A reassessment of the timing of early Archaean crustal evolution in West Greenland

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In last year's Review of Greenland activities, Kalsbeek (1997) divided the recent history of geochronology into three successive periods:

1. single-sample K-Ar and Rb-Sr mineral or whole-rock age determinations;
2. Rb-Sr and Pb/Pb whole-rock isochrons and multigrain zircon U-Pb isotope data;
3. the present, where 'single' zircon U-Pb data are predominantly used.

To these three, we would propose adding a fourth, namely a combination of all three, in order to achieve the maximum age information within complex terrains. For an early Precambrian terrain like that of West Greenland, we consider that the combined use of at least the last two approaches is essential (to which should be added the Sm-Nd method). In recent years, study of the geochronological evolution of the Godthåbsfjord and Isua regions has been dominated by rapid and precise ion-probe U-Pb dating of complex-structured zircons, and it has become fashionable to regard the wide range of zircon dates, and particularly the oldest, as giving the age of rock formation. Dates obtained from whole-rock Rb-Sr, Sm-Nd and Pb/Pb regressions have been regarded as too imprecise for adequate age resolution, whilst constraints on crustal evolution imposed by initial Sr, Nd and Pb isotope ratios have been summarily dismissed or totally ignored. We consider that this sole dependence on ion-probe dating of zircon can lead (as, indeed, in the early Archaean of West Greenland) to a potential misinterpretation of the timing of crustal evolution, especially in those cases where little or no information regarding the relationship between measured date and internal grain structure is available.

Figure 1 shows the localities mentioned in the text.

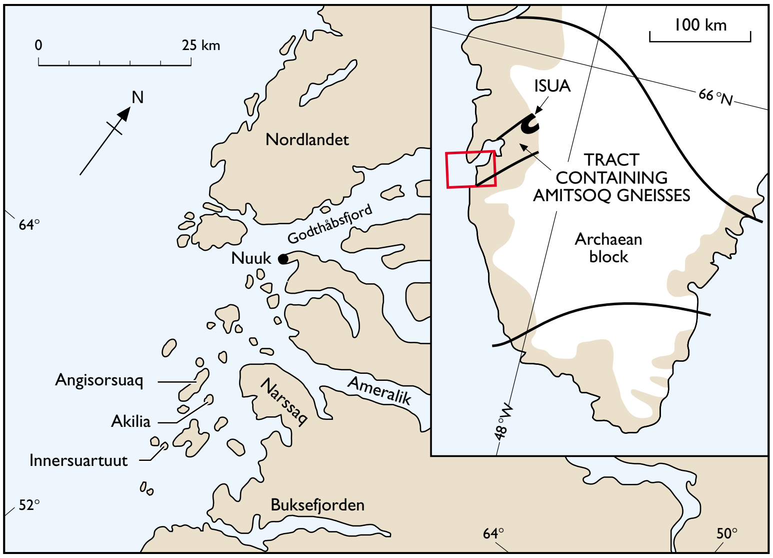

Fig. 1. Sketch-map of the area around Nuuk, West Greenland with localities mentioned in the text.

Geology of Greenland Survey Bulletin 180, 88–93 (1998)

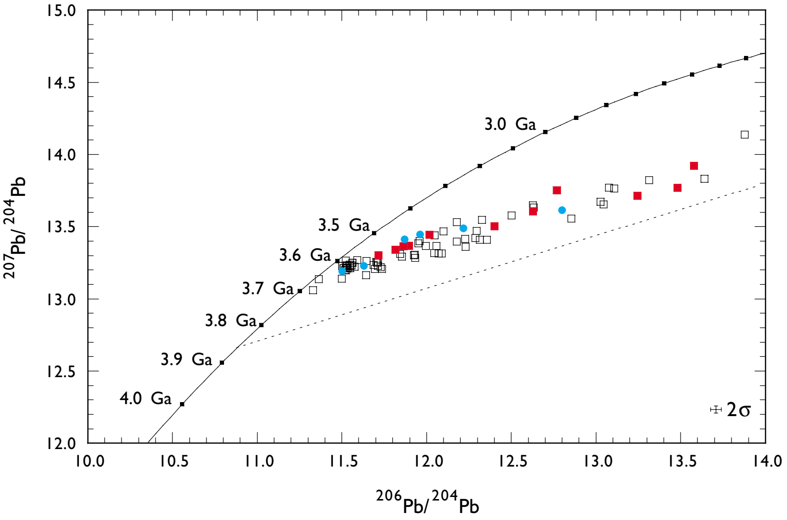

Fig. 2. Common Pb diagram with mantle evolution line after Kramers & Tolstikhin (1997). Black open squares represent 83 published whole-rock data points which regress to 3654 ± 73 Ma (MSWD = 17.6) and intersect the mantle evolution line at 3.66 Ga. Red full squares correspond to whole rock, HF-leached feldspar, and feldspar leachate analyses of four Amîtsoq gneisses claimed to have ages in the range 3.82–3.87 Ga from U-Pb zircon dates (for sampling details see text). Mantle-derived Pb of 3.85 Ga (stippled line) would be expected to lie on a quasi-parallel trend to the bulk Amîtsoq data, but off-set down towards older model intersection ages. Blue full circles are leached plagioclase and whole rock data from gabbroic Akilia Association enclaves. Some of these enclaves are cut by gneiss sheets for which ages of 3.85–3.87 Ga have been claimed. Their Pb isotope composition offers no evidence for such an old age but is compatible with a 3.67 Ga Sm-Nd isochron age (Fig. 3) obtained on similar samples.

Whole-rock regression ages for the Amîtsoq gneisses

We have regressed all available whole-rock isotopic data for the Amîtsoq gneisses (source references available from the authors), to yield concordant Rb-Sr (3660 ± 67 Ma), Sm-Nd (3640 ± 120 Ma), and Pb/Pb (3654 ± 73 Ma) ages. These regressions are by no means perfect isochrons, and the scatter of points about the regressions in excess of analytical error is due to: (1) open-system behaviour for parent or daughter isotopes, or both, during well-attested late Archaean and mid-Proterozoic metamorphism; (2) a small degree of heterogeneity in initial Sr, Nd and Pb isotope ratios for different components of the Amîtsoq gneisses; (3) a combination of these. However, we regard the weighted mean age of 3655 ± 45 Ma (2 sigma error) from all three methods as a reliable estimate for the emplacement age of the magmatic precursors of the Amîtsoq orthogneisses. It is improbable that agreement between these three methods is simply fortuitous, or the result of some massive, regional metamorphic or metasomatic event. Furthermore the initial Sr, Nd and Pb isotopic constraints are also concordant, all strongly indicating a mantle-like source, rather than much older, reworked sialic crust.

All Amîtsoq gneisses studied by the ion-probe U-Pb technique have yielded at least some zircon dates in this range, and *c.* 3.65 Ga is seen as the age of a major crust-forming event by Nutman *et al.* (1993, 1996). However, these workers have also reported many older zircon dates from which it is concluded that the gneiss complex had a complicated earlier history, having been added to, and modified, in several events starting at *c.* 3900 Ma and extending down to *c.* 3600 Ma. Fortunately, it is possible to test these claims independently by combining information obtained by ion-probe U-Pb dating and Pb-isotope systematics (the combined approach 4). Of particular interest is the question of whether the zircon dates really refer to the true age of formation of their host rock, or whether they only refer to the age of the zircon itself. In the latter case, it would have to be concluded that the zircon is inherited from an older rock which may no longer be exposed. Zircon is known to be an extremely hardy, resistant mineral which can survive sedimentary and magmatic cycles (e.g. Lee *et al.* 1997; Mezger & Krogstad 1997).

Pb-isotopic constraints for the age of the Amîtsoq gneisses

The evolution of Pb isotopes in continental crust, oceanic crust, mantle and meteorites through earth's history has been closely studied for over forty years. Part of the primary isotopic growth curve for mantle Pb, which links the most primitive Pb of iron meteorites with modern mantle-derived Pb, is shown in Figure 2. The shape of this curve, as well as the increasing resolution towards older ages, is due to the very different half-lives of ^{235}U (703.8 Ma) and ^{238}U (4468 Ma). Here we use the mantle evolution curve of Kramers & Tolstikhin (1997), which barely differs in the relevant time range from the well-known primary growth curve of Stacey & Kramers (1975). It should be noted that the ^{207}Pb/^{206}Pb compositions of 3.85 Ga and 3.65 Ga-old mantle Pb differ by 13%, far outside any analytical uncertainties (typically *c.* 0.15%).

All 83 Amîtsoq gneiss common leads so far analysed by various workers fall within the data envelope shown in Figure 2. The data points scatter around a regression line which yields an age of 3654 ± 73 Ma. Most present-day Amîtsoq gneiss leads are extremely unradiogenic (because of the low U/Pb ratio of the gneisses), and fall between 11.5 and 12.5 on the ^{206}Pb/^{204}Pb scale (Fig. 2). This is the main reason for the fairly high age error on the regression line. Of much greater, indeed crucial, importance is that the Amîtsoq gneiss Pb-isotope regression intersects the mantle evolution curve precisely at 3.66 Ga. This is, within error, identical to the 3.65 Ga intercept with the earlier growth curve of Stacey & Kramers (1975). From this we conclude that the magmatic precursors of all the analysed Amîtsoq gneisses were derived from the mantle, or from a geochemically similar source, at 3.65–3.66 Ga, after which they became part of the continental, granitoid crust. There is simply no hint of the presence of any Amîtsoq gneiss which began its existence in the crust as long ago as *c.* 3.85 Ga (Fig. 2).

It might be argued that all of the above gneisses would yield ion-probe U-Pb zircon dates of *c.* 3.65 Ga. Unfortunately, few such comparisons are available. We have therefore included in our common Pb isotopic studies several Amîtsoq gneisses which yield much older ion-probe zircon dates as far back as *c.* 3870 Ma, for each of which the oldest measured ion-probe date is interpreted as the true age of rock formation (e.g. Nutman *et al.* 1997a). Of particular interest are Amîtsoq gneisses in and around the island of Akilia, about 25 km south of Nuuk, where ion-probe dates in the range of 3872–3619 Ma have been reported within a small area (Nutman *et al.* 1996, fig 2.). On Akilia itself, discordant sheets of Amîtsoq gneiss with the oldest ion-probe dates of 3860–3870 Ma cut metasedimentary and meta-igneous rocks of the so-called Akilia Association, which are thus regarded as even older (Nutman *et al.* 1997a). Here an enclave of highly metamorphosed banded iron formation contains accessory apatite with graphite inclusions yielding a C-isotope signature regarded as biogenic in origin (Mojzsis *et al.* 1996). Consequently, Nutman *et al.* (1997a) claim that life existed on earth prior to 3860 Ma, and might therefore have overlapped with a time when the earth was still being affected by major impacts, such as probably terminated on the moon at *c.* 3.80 Ga. Overlap of truly major impacts with the existence, or origin, of life is regarded as highly improbable (e.g. Maher & Stevenson 1988; Sleep *et al.* 1989). This is further discussed below.

Pb-isotopic compositions have been measured on whole rocks and feldspars for the following samples with ion-probe U-Pb zircon dates $\gg$3650 Ma: (1) discordant sheets of Amîtsoq gneiss on Akilia, as described above, (2) an Amîtsoq gneiss (GGU 110999) from the island of Angisorsuaq, 2 km west of Akilia, which has been much analysed for 25 years, and which was the first such sample to give an 'old' ion-probe date of 3820 Ma (Kinny 1986), (3) gabbroic Akilia Association enclaves from Akilia and the nearby (10 km to the south) island of Innersuartuut, which are older than the discordant Amîtsoq gneiss sheets with their respective ion-probe zircon dates of 3865 Ma (Nutman *et al.* 1997a) and 3784 Ma (Bennett *et al.* 1993).

Figure 2 shows that the Pb-isotopic compositions of all these samples fall exactly on the regional Amîtsoq field which regresses at 3654 ± 73 Ma and, much more significantly, intersects the mantle evolution curve at 3.65 to 3.66 Ga. We conclude that the magmatic precursors of even those Amîtsoq gneisses which yield ion-probe U-Pb zircon dates $\gg$3650 Ma are the products of a major mantle-crust differentiation episode at around 3.65 Ga (e.g. Moorbath & Taylor 1981). There is no sign from the Pb isotopes that crustal development of any of these Amîtsoq gneisses or gabbroic Akilia enclaves began as early as the times given by the ion-probe dates (Fig. 2).

The inescapable corollary from these results is that zircons significantly older than *c.* 3.65 Ga are inherited grains from some older, evolved, regional crust of as yet unspecified type, which may no longer be exposed. Our analysis of all published ion-probe data (Kamber & Moorbath 1998), together with recent ion-probe data

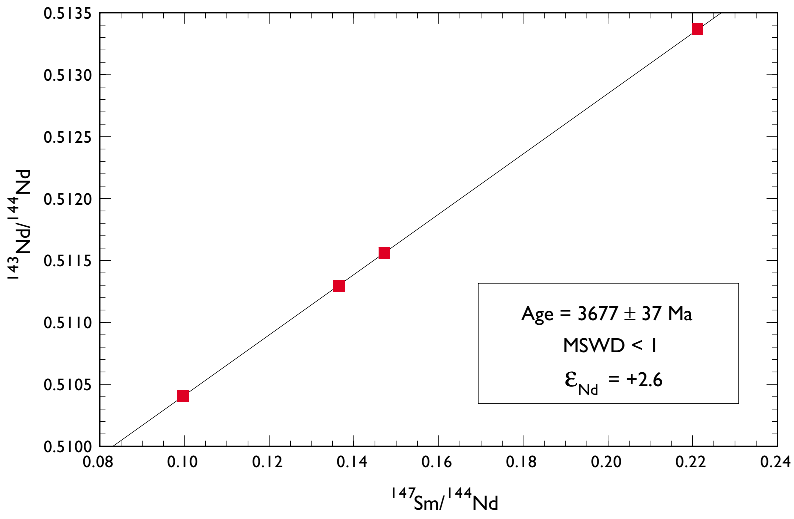

Fig. 3. Sm-Nd isochron plot for data of Bennett *et al.* (1993) on Akilia Association enclaves from the island of Akilia (one sample – the highest point), and the nearby island of Innersuartuut (three samples). The mean square weighted deviate (MSWD) of < 1 shows that this is a statistically perfect isochron. ε_{Nd} is a measure of the initial ^{143}Nd/^{144}Nd ratio, which is of great importance for petrogenetic and geochemical studies as well as for modelling mantle evolution. The quoted error on the age is 2 sigma (95% confidence level).

(Nutman *et al.* 1997b) on detrital zircons from a metaquartzite in the Isua supracrustal belt, some 150 km north-east of Nuuk, suggests that an event at *c.* 3.85 Ga is of particular regional importance. Thus, whilst the discovery of $\gg$3650 Ma-old zircons with the ion-probe has been of great importance, we consider that they do not date the time of formation of the rocks which presently host them. The geochemical nature of the *c.* 3.85 Ga-old source rocks is difficult to constrain. Contamination of the younger melts with older material (i.e. the source-rocks of the *c.* 3.85 Ga-old zircons) had minimal effects on the Pb-, Nd-, and Sr-isotope systematics (although some of the scatter around the regressions might perhaps be explained as stemming from very minor contamination with country-rock). Detailed multidisciplinary work on the ancient zircons themselves will hopefully elucidate the nature of their source rocks.

Significance for age of earliest life

Our re-interpretation of a rock formation age of *c.* 3.65 Ga for discordant Amîtsoq gneiss sheets on Akilia provides a new, less spectacular, minimum age for those Akilia Association enclaves which bear C-isotope evidence for possibly biogenic processes (Mojzsis *et al.* 1996). The fact that Akilia Association enclaves from Akilia and Innersuartuut fall on an indistinguishable Pb-isotopic trend from the discordant (and other) Amîtsoq gneisses means that the enclaves cannot be more than a few tens of millions of years older than the gneisses (provided they were derived from a mantle-like source, which seems likely given their gabbroic composition and association with ultramafic rocks). There is some published, independent evidence for this, which we now discuss briefly.

Bennett *et al.* (1993) reported Sm-Nd data for a suite of gabbroic enclaves of the Akilia Association, including Akilia and Innersuartuut. Using minimum age constraints obtained from ion-probe U-Pb zircon data in the range of 3872 to 3784 Ma from discordant and enclosing Amîtsoq gneisses (see above), they calculated initial Nd isotope ratios for the Akilia gabbros and, together with analogous comparative data for the Amîtsoq gneisses, arrived at a model of major Nd-isotope heterogeneity in the earth's mantle in early Archaean times. This approach, which has been strongly criticised by Moorbath *et al.* (1997), assumes that every analysed rock remained a closed system to Sm or Nd diffusion since the time given by the U-Pb zircon date. But were the bulk rocks already in existence at the time given by the U-Pb zircon dates? If one plots the Sm-Nd data of Bennett *et al.* (1993) for five separate localities (seven data points) of Akilia Association gabbroic enclaves, they yield an isochron age of 3675 ± 48 Ma. Plotting only the data from Akilia (one sample) and Innersuartuut (3 samples) yields a perfect Sm-Nd isochron (MSWD < 1) with an age of 3677 ± 37 Ma, as shown in Figure 3. It is probable that this is a close estimate for the age of not only the gabbroic enclaves on these islands, but also for the closely associated banded iron formation lithologies which (on Akilia) contain apatite with graphite inclusions of probable biogenic origin (Mojzsis *et al.* 1996). It should be remembered that on Akilia, the Akilia Association enclaves are cut by a gneissic granitoid sheet which yields zircon U-Pb dates up to 3870 Ma, which we regard as inherited zircons from a time when the present host rocks did not even exist.

The only ion-probe zircon U-Pb date so far measured directly on an Akilia Association rock, namely a schist from Innersuartuut, was reported by Schiøtte & Compston (1990). They obtained a complex age pattern, but favoured 3685 ± 8 Ma as representing the original age of this part of the Akilia Association and found no zircons approaching the value of *c.* 3865 Ma obtained by Nutman *et al.* (1997a) for the discordant gneiss sheets on Akilia.

Direct age constraints on the Akilia Association obtained with three independent methods thus yield a concordant deposition age: (1) Pb/Pb model age constraints on gabbroic samples indicate a mantle extraction age between 3.70 and 3.65 Ga; (2) Sm-Nd analyses of similar gabbroic samples yield an isochron age of 3677 ± 37 Ma, and (3) a volcanogenic Akilia Association schist was dated at 3685 ± 8 Ma with the U-Pb ion-probe method. The combined age of *c.* 3.67–3.68 Ga is in direct conflict with the interpretation of U-Pb zircon age spectra of younger, cross-cutting gneiss sheets, which were believed to be as old as 3.87 Ga (Nutman *et al.* 1997a). However, a closer inspection of the age spectra, in other words the data themselves, reveals that an alternative interpretation is equally plausible. The ion-probe U-Pb zircon age spectra of all three analysed discordant gneiss sheets can be statistically analysed to yield between two and four age populations per spectrum (Nutman *et al.* 1997a, table 3). No matter which analysis is preferred, prominent, co-existing age populations are always found in the range of 3.81–3.86 Ga and 3.60–3.65 Ga. Whilst Nutman *et al.* (1997a) prefer to view the older population as representing the rock formation age, the combined geochronological evidence in fact clearly shows that the younger 3.60–3.65 Ga population corresponds to the rock formation age and that the 3.81–3.86 Ga population was inherited. Our re-interpretation is not only compatible with the direct age constraints on Akilia Association rocks but also with the aforementioned Pb isotope characteristics of the cross-cutting Amîtsoq gneiss sheets, thereby demonstrating that the most reliable age constraints in complex gneiss terrains are obtained by a combination of geochronological techniques, rather than by application of only one (the most precise) geochronometer.

The revised dates presented here for Akilia Association enclaves of possible significance for the study of earliest life are nearly 200 Ma younger than the minimum date of *c.* 3865 Ma proposed by Nutman *et al.* (1997a). If our re-interpretation is correct, the question of overlap of earliest life with a lunar-type impact scenario terminating at *c.* 3.80 Ga, as suggested by Nutman *et al.* (1997a), becomes irrelevant.

Space limitations do not allow discussion here of the age of the Isua greenstone belt. However, we agree with Nutman *et al.* (1997b) that deposition of the major part of the belt probably occurred at *c.* 3.71 Ga.

This paper summarises a major conflict between current interpretations of the geochronological evolution of the early Archaean complex of the Godthåbsfjord region of West Greenland. We trust that future work, combining approaches (2) and (3) of Kalsbeek (1997), will resolve this controversy.

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