depleted mantle values to those of the compositions of the oldest crust in the area (DePaolo, 1981). The samples with the most positive ϵ_{Nd} values are generally taken as most representative of the mantle, but the less positive values are not in error, but reflect a mixture of source materials.

Although much has been said about the potential role of secondary Sm/Nd modification leading to the calculation of erroneous initial compositions, recent studies suggest that careful sample selection can minimise these effects. For example, Baxter and DePaolo (2004) demonstrated that even during severe metamorphism mobility of Sm and Nd in solid systems is only on the cm scale. Thus single-phase gneisses, such as the “best” samples that we have presented in this paper, should be able to preserve Sm-Nd systematics, when sampled and prepared carefully. Therefore we are confident that the ^{143}Nd database for the oldest, single-component, homogeneous felsic samples provides strong evidence for strong early differentiation of the pre-3850 Ma mantle.

As has been discussed in numerous papers (e.g. Bennett et al., 1993; Caro et al., 2003), that generating $\epsilon_{\text{Nd}} = +3$ before 3850 Ma in the upper mantle source of the ancient tonalites requires rapid early depletion (increase in Sm/Nd). Mechanisms suggested to create a high Sm/Nd upper mantle in the early Earth include production of voluminous amounts of early continental crust (first proposed by Armstrong; 1981 and more recently advocated by Bowring and Housh; 1995 and Harrison et al.; 2005), early formation of a LREE-enriched basaltic crust (Chase and Patchett 1988) and formation of early, deep mantle reservoirs (e.g. Tolstikin and Hofmann, 2005). Additional support for deep reservoir models comes from recent ^{142}Nd results showing apparent distinctions between the Earth and chondrites (Boyet and Carlson, 2005) implying rapid early global Earth differentiation.

Country rocks to c. 3850 Ma tonalites

Tonalites do not represent primary crust produced by directly melting the mantle. Instead, they are secondary crust, and are mostly considered to be produced by melting of hydrated mafic crustal rocks in the stability field of garnet (Martin et al. 2005 and references therein). Therefore the 3850 Ma tonalites described here must have been intruded into older crustal rocks. The most common host for tonalites throughout the Archaean geological record of the whole world are mafic rocks, derived largely from meta-basalts with some gabbros (McGregor, 1973 onwards). In accordance with this, Nutman et al. (1997a, 2000, 2002, this paper) have presented field evidence (discordant relationships) at localities, including Akilia, that indicate c. 3850 Ma tonalites were intruded into older mafic rocks, with rare layers of silica- and iron-rich rocks (Fig. 4; Nutman et al. 1997, 2000, 2002). On Akilia these silica- and iron-rich rocks display an iron isotopic signature (Dauphas et al. 2004) and trace element spectra identical to that observed in Isua supracrustal belt banded iron formations (Friend et al. in press). Thus in our interpretation, the Itsaq Gneiss Complex contains rare ≥ 3850 Ma mafic and sedimentary rocks that are older than those in the Isua supracrustal belt, and hence the oldest known on Earth. However, it should be noted that others contest this interpretation (e.g. Whitehouse and Kamber, 2005).

Conclusions

(1) The state of preservation of 3850 Ma quartzo-feldspathic rocks ranges from geochemically modified palaeosome within polyphase migmatites to near-homogeneous tonalites and quartz-diorites. A few samples of the latter are the best candidates to examine the formation of the oldest portions of quartzo-feldspathic crust in Greenland by whole rock geochemistry and Nd isotopes. We consider that tonalite G01/113 is presently the world's best-preserved "pre-Isua" (i.e. pre- 3710 and 3810 Ma) rock. The only known older terrestrial quartzo-feldspathic rocks are rare migmatite components in the Acasta Gneisses (Bowring et al., 1989; Bowring and Williams 1999) and at Mt Sones in Antarctica (Black et al., 1986).

(2) Detrital 3850 Ma zircons in rare clastic metasediments from the Isua supracrustal belt display negative Eu anomalies in their chondrite-normalised REE patterns, with the heavy REE showing chondrite-normalised values of c. 1000. Combined with the

oscillatory zoning displayed by some of these zircons, it is likely that they were derived from c. 3850 Ma quartzo-feldspathic igneous rocks that were destroyed by Eoarchaeon erosion.

(3) The amount of c. 3850 Ma quartzo-feldspathic crust detected in the Itsaq Gneiss Complex, on the basis of present information, is volumetrically much less than the 3810-3790, 3760-3740 and 3700-3690 Ma tonalite suites.

(4) Initial ϵ_{Nd} values determined from the five best preserved 3850 Ma rocks demonstrate a narrow range of compositions. These data provide strong evidence for a mantle value of $\epsilon_{Nd} = +3$ at 3850 Ma and strengthen arguments for rapid early depletion of at least portions of the upper mantle (e.g. Bennett et al, 1993; Caro et al., 2003). The major and trace element compositions of these tonalites are similar to other Archaean TTG suites both in West Greenland (Nutman et al, 1999) and worldwide (e.g. Martin et al, 2005) indicating continuity of TTG crust formation processes throughout the Archaean.

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Figure captions

Figure 1. Sketch geological map of the Itsaq Gneiss Complex in the Nuuk region, southern West Greenland, showing location of samples discussed.

Figure. 2. Summary of zircon age determinations from the Itsaq Gneiss Complex. Each date on the histogram is based on multiple zircon analyses, with a total of at least 2500 individual zircon analyses.

Figure 3. (a) Field setting of meta-tonalite sample G01/113. (b) Sample G01/113, coin is 1 cm diameter.

Figure 4. (a) CL images of zircons from G01/113. Grain 16 is the only grain out of c. 140 mounted that has a rim broad enough ($>10\text{ }\mu\text{m}$) for SHRIMP analysis. The dark spots on the grains labelled a,b,c are pits created by LA-ICP-MS analysis. Site * is a mark on a grain made when checking the position of the laser beam, but no analysis was made. (d) CL images of zircons from c. 3810 Ma metatonalite sample G97/18 from near Isua (after Nutman et al., 1999). SHRIMP analysis sites are shown by white ellipses and $^{207}\text{Pb}/^{206}\text{Pb}$ dates are given with analytical errors at the 2σ level.

Figure 5. Variable state of non-homogeneous rocks from the Itsaq Gneiss Complex with c. 3850 Ma zircons. (a) G93/07 weakly deformed metatonalite with some nebulitic felsic segregation patches. (b) G01/109 weakly banded gneiss with some pegmatites. (c) VM95/02 neosome-rich migmatite.

Figure 6. $^{238}\text{U}/^{206}\text{Pb}$ vs. $^{207}\text{Pb}/^{206}\text{Pb}$ concordia diagrams with errors depicted at the 2σ level. On the right hand side of each frame is shown the cumulative probability distribution for $^{207}\text{Pb}/^{206}\text{Pb}$ of the data set.

Figure 7. Laser ablation ICP-MS analysis profiles 3A and 10C through the edges of 2 zircons in metatonalite G01/113 (a) $^{207}\text{Pb}/^{206}\text{Pb}$ date age and (b) Th/U ratio. Typical error on the $^{207}\text{Pb}/^{206}\text{Pb}$ date for each 2.5s segment is $\pm 50\text{ Ma}$ (2σ – C. Allen personal communication, 2006).

Figure 8. Whole rock geochemistry. On frames a, b and c filled diamonds are “best” 3850 Ma samples, open triangles are c. 3795 and 3810 Ma Itsaq Gneiss Complex TTG (Nutman et al., 1999) and the open square is average value for $>3500\text{ Ma}$ TTG from Martin et al. (2005). (a) $\text{Al}_2\text{O}_3/\text{CaO}+\text{Na}_2\text{O}+\text{K}_2\text{O}$ vs $\text{Al}_2\text{O}_3/\text{Na}_2\text{O}+\text{K}_2\text{O}$ plot demonstrating metaluminous character of 3850 Ma rocks. (b) primitive mantle normalised REE plots (McDonough and Sun, 1995). (c) Y+Nb vs Rb discrimination plot demonstrating Volcanic Arc Granite (VAG) character. (d) SiO_2 vs MgO plot showing that the 3850 Ma rocks plot in the field of $>3500\text{ Ma}$ TTG of Martin et al. (2005).

Figure 9. Initial ϵ_{Nd} calculated at the crystallization age for 3850-3800 Ma felsic rocks Itsaq Gneiss Complex (includes data from Bennett et al, 1993). Only data for samples where there is independent age determinations by U-Pb zircon dating are included. The values for the c. 3850 Ma samples show a narrow range of positive ϵ_{Nd} .

Figure 10. Laser ablation ICP-MS chondrite-normalised REE analyses for (a) detrital grains from metaquartzite G93/25 and (b) inherited 3850 Ma zircon core in 3660 Ma granite G97/92.

2560 Ma Qôrqut
Granite Complex

regional Neoarchaean
mylonites - along which
terrane were assembled

ortho-
gneisses

Neo- Meso-
Archaean
terrane
(different
ages in
each terrane)

ortho-
gneisses

Itsaq Gneiss Complex;
terrane of
3600-3870 Ma
rocks (only
the largest
supracrustal
units are shown)

F=Færingehavn
I=Isukasia

G91/xx discussed zircon-dated sample

SHRIMP-U/Pb zircon dating of
Itsaq Gneiss Complex
tonalitic orthogneiss components

no significant
3600-3660 Ma
migmatisation

tonalite date

significant
3600-3660 Ma
migmatisation

▲ 3840-3870 Ma ▲
◆ other age groups ◆
3660-3820 Ma

due to space restrictions - multiple samples at
closely-spaced localities are not shown

Nutman et al. Fig. 2