Vestiges of life in the oldest Greenland rocks? A review of early Archean geology in the Godthåbsfjord region, and reappraisal of field evidence for >3850 Ma life on Akilia

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Abstract

The Godthåbsfjord region of West Greenland contains the most extensive, best exposed and most intensely studied early Archean rocks on Earth. A geological record has been described of numerous magmatic events between ~3.9 and 3.6 Ga, and evidence of life at >3.85 Ga and ~3.8–3.7 Ga has been proposed from two widely-separated localities. Some of these claims have recently been questioned, and the nature of the best preserved remnants of the oldest known terrestrial volcanic and sedimentary rocks in the Isua greenstone belt are being reinvestigated and substantially reinterpreted. The first part of this article reviews the evolution of geological research and interpretations, outlining the techniques by which the geological history has been determined and the ensuing controversies. The second part re-examines crucial field evidence upon which the antiquity of the oldest terrestrial life is claimed from the island of Akilia. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

The Godthåbsfjord region lies in the centre of the Archean gneiss complex on the west coast of Greenland in the vicinity of Nuuk (Fig. 1, inset map). Most of the Archean gneiss complex is derived from sheets of tonalite and granodiorite, and a small amount of granite and diorite, that were intruded into basaltic volcanic rocks and minor sedimentary rocks during the late Archean. These rocks were repeatedly deformed and metamorphosed, developing gneissosity that was folded, refolded and transposed into new tectonic layering, and recrystallizing during and after deformation at amphibolite or granulite facies (Bridgwater et al., 1976).

In a belt 25–75 km wide, extending for 200 km through Godthåbsfjord (Fig. 1), similar late Archean plutonic rocks were intruded into, and tectonically interleaved with, early Archean tonalitic and granodioritic gneisses, and both early and middle Archean metavolcanic and metasedimentary schists and gneisses.

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The first part of this article (Sections 2–4) reviews knowledge of the early Archean rocks that formed before \( \sim 3600 \) Ma, synthesizing previous observations and interpretations, and outlining current controversies. Most of the early Archean rocks were intensely, and repeatedly, de-
formed and metamorphosed at high grade during late Archean events and, except in the vicinity of Isua, the present structure and appearance largely reflect these late Archean events (cover of Precambrian Research, this volume). Therefore a brief outline of the late Archean tectonic evolution is included in this review (Section 5), indicating current interpretations of how the early Archean rocks were intruded by, and tectonically interleaved with, younger Archean rocks.

The second part of this article (Section 6) re-examines the field evidence from the island of Akilia upon which the antiquity of life is claimed to be \( \geq 3800 \) Ma (Mojzsis et al., 1996) and \( \geq 3850 \) Ma (Nutman et al., 1997a; Mojzsis and Harrison, 2000), in the vicinity of the gneiss shown on the cover of Precambrian Research (this volume).

2. Pioneering studies in outer Godthåbsfjord

Current understanding of the geology stems from the pioneering work of Berthelsen (1955) and McGregor (1966, 1968, 1973), who demonstrated that basic dykes could be used as field criteria to subdivide the Archean gneisses into older and younger components. The basic dykes cut across older rocks, structures and gneissosity, and are cut by younger granitoid rocks that were subsequently deformed, metamorphosed and converted to gneisses.

This technique had previously been developed in gneiss complexes elsewhere, especially in northwest Scotland by Peach et al. (1907) and Sutton and Watson (1951), and in southern Finland by Sederholm (1923, 1926) and Wegmann (1931). Wegmann (1938) introduced this concept to southern Greenland, distinguishing major tectonic and metamorphic episodes (subsequently recognized as Archean and Proterozoic) on the basis of intervening dyke swarms. During field studies between 1946 and 1955, Ramberg (1948) and Noe-Nygaard and Ramberg (1961), assisted by Berthelsen, applied this concept further north and presented the first fundamental subdivision of the Precambrian gneiss complex from Godthåbsfjord northwards for 600 km. They used early Proterozoic dykes to distinguish unmodified Archean rocks cut by undeformed dykes from Archean rocks and dykes that were deformed and metamorphosed during the early Proterozoic.

Berthelsen and McGregor were the first to use basic dykes to distinguish between Archean tectonic, magmatic and metamorphic events in Greenland. Berthelsen (1955) recognized that basic dykes could be used to distinguish between older and younger geological events in the southeastern part of the island of Qilângârsuit (Fig. 1). McGregor (1966, 1968, 1973), during a detailed investigation of the gneisses in the vicinity of Nuuk (formerly Godthåb and Núk) between 1965–71, discovered that these basic dykes could be used as a regional mapping criterion separating older from younger events. McGregor (1968) called the dykes Ameralik dykes and recognized that intense deformation had severely modified the original structure of the dykes and their host rocks such that most dykes and host rocks were rotated into a new common gneissosity (e.g. cover of Precambrian Research, this volume). Cross-cutting relationships were preserved only in small areas of relatively low strain. Likewise, McGregor (1973) described how the cross-cutting relationships of granitoid rocks that were intruded after the dykes were also widely obliterated by intense deformation that rotated most components of the gneiss complex into subparallel layers.

Many were sceptical of McGregor’s interpretation, and some considered metamorphic grade to be a key indicator of the relative age of rocks and events. Based on a wider regional survey of the Archean gneisses of West Greenland, Windley (1968, 1969) regarded the linear NNE-trending belt of amphibolite facies gneisses in the Godthåbsfjord region, including the gneisses described by McGregor, as derived by tectonic reworking and retrogression of older granulite facies gneisses to the north and south. He considered that the Ameralik dykes of McGregor (1968) cut older granulite facies gneisses to the south of Ameralik (Fig. 1) and ‘can be followed… into the linear belts where they become progressively deformed and migmatised’ (Windley, 1969, p. 159). Thus, in contradiction of McGregor’s hypothesis, the dykes and relatively straight NNE-trending belt of highly deformed amphibolite facies
gneisses through Godthåbsfjord were interpreted as younger than regional granulite facies metamorphism. However, McGregor’s hypothesis was subsequently supported by geochronology. Black et al. (1971) discovered that the whole rock Rb–Sr and Pb–Pb isochron ages of gneisses that were cut by Ameralik dykes in the Godthåbsfjord belt were one billion years older than regional granulite facies metamorphism, and were far older than any other terrestrial rocks known at that time.

Black et al. (1971) called the rocks that were older than the Ameralik dykes ‘Amitsq gneisses’ and discovered that they were characterized by extremely unradiogenic whole-rock lead isotopes. They described the sequence of events following the intrusion of the Ameralik dykes as: eruption of basic volcanic rocks (now mostly amphibolite) and deposition of sedimentary rocks (mainly quartz-biotite-garnet schist), collectively called Malene supracrustals by McGregor (1969); tectonic interleaving with the Amitsq gneisses; emplacement of stratiform anorthosites; and syntectonic intrusion of a large volume of calc-alkaline rocks that were deformed and metamorphosed to become gneisses that they called Nûk gneisses. The protoliths of the Nûk gneisses were largely intruded as sills and were further interleaved with all the older rocks by tectonic processes, producing a complex tectono-stratigraphy (Bridgwater et al., 1974).

Isotopic ages of the gneisses were extensively studied during the 1970s. Protolith ages of the Amitsq gneisses were found to range between ~3.8–3.65 Ga and those of the Nûk gneisses between ~3.0–2.8 Ga. Results included Rb–Sr whole rock isochrons of ~3.75 (Moorbath et al., 1972), Pb–Pb whole rock isochrons of ~3.62 Ga (Black et al., 1971) and ~3.8 Ga (Moorbath et al., 1975), and U–Pb discordia upper intercepts of ~3.65 Ga from bulk zircons (Baadsgaard, 1973) and single zircons (Michard-Vitrac et al., 1977). Ages of Nûk gneisses determined during the 1970s included Rb–Sr whole rock isochrons of ~3.04 Ga (Pankhurst et al., 1973) and ~2.93–2.78 Ga (Moorbath and Pankhurst, 1976).

Complications in the use of amphibolite dykes as time markers between Amitsq and Nûk gneisses were highlighted by Coe et al. (1976) and Chadwick and Coe (1983) who discovered intra-Nûk dykes (Neriuneq and Qaqatsiaq dykes) south of Ameralik (Fig. 1), broadly similar in appearance to many Ameralik dykes. Chadwick (1981) described another, smaller and more controversial group of dykes he called Tinissaq dykes, thought to be intruded into an early phase of Nûk gneisses. On the island of Qilângârsuit to the west (Fig. 1), Chadwick (1981) recognized eight types of Ameralik dykes intruded into Amitsq gneisses and two types of amphibolite dykes, ‘similar to two main categories of Ameralik dykes’ (ib. cit. P. 221) cutting the Malene supracrustals. Chadwick (1981), pp. 223–224) concluded that ‘limited evidence of dyke intersections suggests some Ameralik dykes may be older than the Malene supracrustal rocks, and others, including Malene dykes, may have been injected after the tectonic interleaving’ of Amitsq gneisses and Malene supracrustals.

The Malene supracrustals were thought to have been deposited on Amitsq gneisses (after 3600 Ma) before the intrusion of Nûk gneisses at 3070 Ma (Chadwick and Nutman, 1979; Nutman and Bridgwater, 1983). However, U–Pb studies of metasedimentary rocks within the Malene supracrustals by Schiøtte et al. (1988) delineated a range in the age of detrital zircons from ~2900 to 2650 Ma. They found some rocks with < 2800 Ma detrital zircons, younger than Nûk gneisses and high grade regional metamorphism at ~2800 Ma. Therefore ‘the concept of the Malene supracrustals as a single lithostratigraphic unit’ was found to be ‘no longer valid’ (Schiøtte et al., 1988, p. 56). This work also indicated a more prolonged and complex sequence of late Archean tectonic, magmatic and metamorphic events than previously recognized.

The Amitsq gneisses contain small bodies of highly metamorphosed basic, ultrabasic and sedimentary rocks that were first described, and called the Akilia association, by McGregor and Mason (1977). They stated that ‘one of the largest and best exposed occurrences… is on the southwestern tip of the island of Akilia. This is designated the type locality for the Akilia association, an informal term introduced here for all the enclaves of
older rocks in the Amitsq gneisses in the Godthåb region with the exception of those in the Isua supracrustal belt (p. 889). The geology and current controversies of southwestern Akilia (Fig. 1) are described later in this paper (Section 6).

In this region south of Nuuk, the Akilia association and the main, older, components of the Amitsq gneisses were metamorphosed to granulite facies at \(\sim 3600\) Ma (Griffin et al., 1980). The original extent, and tectonic and magmatic context, of this metamorphism are unknown.

The Isua supracrustal belt (Isua greenstone belt of Appel et al., 1998) (Fig. 1) was considered by McGregor and Mason (1977) to be an exceptionally large, temporal equivalent of the Akilia association, at lower metamorphic grade and with a well preserved stratigraphy.

3. Isua

The metavolcanic and metasedimentary rocks at Isua were initially thought to be Proterozoic (Windley, 1969) because of their relatively low metamorphic grade and a K/Ar whole rock age of \(1940 \pm 50\) Ma on a ‘low-grade metabasic’ rock ‘forming…sills in the weakly metamorphosed quartzitic component’ (Lambert and Simons, 1969, p. 69). However, Moorbath et al. (1972) obtained a Rb-Sr whole rock isochron of 3700 \(\pm 140\) Ma on the adjacent tonalitic gneiss (subsequently recalculated to 3640 \(\pm 50\) Ma, see Moorbath and Whitehouse, 1996), and a whole rock Pb-Pb age of 3760 \(\pm 70\) Ma on a banded iron formation (Moorbath et al., 1973) (subsequently recalculated to 3710 \(\pm 70\) Ma, see Moorbath and Whitehouse, 1996), indicating that this greenstone belt comprised the oldest known metavolcanic and metasedimentary rocks on Earth. Bridgwater and McGregor (1974) outlined the main features of the geology and postulated that the well-preserved metadolerite dykes cutting the Isua greenstone belt and adjacent tonalitic gneiss were equivalent to the Ameralik dykes.

Recognition of the extreme antiquity of the metavolcanic and metasedimentary rocks at Isua led to a spate of diverse research during the 1970s and early 1980s. This research included stratigraphy and sedimentology (Dimroth, 1982; Nutman et al., 1984), structure (James, 1976), petrology, mineralogy and geochemistry (Schidlowski et al., 1979; Gill and Bridgwater, 1979; Gill et al., 1981; Boak et al., 1983; Nutman and Bridgwater, 1986), metamorphism (Boak and Dymek, 1982), geochronology (Moorbath et al., 1975; Baagaard, 1976; Michard-Vitrac et al., 1977; Hamilton et al., 1978), oxygen and sulphur isotope studies (Oehler and Smith, 1977; Oskvarek and Perry, 1976; Perry and Ahmad, 1977) and organic chemistry (Nagy et al., 1975). The supracrustal rocks and adjacent tonalitic gneisses were mapped and described by Allaart (1976), Nutman et al. (1984) and Nutman (1986).

Many interpretations from this era of research have since been questioned and many fundamental aspects of the geology remain controversial.

Claimed discoveries of early life by Walters, 1979, cited in Nagy et al., 1981) based on hydrocarbons, and ‘yeast-like microfossils’ called Isuaspheara by Pflug (1978) and Pflug and Jaeschke-Boyer (1979), were refuted by Nagy et al. (1981) and Bridgwater et al. (1981) respectively, on the grounds that these claims were incompatible with the highly deformed and metamorphosed state of the rocks.

More extensive controversy has ranged over the interpretation of rocks claimed to be of sedimentary origin, especially conglomerates and sedimentary carbonates that were interpreted as indicating shallow-water deposition (Dimroth, 1982; Nutman et al., 1984; Nutman, 1986). Rose et al. (1996) and Rosing et al. (1996) demonstrated that the carbonates are largely of metasomatic origin, and Fedo (2000) has reinvestigated the conglomerates and associated clastic rocks and reviewed the controversies about their origin.

Recently, there have been fundamental reinterpretations of the original nature of the rocks that comprise most of the Isua greenstone belt. Previous interpretations were based on detailed mapping by Allaart and Nutman between 1974–82 (Nutman et al., 1984; Nutman, 1986). They interpreted the greenstone belt as an upward-facing syncline on the basis of stratigraphy and small-scale way-up criteria. The mapped stratigraphy
was defined by a mixture of features including metamorphic rock types, metamorphic textures and interpreted protoliths. Studies during the 1990s, especially of the metacarbonate rocks by Rose et al. (1996) and Rosing et al. (1996), recognized that ‘most of the supracrustal rocks have undergone pervasive metasomatism, which has obscured their origin’ (ib. cit., p. 43), and questioned the significance of the stratigraphy described by Nutman et al. (1984) and Nutman (1986).

Remapping of parts of the greenstone belt in 1997–99 by Myers (2000) supports the general conclusions of Rose et al. (1996) and Rosing et al. (1996). Myers (2000) found that, although most of the rocks were intensely deformed and many were substantially altered by metasomatism, the deformation and metasomatism were heterogeneous, and transitional stages could be traced from rocks with recognizable primary volcanic and sedimentary structures into schists in which all primary features were obliterated. This mapping demonstrated that most of the Isua greenstone belt was derived from basaltic and high-Mg basaltic pillow lava and pillow lava breccia, with a smaller amount derived from chert-BIF, layered mafic-ultramafic intrusive sheets, ultramafic rocks (of autochthonous extrusive and/or intrusive origin, and/or allochthonous origin), and a minor component of clastic sedimentary rocks (see Fedo, 2000). The mapping also revealed a complex tectonic history of polyphase deformation and high grade metamorphism in which compositional layering and foliations were isoclinally folded and refolded before the greenstone belt was assembled as a number of fault-bounded packages of strongly to intensely deformed rocks. These structures and schistosities were cut by swarms of basic and ultrabasic dykes (equivalent to Ameralik dykes) and then deformed again, probably in the late Archean.

Komiya et al. (1999) also interpreted the northeastern part of the belt as a stack of fault-bounded rock packages on the basis of detailed mapping. They identified a number of duplex structures and reconstructed the lithostratigraphy as a tectonically repeated, simple upward sequence of originally low-K tholeiitic basalt, chert-BIF and turbidite. They interpreted the greenstone belt as an accretionary complex that developed in an intraoceanic environment, analogous to the late Phanerozoic tectonic evolution of Japan, and attributed most of the structural evolution of the belt to this episode of intraoceanic accretion. However, this interpretation does not appear to recognize the multiple episodes of intense regional ductile deformation, metamorphism and metasomatism, described by most other investigators such as Bridgwater and McGregor (1974), James (1976), Nutman et al. (1984), Rosing et al. (1996) and Myers (2000), that converted most of the Isua belt to schists, and formed and deformed the schistosity in the adjacent tonalitic gneiss.

The new mapping by Komiya et al. (1999) and Myers (2000) indicates that a major component of the Isua greenstone belt was derived from basaltic pillow lava, in contrast to previous detailed accounts by Nutman et al. (1984) and Nutman (1986), who described many of these rocks in terms of metamorphic textures (such as ‘garbenschiefer unit’, ib. cit., p. 15) and interpreted the protoliths as mafic intrusions (such as metagabbro, Nutman, 1997).

Another controversial major component of the Isua greenstone belt is quartz-feldspathic schist and mylonite described as felsic formations A6 and B1 by Nutman et al. (1984) and Nutman (1986), and dated as $>3790$ Ma and $\sim3710$ Ma respectively by Nutman et al. (1997b). Parts of this schist contain ellipsoidal fragments of granitoid rocks that have been interpreted as of volcanic pyroclastic origin (Allaart, 1976; Bridgwater et al., 1976; Dimroth, 1982). However, Nutman et al. (1984) and Nutman (1986) attributed the fragmentation to tectonic processes in a felsic volcanic rock. They described how the ellipsoidal fragments were located in fold hinges, and that away from fold hinges the fragments passed into tabular bodies and then continuous layers. Rosing et al. (1996) reinterpreted the supposed felsic volcanic rocks as products of ‘metasomatic alteration of intrusive Amitsoq tonalite-granite gneiss’ (p. 44). Myers (2000) described how some layers with supposed pyroclas-
tic fragments were derived from metasomatically altered basaltic pillow lavas and tectonically disrupted intrusive sheets of tonalite. In other parts of the felsic formation A6 of Nutman et al. (1984), Myers (2000) found large scale, along-strike gradations between quartzo-feldspathic schist and mylonite, and tonalitic gneiss.

Frei et al. (1999) discovered heterogeneity in late Archean metamorphic recrystallization of the Isua greenstone belt by Pb stepwise leaching of magnetite from banded iron formations. They recognized that the amphibolite facies metamorphic mineral assemblages of banded iron formations in the northeastern part of the belt developed at ~3.69 Ga. These rocks were cut by magnetite and sulphide-bearing veins associated with metasomatic alteration at ~3.63 Ga. In contrast, in the western part of the Isua greenstone belt, step leaching of magnetite from similar banded iron formations yielded a Pb–Pb isochron age of ~2.84 Ma, interpreted as the age of peak amphibolite facies metamorphism in this region.

Carbon isotopic ratios, considered to be of biogenic origin, were determined by Rosing (1999) from graphite in schistose rocks interpreted as metagraywackes in the Isua greenstone belt. These metasedimentary rocks were recognized in a lenticular zone of relatively low strain within a thick sequence of deformed amphibolite schist, mainly derived from basaltic volcanic rocks. This interpretation, and the >3700 Ma age of the graphite, remains unchallenged.

4. Numerous magmatic events between ~3870 and 3625 Ma?

Nutman et al. (1993) proposed on the basis of SHRIMP U–Pb zircon data that ‘the Amitsaq gneisses comprise 3870, 3820–3810, 3760, 3730, 3700, and 3625 Ma TTG and 3660–3650 and 3625 Ma granites, and their inclusions belong to several supracrustal sequences with a similar spread of ages’ (ib. cit., p. 415). They concluded that ‘these results show that the complex grew by episodic addition of new TTG and welding together of rocks of different ages’ (p. 415) and proposed a plate tectonic scenario.

This interpretation has been challenged in a number of papers by Kamber, Moorbath and Whitehouse. Kamber and Moorbath (1998) discussed new and published Pb isotope data for Amitsaq gneiss feldspars and whole rocks and concluded ‘that the magmatic precursors of the Amitsaq orthogneisses separated from a depleted mantle-like source at ca. 3.65 Ga’ (p. 19). They proposed that zircons described by Nutman et al. (1993, 1996) with ages significantly older than 3.65 Ga were inherited from older rocks. This conclusion was supported by cathodoluminescence imaging and ion-microprobe U–Th–Pb dating of zircons from Amitsaq gneisses by Whitehouse et al. (1999), who found ~3.8 Ga cores mantled by overgrowths at ~3.65 Ga. They interpreted the cores as inherited grains and the overgrowths as indicating the magmatic emplacement age, in contrast to Nutman et al. (1993), who interpreted similar overgrowths as metamorphic, resulting from granulite facies metamorphism first described from the same region south of Nuuk by Griffin et al. (1980). Subsequently, from a region unaffected by early Archean granulite facies metamorphism, Nutman et al. (1999) provided a detailed description of the ~3800 Ma age of little deformed metatonalites and metaquartz-diorites immediately south of the Isua greenstone belt.

Controversy also surrounds the interpretation of Sm–Nd isotopic data from the Amitsaq gneisses. Bennett et al. (1993) interpreted the wide range in initial εNd values of Amitsaq gneisses as indicating transient, highly depleted mantle reservoirs, and proposed a major change in processes between early Archean and later styles of depleted-mantle evolution. These hypotheses were challenged by Vervoort et al. (1996), Gruau et al. (1996), Moorbath et al. (1997) and Frei et al. (1999), who argued that the Sm–Nd systems, assumed to have been closed systems by Bennett et al. (1993), were modified by subsequent tectono-thermal events. This prompted substantial debate by Bennett and Nutman (1998) and Kamber et al. (1998).
5. Terranes and late Archean tectonic evolution

Detailed mapping of the geology between Tre Brødre and Ameralik (southwestern part of Fig. 1) led to the recognition of three tectonostratigraphic terranes, distinguished by different components and geological histories, that were called the Færingehavn, Tre Brødre and Tasiussarsuaq terranes (Friend et al., 1987). Regional reconnaissance studies by Friend et al. (1988) and Nutman et al. (1989) extended this concept throughout the Godtha˚bsfjord region and defined a fourth terrane (called Akia) to the north (Fig. 1). McGregor et al. (1991) subsequently combined the Færingehavn and Tre Brødre terranes into a single terrane termed Akulleq. The Akia, Akulleq and Tasiussarsuaq terranes (Fig. 1) were interpreted as originally independent rafts of continental crust, distinguished by different rock assemblages with different SHRIMP U–Pb zircon ages and metamorphic histories, that were assembled at ~2720 Ma (Friend et al., 1996).

The early Archean Amı ˆtsoq gneisses and younger Ameralik dykes are confined to the Akulleq terrane, where they are tectonically intercalated with younger metavolcanic and metasedimentary rocks and layered anorthosite complexes. During this tectonic intercalation and associated amphibolite facies metamorphism, the Akulleq terrane was intruded by granodiorite (Ikkattoq gneisses) at ~2820 Ma (McGregor et al., 1991; Nutman, 1997). Nutman et al. (1996) attributed this event to the development of the Akulleq terrane as an accretionary complex in which diverse crustal fragments accreted to the margin of a southern continent marked by the Tasiussarsuaq terrane. They envisaged that the protoliths of the Ikkattoq gneisses formed during an early stage of a 2830 and 3000 Ma dioritic, tonalitic, trondhjemitic and granitic gneisses, amphibolite largely derived from volcanic rocks, and intrusions of leucogabbro and norite, all of which experienced amphibolite facies metamorphism at ~3000 Ma (Riciputi et al., 1990; McGregor et al., 1991; Nutman, 1997).

This subdivision of the Godtha˚bsfjord region into terranes led to revision of the previous nomenclature because rocks formerly called Malene supracrustals (McGregor, 1969) and Nûk gneisses (Black et al., 1971) were found to be of different ages in the different terranes. McGregor et al. (1991) recommended that the name Malene supracrustals be discontinued and the name Nûk gneiss be restricted to rocks in the Akia terrane. Nutman et al. (1996) introduced a term 'Itsaq Gneiss Complex' to include all the early Archean rocks in the Godtha˚bsfjord region: Amı ˆtsoq gneisses, Isua supracrustal belt, and Akilia association. These rocks are restricted to, and partly define, the Akulleq terrane (McGregor et al., 1991).

6. Life on Akilia ≥ 3850 Ma?

Here we re-examine fundamental evidence relating to the discovery claimed by Mojzsis et al. (1996) of the oldest trace of terrestrial life in carbonaceous inclusions in apatite crystals from a thin layer of quartz-rich rock on the small island of Akilia south of Nuuk (Figs. 1 and 2). We focus
on new field evidence of the nature of the rocks, their geological history and relative ages. We do not discuss whether the isotopic composition of the carbon described by Mojzsis et al. (1996) is of unequivocal organic origin or ‘why the apatite should act as a safe-deposit vault’ (Hayes, 1996, p. 22). Such questions were raised by Hayes (1996) in his Nature review that accompanied the publication of Mojzsis et al. (1996).

The age of \( \geq 3850 \) Ma for the Akilia island sediments is... significant because it would place their deposition simultaneous with the Late Heavy Bombardment of the Moon at 3800–3900 Ma’ (Mojzsis and Harrison, 2000, p. 3). During this event, the Earth is thought to have suffered more severely from frequent and large meteorite impacts that repeatedly vapourized the oceans and created difficult conditions for the development and survival of life (Sleep et al. 1989). Therefore the claimed traces of terrestrial life \( \geq 3800 \) Ma are especially significant and have wider consequences for interpreting the cause and extent of the lunar bombardment event.

6.1. Geology of southwestern Akilia

The small island of Akilia south of Nuuk (Figs. 1 and 2) consists of early Archean Amı́tsı́q gneisses containing numerous layers of amphibolite (Ameralik dykes) that were intensely deformed during the late Archean (Chadwick and Nutman, 1979; Chadwick and Coe, 1983) (cover of Precambrian Research, this volume). The Amı́tsı́q gneisses range in composition from diorite to granite; their plutonic origin, and the intrusive origin of the amphibolite layers (Ameralik dykes), were recognized nearby on Qı́llı́ŋaaq by Berthelsen (1955) and around Nuuk by McGregor (1973). In the region south and southeast of Nuuk, the Amı́tsı́q gneisses comprise two main components, ‘banded grey gneisses’ and ‘augen and ferrodioritic gneisses’ (Chadwick and Coe, 1983), both of which exist on Akilia (Fig. 2). Augen gneisses range from quartz-diorite to granite and are characterized by megacrysts of microcline and by a high iron content (Chadwick and Coe, 1983). Amı́tsı́q gneisses contain fragments of diverse high grade metamorphic rocks, called Akilia association by McGregor and Mason (1977), that were thought to be mainly of supracrustal origin and were interpreted as the host rocks into which the igneous precursors of the Amı́tsı́q gneisses were intruded.

On the southwestern peninsula of Akilia (Fig. 3), the type locality of the Akilia association (McGregor and Mason, 1977) comprises disrupted layers of mafic and ultramafic gneiss (mainly hornblende-diopside amphibolite, hornblende-pyroxenite and minor serpentinite) and a thin layer of quartz-rich rock interpreted by Nutman et al. (1997a) as banded iron formation and the oldest terrestrial record of water-lain sedimentary deposits.

The adjacent quartzofeldspathic gneiss is heterogeneous and comprises numerous phases of
mainly tonalitic or quartz-dioritic composition that range from melanocratic to leucocratic and medium to coarse grained (Figs. 4 and 5). Further heterogeneity reflects variations in the intensity of the deformation, and the irregular distribution of numerous small fragments of tectonically dis-

Fig. 4. Heterogeneous gneiss comprising layers of pegmatite-banded tonalitic and dioritic Amitsaq gneiss (grey), parallel layers and boudins of amphibolite (black) derived from Ameralik dykes, and pegmatite veins (white). The superficial simplicity reflects repeated episodes of intense ductile deformation by which layers of rock initially at high angles to each other were rotated, attenuated and transposed into parallelism. View to the south on southwestern Akilia, in the steep attenuated limb of a gently south-plunging fold that refolded isoclinal folds, boudins and previously attenuated parallel layering. Located on Fig. 3. Part of the same rock surface appears on the cover of Precambrian Research (this volume). The hammer is 33 cm long.

ruptured layers of hornblende-pyroxene rocks, similar to parts of the larger bodies of mafic and ultramafic gneiss shown on Fig. 3. After deformation and the development of gneissosity, these rocks were intruded by sheets of more homogeneous melanocratic tonalitic rock before the intrusion of the Ameralik dykes. All the rocks were repeatedly, intensely deformed, and layers were isoclinally folded, refolded and segmented into boudins, resulting in a superficially simple banded gneiss composed of thin, greatly attenuated, parallel layers and boudins (Fig. 4 and cover of Precambrian Research, this volume).

Fig. 3. Simplified geologic map of southwestern Akilia.
The amphibolite layers interpreted as deformed remnants of dykes (Ameralik dykes) are generally more homogeneous than the Amitsoq gneisses and mafic and ultramafic gneiss, do not contain abundant thin layers of pegmatite that are an integral part of the gneiss, and can locally be seen cutting across heterogeneity in the gneiss and folded gneissosity. The Ameralik dykes were intruded into the Amitsoq gneisses and mafic and ultramafic gneiss after the protoliths of these rocks had already been converted into gneisses by deformation and metamorphism. This early gneissosity was substantially modified during late Archean episodes of deformation when it was rotated into parallelism with the Ameralik dykes.

Thus, although the gneissosity of both quartzofeldspathic Amitsoq gneisses and mafic and ultramafic gneiss of the Akilia association is parallel, it did not all form at the same time and reflects a long history of development, reworking and transposition. Recognition of the complete history of development of the gneissosity on southwestern Akilia is rendered difficult, and probably impossible, because the late Archean tectonic modifications were so intense that the present structure is superficially simple. Except for a few relatively little-deformed pegmatites that mostly strike east-west or northwest-southeast, the rock layers are generally parallel, subvertical and strike north-south, and most fold axes and lineations plunge 20–45° to the south (Fig. 3). However, the map (Fig. 3) indicates that the main layer of mafic and ultramafic gneiss (the type Akilia association) is a complex fold interference structure. The two trains of lenticular bodies of mafic and ultramafic gneiss define the limbs of a major isoclinal fold that, in the southwest, is refolded about a steep, northwest-southeast trending axial surface.

The development of the main isoclinal fold was accompanied and followed by further attenuation of the Amitsoq gneisses and Ameralik dykes. Isoclinal folded remnants of Ameralik dykes were disrupted into trains of boudins (Figs. 4 and 6, and cover of Precambrian Research, this volume) and then deformed by tight upright southerly plunging folds (Fig. 7). These younger folds are probably minor structures associated with the fold with a northwest-southeast trending axial trace that deformed the major isoclinal fold in the southwest of Fig. 3. The lenticular outcrop pattern of the mafic and ultramafic gneiss reflects older small-scale fold interference structures, such as those on the western limb of the major isoclinal fold. Similar structures indicating refolding with axial surfaces at high angles to each other are marked in the lenticular outcrops on the eastern limb of this major isoclinal fold by thin layers of serpentinite that are too thin to show at the scale of Fig. 3.

The context of Akilia in the regional tectonic framework (Fig. 2) indicates that all the folds seen on Fig. 3 were refolded on a larger scale. The
Fig. 7. Upright, gently plunging folds of composite gneissosity of heterogeneous Amitsog gneiss on southwestern Akilia.

Fig. 8. U–Pb concordia plot. Ellipses for analyses represent the 2σ uncertainty. See Table 1 for analytical data.

youngest fold axial trace in the southwestern part of Fig. 3 may equate with D3 structures on Fig. 2, where it can be seen that D3 structures are folded by D4. The older two episodes of folding in southwestern Akilia post-date the Ameralik dykes and appear to be additional to the D2 thrusts of Chadwick and Nutman (1979) (Fig. 2) and their D1 structures that predate the Ameralik dykes.

To obtain precise control on the age of some late Archean deformation and metamorphism on Akilia, we determined the U–Pb age of zircons in pegmatite intruded between boudins of Ameralik dyke amphibolite (Figs. 3 and 6) during development of the boudins. The pegmatite has an undeformed igneous texture. Therefore, the age of the pegmatite may date a late stage of the last major episode of intense ductile deformation, when the dykes and their host rocks underwent further attenuation following repeated isoclinal folding, dismemberment and transposition into the main gneissosity (cover of Precambrian Research, this volume). Large (200–400 µm long), pink to colourless, elongate (aspect ratio of 3:1:1) to stubby (aspect ratio of 4:3:1), prismatic zircon grains were obtained from the pegmatite. The clearest and least magnetic grains with the fewest inclusions and cracks were abraded (Krogh, 1982). U–Pb dating by isotope dilution thermal ionization mass spectrometry was performed on five single grains. Routine sample preparation and analytical procedures were similar to those described in Dubé et al. (1996). Two analyses are concordant with 207Pb/206Pb ages of 2706.2 and 2701.6 Ma (Table 1, Fig. 8). Three other grains yielded discordant ages. The two concordant analyses and two of the discordant analyses are collinear (MSWD = 0.03) with a poorly defined, early Archean upper intercept. The igneous crystallization age of the pegmatite is interpreted as 2704 ± 3 Ma, which is an age that spans the uncertainties of both the concordant analyses. The discordant analyses are interpreted as indicating the presence of a minor amount of zircon that was inherited from the host gneiss. This interpretation is supported by the discordia with an upper intercept that agrees with zircon ages in nearby tonalitic gneiss (Nutman et al., 1996, 1997a; Whitehouse et al., 1999).

In summary, the rocks on Akilia indicate a complex history of repeated intense ductile deformation in which most geological features were attenuated, rotated and transposed into a new tectonic fabric (Figs. 4 and 5 and cover of Precambrian Research, this volume). Early Archean granulite facies metamorphism at ~3600 Ma (Griffin et al., 1980), that predated the Ameralik dykes, was followed by probably multiple episodes of late Archean amphibolite facies metamorphism at ~2830–2710 Ma (Nutman et al.,
Table 1
U–Pb analytical data

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Concentration(^c)</th>
<th>Atomic ratios(^d)</th>
<th>Age (Ma)(^e)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wt.(^b) (μg)</td>
<td>U (ppm)</td>
<td>Pb(^f) (ppm)</td>
</tr>
<tr>
<td>JC-001-99. Pegmatite between amphibolite boudins at lat. 63°56'06&quot;N, long. 51°40'47&quot;W</td>
<td></td>
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<td></td>
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<tr>
<td>Z1 pk, 5:2</td>
<td>34</td>
<td>97</td>
<td>53.9</td>
</tr>
<tr>
<td>Z2 pk, 3:1</td>
<td>15</td>
<td>192</td>
<td>107.3</td>
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<td>122.5</td>
</tr>
<tr>
<td>Z5 co, 4:3</td>
<td>23</td>
<td>123</td>
<td>67.5</td>
</tr>
</tbody>
</table>

\(^a\) Fraction code, followed by grain colour (pk, pink; co, colourless) and length to width ratio.
\(^b\) Weight of grain estimated visually using a microscope.
\(^c\) Concentration uncertainty varies with sample weight: estimated >10% for grains weighing <10 μg, <10% for grains weighing >10 μg.
\(^d\) Ratios corrected for spike, fractionation, blank, and initial common Pb, except 206\(^{206}\)Pb/204\(^{204}\)Pb ratio corrected for spike and fractionation only. Errors are 1σ in percent.
\(^e\) Errors are 2σ in Ma. Pb blanks were 10–15 pg and U blanks were <1 pg.
\(^f\) Pb, radiogenic Pb; Pb\(_c\), total common Pb in analysis corrected for spike and fractionation.
These episodes of metamorphism accompanied the main deformation features now seen on Akilia and extended to ~2704 Ma (new data above) and the younger D3 and D4 events described by Chadwick and Nutman (1979). The rocks on Akilia were also subjected to a major thermal and magmatic episode at ~2550 Ma during the emplacement of the nearby Qørqut granite (Figs. 1 and 2) (Baadsgaard, 1976; Brown et al., 1981; Moorbath et al., 1981), and some of the cross-cutting pegmatites on the island could be of this age. Another major thermal episode of regional extent is recorded by biotites that suffered extensive loss of radiogenic $^{87}\text{Sr}$ at ~1700–1600 Ma (Pankhurst et al., 1973).

The possibility of any trace of early Archean life that may have existed in southwestern Akilia surviving these multiple episodes of intense ductile deformation and high grade metamorphism, and being recognizable as early Archean, appears miraculous. Yet such a miracle was claimed by Mojzsis et al. (1996) and received world-wide publicity.

### 6.2. Host rock of ‘oldest life’

Mojzsis et al. (1996) measured ‘the carbon-isotope composition of carbonaceous inclusions within grains of apatite’ (p. 55) and found compositions that they interpreted to be the result of ‘biological activity’ ‘at least 3800 Myr before present’ (p. 56).

The apatite grains were extracted from a thin layer of highly deformed and metamorphosed quartz-rich rock within mafic and ultramafic gneiss on the southwestern tip of Akilia (Fig. 3). This quartz-rich rock was interpreted as a banded iron formation and is described in detail by Nutman et al. (1997a). The rock is claimed to be ‘the oldest known sediment … and the oldest known rock with evidence of biological processes active during the time of deposition’ (Mojzsis and Harrison, 2000).

We found that this layer of rock is more than twice as extensive as previously indicated by Nutman et al. (1997a, their Fig. 1) and Mojzsis and Harrison (2000, their Fig. 4). The layer extends north and north-northeast from the locality near the southern shore sampled by Mojzsis et al. (1996) (Fig. 3), and defines the eastern limb of a third-generation fold of the thickest layer of mafic and ultramafic gneiss. Thinner layers of this quartz-rich rock were also seen to the north-northwest in the mafic and ultramafic gneiss on the west coast in the vicinity of the word ‘sea’ on Fig. 3, but are too thin to be shown on this map.

The rock mainly consists of quartz with a few thin layers and lenses rich in diopside and magnetite, and thin cross-cutting layers of diopside and quartz of similar thickness. Smaller amounts of hornblende, orthopyroxene and garnet occur with the magnetite and diopside. These thin melanocratic layers are unevenly distributed within the layer of quartz-rich rock. The rock has a post-tectonic, very coarse grained metamorphic texture. The large grain size suggests substantial diffusion during metamorphism.

The age of the recrystallization is unknown, but in view of the tectonic history, the rock must have undergone substantial ductile deformation and recrystallization during the late Archean. Sano et al. (1999) determined U–Pb and Pb–Pb isotopic ages of apatites from this locality to be ~1500 Ma and concluded that ‘either the apatites in the BIFs grew about 1500 Myr ago, or that they grew earlier than that but were substantially affected by recrystallization, and/or diffusive exchange with the environment, which reset the U–Pb system of the samples’. As noted by Sano et al. (1999), this metamorphic event, which they estimated reached 600°C, could have been part of the regional thermal event recognized by Pankhurst et al. (1973).

In reply to the discussion of Sano et al. (1999), Mojzsis et al. (1999, p. 128) asserted that ‘this rock, which is essentially a quartzite, has no intrinsic capacity to form apatite by metamorphic reactions following diagenesis. Thus, the apatite present in this rock must be original (formed before 3850 Myr) unless phosphate-bearing fluids were subsequently introduced metasomatically.’ The latter possibility cannot be lightly dismissed in view of the very coarse metamorphic grain size of the rock and the presence of syn- and/or pre-metamorphic veins of quartz and quartz-diopside, with the same coarse grain size and texture as the host rock. Nor can the rock with certainty be
classified as ‘essentially quartzite’ (or metamorphosed banded iron formation) with apatites that have suffered little more than diagenesis. A sedimentary origin is not impossible, but alternative origins or multiple origins, such as all or part of the rock being derived from vein quartz, need to be considered and discounted. The apparent absence of ‘apatites with graphite inclusions in the immediately adjacent, encompassing gneisses’ noted by Mojzsis et al. (1999), p. 128) as an indication that apatite was not derived from the adjacent rocks does not preclude metasomatic transfer along the quartz-rich layer. If all or part of the quartz-rich layer was derived from vein quartz then mechanical transport of mineral grains along a ductile fault zone is also a possibility to be considered.

Thus the age of crystallization, and primary source, of the carbonaceous inclusions in the apatite crystals are uncertain. The rock may be derived from a banded iron formation, but it appears to have been so substantially modified by deformational and metamorphic processes that this interpretation is a hypothesis. This hypothesis needs to be substantiated, and alternative hypotheses, such as that some or all of this layer could have been derived from vein quartz that was repeatedly deformed and metamorphosed, need to be dismissed before a sedimentary origin can unequivocally be established.

6.3. Age of host rock

Nutman et al. (1997a) extracted zircons from the quartz-rich rock (Fig. 3) ‘in the hope that either a few volcanogenic or extremely old detrital grains might be found’ (p. 2481). However, all zircons yielded ages of ~2700–2590 Ma that were interpreted as growing ‘during one or more episodes of late Archaean high grade amphibolite facies metamorphism…and provide no information on the deposition of the sediment’ (p. 2481). Consequently, Nutman et al. (1997a) concluded that only a minimum age of the quartz-rich rock could be determined by dating granitoid rocks that intruded the quartz-rich rock or the spatially associated mafic and ultramafic gneiss.

The tonalitic gneiss adjacent to the eastern margin of the mafic and ultramafic gneiss, near the southern shore of Akilia (Fig. 3), was dated by Nutman et al. (1996) at 3872 ± 10 Ma (SHRIMP U–Pb zircon date, sample G88-66). Mojzsis et al. (1996), referring to this locality, stated that the mafic and ultramafic gneiss was ‘cut by a deformed quartz-dioritic sheet’ (p. 57), the same gneiss dated by Nutman et al. (1996). The age of the ‘sheet’ was considered to be the minimum age of the quartz-rich rock hosting the apatites with carbonaceous inclusions (Mojzsis et al., 1996).

Nutman et al. (1997a) contended that the ‘sheet’ should not be used to constrain the age of the mafic and ultramafic gneiss and associated quartz-rich layer because ‘given the strong deformation at the contact, it cannot be totally ruled out that the gneisses and supracrustal rocks have been tectonically juxtaposed’ (p. 2477). Therefore, the age of another layer of quartz-dioritic gneiss in contact with the mafic and ultramafic gneiss was investigated by Nutman et al. (1997a) (sample G93-05, located by the arrow marked (Figs. 9–11 in Fig. 3). They described this layer as a ‘quartz-dioritic sheet within amphibolites of the supracrustal body… Where sampled, this sheet is ~1 m wide and its contacts are up to 10° discordant to the compositional layering in host layered amphibolites’ (p. 2477). They stated that ‘apart from the mafic inclusions and the sparse pegmatite veins, the quartz diorite sheet is homogeneous—it is not a composite banded gneiss. On the basis of the field relations, the quartz-diorite sheet definitely cuts the supracrustal rocks’ (p. 2477). The age for this sheet, and thus the minimum age for the mafic and ultramafic gneiss, was interpreted from SHRIMP U–Pb zircon dating as being ‘definitely ~3840, and possibly 3865 ± 11 Ma’ (pp. 2481–2482).

Whitehouse et al. (1999) reinvestigated the age of this ‘sheet’ by performing U–Pb zircon ion-microprobe dating in conjunction with cathodoluminescence imaging on a sample (SM/GR/97/7) collected from the same locality as sample G93-05. The imaging revealed cores and overgrowths of zircon, and in contrast to Nutman et al. (1997a) little evidence for zircon older than ~3650 Ma was found (only one core with an age of
~ 3800 Ma was discovered). Whitehouse et al. (1999) concluded that the rock 'shows unambiguous evidence for a ca. 3.65 Ga magmatic event' (p. 217) and that pre-3.65 Ga zircon dates obtained by Nutman et al. (1997a) were from inherited grains.

6.4. Field relations of ‘quartz-diorite sheet’

Given the importance of the contacts between the ‘quartz-diorite sheet’ and the mafic and ultramafic gneiss, we mapped the outcrop at a scale of 1:12. The outcrop lies within mafic and ultramafic gneiss, on the eastern limb of the major isoclinal fold (Fig. 3; outcrop located by the arrow marked Figs. 9–11 on Figs. 3 and 5). Our map is shown in Fig. 9 and a photograph of the outcrop is shown in Fig. 10. Part of this outcrop (shown in detail in our Fig. 11) was previously portrayed by Nutman et al. (1997a) as evidence of discordance between the ‘quartz-diorite sheet’ and the mafic and ultramafic gneiss. Their figure (ib. cit., Fig. 2, p. 2478), a sketch from a photograph, was unfor-
Unfortunately drawn in reverse image and the scale indicated was incorrect (the scale bar should be 40% longer).

Figs. 9–11 show that geologic relationships in this outcrop are considerably more complex than depicted by Nutman et al. (1997a). The ‘sheet’ is a strongly deformed composite layer, 0.6–0.8 m wide, consisting of discontinuous layers of: heterogeneous gneiss (thinly banded mafic and felsic layers), relatively homogeneous tonalitic gneiss, leucocratic pegmatite, hornblendite, and vein quartz (Figs. 9–11). These rocks are cut by an undeformed, gently north-dipping pegmatite dyke (probably late Archean). Compositional layering in the heterogeneous gneiss parallels the foliation in the tonalitic gneiss, the margins of the composite layer, and the gneissosity in the adjacent mafic and ultramafic gneiss (Figs. 9–11). The ‘up to ~10°’ discordance between the composite layer and gneissosity in the adjacent rocks that is claimed by Nutman et al. (1997a), p. 2477) does not exist; apparent discordance seen in Fig. 11 is due to the perspective of the photograph and the three-dimensional outcrop surface. The gneissosity in the mafic and ultramafic gneiss is also parallel to the contact with, and foliation in, the tonalitic gneiss across strike to the east as can be seen in Fig. 5 (outcrop located on Fig. 3 by the arrow marked Fig. 5).

Nutman et al. (1997a) and Whitehouse et al. (1999) did not indicate where their U–Pb samples were collected, but V.R. McGregor and M.J. Whitehouse (personal communications, 1999) indicated the samples were taken from the tonalitic gneiss at location 3 in Fig. 11b. The tonalitic gneiss appears to have a less complex history than the heterogeneous gneiss (Figs. 9–11), but there is no field evidence suggesting that it intruded into the heterogeneous gneiss or the adjacent mafic and ultramafic gneiss. Likewise, the fragmentary
nature of the hornblendite lenses in the composite layer probably reflects deformational rather than intrusive processes.

This outcrop on southwestern Akilia, which forms the basis for the age attributed to the oldest life claimed by Mojzsis et al. (1996), comprises highly strained rocks. These rocks underwent multiple deformation and high grade metamorphic events that obliterated primary relationships between the tonalitic gneiss and the mafic and ultramafic gneiss (Figs. 9–11). Although our observations do not rule out intrusion of part of the protolith of the tonalitic gneiss into the protolith of the mafic and ultramafic gneiss, they do suggest that other primary relationships are equally plausible. These relationships include (i) deposition of the protoliths of the mafic and ultramafic gneiss as lava flows and/or clastic or pyroclastic fragments onto the tonalitic gneiss; (ii) intrusion of the protoliths of the mafic and ultramafic gneiss into the tonalitic gneiss; (iii) intrusion of the protolith of a younger component of the tonalitic gneiss (carrying xenoliths of older heterogeneous gneiss) into the mafic and ultramafic gneiss or its protoliths, and (iv) tectonic juxtaposition, such as the D2 thrusting of Chadwick and Nutman (1979).

Nutman et al. (1997a) stated that ‘extreme caution has to be exercised in establishing the age of any unit of supracrustal rocks...given evidence for supracrustal rocks of more than one age in the Itsaq Gneiss Complex (Nutman et al., 1996), (p. 2477). Need for caution was further stressed by Nutman et al. (2000): ‘bearing in mind that the older components of the geology on southern Akilia underwent granulite-facies metamorphism and some partial melting at ca. 3650 Ma and that most of them were highly deformed in both the early and late Archaean, a degree of caution may be warranted regarding whether the dates from samples G88-66 and G93-05 give a minimum age for the unit of banded iron formation... that is interpreted as the oldest evidence of a hydrosphere on Earth’.

We agree that the evidence needs to be rigorously evaluated and that even greater care than that exhibited by Nutman et al. (1997a) must be taken in order to prove that any components of the Akilia association on southwestern Akilia were intruded by any of the protoliths of the adjacent tonalitic gneiss and may therefore be older than 3.85 Ga (Nutman et al., 1997a) or 3.65 Ga (Whitehouse et al., 1999). The layer of gneiss (Figs. 9–11) is heterogeneous and clearly contains components of different composition and age. The current controversy between Nutman et al. (2000) and Whitehouse et al. (2000) over the interpretation of disparate ages of zircon populations in this rock could reflect differences in the components, or different mixtures of components, that were studied from within this composite layer.

The southwestern tip of Akilia is the type locality of the Akilia association (McGregor and Mason, 1977) and therefore it would be important to obtain unequivocal protolith ages directly from the mafic and ultramafic gneiss at this location. However, in order to constrain the age of any early life on Akilia, it would also be necessary to determine the primary age relationships between the mafic and ultramafic gneiss, the quartz-rich rock, and the apatite with carbonaceous inclusions (Mojzsis et al., 1996). At present these crucial relationships are unknown and appear to be extremely difficult to resolve in the intensely deformed and metamorphosed rocks on Akilia.

7. Conclusions

What do we know about the Earth’s oldest continental crust in the Godthåbsfjord region? The early Archean gneisses were mainly derived from plutonic igneous rocks, tonalite and granodiorite and a smaller amount of quartz-diorite, trondhjemite, diorite, ferrodiorite and granite. The precise ages of intrusion as magmas is controversial. Largely on the basis of SHRIMP U–Pb data on zircons, Nutman et al. (1996) considered that the magmas that formed these early Archean rocks were intruded over a protracted period between ~3870 and 3625 Ma. In contrast, Kamber and Moorbath (1998) used Pb–Pb data from feldspars and whole rocks to conclude that ‘the magmatic precursors of the Amitsq orthogneisses separated from a depleted mantle-like
source at ca. 3.65 Ga’ (p. 19). A broadly similar conclusion was reached by Whitehouse et al. (1999), based on U–Pb zircon data and cathodoluminescence imaging. They found that the Amitsoq gneisses they studied were derived from rocks intruded at ~3.65 Ga, and older zircons are xenocrysts.

The Amitsoq gneisses are diverse, extensive, and heterogeneous, and although the amount of geochronology carried out on these rocks is probably greater than on any other region of early Archean rocks, it is still far from adequate to define the whole temporal evolution of the gneiss complex. However, it is probably significant that the age determinations all fall in the range of ~3850–3600 Ma and that no significantly older zircon xenocrysts have been found. This contrasts with the Acasta gneiss complex in the Slave Province of Canada and the Narryer gneiss complex in the Yilgarn Craton of Australia that have both yielded much older zircons. Tonalitic and granodioritic gneisses from the Acasta region contain zircons with SHRIMP U–Pb zircon ages between ~4.0–4.03 Ga (Bowring et al., 1989; Stern and Bleeker, 1998; Bowring and Williams, 1999), and in the Narryer region, late Archean granites contain >4.0 Ga zircon xenocrysts (Nelson et al., 1997), and detrital zircons in late Archean metasedimentary rocks range back, beyond the oldest known 3.73 Ga rocks of the region, from ~3.9–4.3 Ga (Froude et al., 1983; Compston and Pidgeon, 1986; Maas et al., 1992). The wide range of extremely ancient zircons in the Narryer gneiss complex indicates the presence, or former presence, of substantially older and more complex continental crust in this region than appears likely in the Godthåbsfjord region.

Small fragments of diverse composition (Akilia association) are widespread in the Amitsoq gneisses. They are generally considered to be derived from highly metamorphosed mafic and ultramafic intrusions and sedimentary rocks, and to be older than the Amitsoq gneisses. Nutman et al. (1996, 1997a) considered that the age of the Akilia association ranges back to over ~3850 Ma, whereas Kamber and Moorbath (1998) argued that these rocks formed at ~3700–3650 Ma.

The Isua greenstone belt is generally considered to be a better preserved equivalent of the Akilia association at lower metamorphic grade. Nevertheless, these rocks are also intensely deformed and suffered numerous episodes of deformation and metamorphism to amphibolite facies. The ages of these rocks are poorly constrained but thought to be ~3.8–3.7 Ga (Nutman et al., 1996, 1997b; Moorbath and Whitehouse, 1996).

Is there any direct trace of life in the early Archean rocks of the Godthåbsfjord region? The answer appears to be very little. The age and significance of the graphite described from apatite crystals on Akilia by Mojzsis et al. (1996) are controversial. The age and origin of the host rock are unknown. Previous claims that the rock is >3850 Ma are unsupported by reinvestigation of the field evidence. The discovery by Rosing (1999) of carbon of possible biogenic origin in >3700 Ma schists interpreted as metasedimentary rocks of turbiditic and pelagic origin in the Isua greenstone belt is more plausible. These rocks are from a zone of relatively low strain where primary features can be recognized, but the tectonostratigraphy of the greenstone belt is complicated and there is insufficient precise geochronology to define the ages of all the tectonostratigraphic units. However, existing data suggest that much of the greenstone belt is >3700 Ma, and life, if it then existed, is more likely to be preserved in these rocks than in any other early Archean rocks in the region.

Banded iron formations are widely considered to reflect the precipitation of insoluble ferric iron as a result of oxidation of soluble ferrous iron in seawater (e.g. Awramik, 1981, p. 357). The required oxygen is generally thought to have been generated by organic photosynthetic processes. Thus the presence of banded iron formation within the >3700 Ma Isua greenstone belt, and possibly within the Akilia association, could be macroscopic indications of photosynthetic processes.

Although these ancient rocks of the Godthåbsfjord region have been dead and cold for a long time, there is still plenty of heat and life left in the current research and controversies surrounding their interpretation. The geology around
Godthaabsfjord is exceptionally well exposed in a rugged glaciated terrain with vertical relief of 2000 m. Access and infrastructure are, for such an Arctic region, very good due to the fjord complex and the location of the main Greenland town of Nuuk at the mouth of the fjord (Fig. 1). There remains plenty of scope for substantial research into the early history of the Earth, for better constrained mineral exploration, and for lively geological debate well into the 21st century and beyond.

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References


Bowring, S.A., Williams, I.S., Compston, W., 1989. 3.96 Ga gneisses from the Slave Province, Northwest Territories, Canada. Geology 17, 971–975.


Chadwick, B., 1981. Field relations, petrography and geochemistry of Archaean amphibolite dykes and Malene


Nutman, A.P., McGregor, V.R., Friend, C.R.L., Bennett, V.C., Kinny, P.D., 1996. The Itsaq gneiss complex of southern West Greenland; the world’s most extensive
Rosing, M.T., Rose, N.M., Bridgwater, D., Thomsen, H.S., 1996. Earliest part of Earth’s stratigraphic record: a reappraisal of the > 3.7 Ga Isua (Greenland) supracrustal sequence. Geology 24, 43–46.
Schonette, L., Compston, W., Bridgwater, D., 1988. Late Archaean ages for the deposition of clastic sediments belonging to the Malene supracrustals, southern West Greenland: evidence from an ion probe U-Pb zircon study. Earth Planet. Sci. Lett. 87, 45–58.